# TYPES, FEATURES, AND OCCURRENCE OF SINKHOLES IN THE KARST OF WEST-CENTRAL FLORIDA

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## CONTENTS

## ILLUSTRATIONS

ILLUSTRATIONS--Continued

ILLUSTRATIONS--Continued

TABLES

# CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.0348 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| square inch ($in^2$) | 645.2 | square millimeter ($mm^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| cubic inch ($in^3$) | 16.39 | cubic centimeter ($cm^3$) |
| gallon per minute (gal/min) | 0.630 | liter per second (L/s) |
| million gallons per day (Mgal/d) | 0.0438 | cubic meter per second ($m^3/s$) |

Temperatures in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°F = 1.8°C + 32$$

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## ABSTRACT

Sinkholes are a natural and common geologic feature in areas underlain by limestone and other soluble rocks. Four major types of sinkholes are common to west-central Florida. They include limestone-solution, limestone-collapse, cover-subsidence, and cover-collapse sinkholes. The first two occur in areas where limestone is bare or is thinly covered. The second two occur where there is a thick cover (30 to 200 feet) of material over limestone.

Limestone-solution sinkholes result from subsidence of overlying materials that occurs at approximately the same rate as dissolution of the limestone. The sinkholes reflect a gradual downward movement of the land surface and development of funnel-shaped depressions. Limestone-collapse sinkholes occur when a solution cavity grows in size until its roof can no longer support its weight, causing generally abrupt collapse that is sometimes catastrophic.

Cover-subsidence sinkholes develop as sand in the cover material moves downward into space created in limestone by dissolution. Resultant sinkholes develop gradually and are generally only a few feet in diameter. Cover-collapse sinkholes occur where clay layers that overlie limestone have sufficient cohesiveness to bridge the developing cavities in the limestone. Eventual failure of the bridge results in a cover-collapse sinkhole that may develop suddenly.

Large withdrawals of water for various uses may provide a triggering mechanism for sinkholes to occur. Loss of water's buoyant support of unconsolidated deposits that overlie cavities can cause the materials that bridge the cavity to fail and sinkholes to appear. Conversely, loading of the land surface by construction, such as impoundments, may cause collapse of materials that bridge cavities and sinkholes to develop. Impoundments may also provide continuous sources of recharge water and hasten development of cavities in limestone.

West-central Florida was divided into seven zones based on geology, landscape, and geomorphology and the relationship of these factors to the types of sinkholes that occur in each zone. The zones are: (1) areas of bare or thin cover that experience slow developing limestone-solution sinkholes; (2) areas of thin cover, little recharge, high overland runoff, and few sinkhole occurrences; (3) areas of incohesive sand cover of 50 to 150 feet that have high recharge and generally experience cover-subsidence sinkholes; (4) areas that have 25 to 100 feet of cover, many sinkhole lakes, and cypress heads and experience predominantly cover-collapse sinkholes; (5) areas of 25 to 150 feet of sand cover overlying clay that experience cover-collapse and cover-subsidence sinkholes; (6) areas with more than 200 feet of cover, numerous lakes and sinkholes, and high land-surface altitudes that experience numerous cover-subsidence sinkholes and occasional large-scale cover-collapse sinkholes; and (7) areas with cover greater than 200 feet that have 100 or more feet of clay with high bearing strength and low leakance that preclude infiltration of corrosive water and development of sinkholes; however, some cover-collapse sinkholes do occur.

# INTRODUCTION

Sinkholes are a natural and common geologic feature in areas underlain by limestone and other rock types that are soluble in natural water. Topographically, sinkholes are usually identified by closed depressions in the land surface. In west-central Florida, sinkholes are formed by solution of near-surface limestone or by collapse of near-surface materials into underlying solution cavities. Sinkholes are a part of the erosion process analagous to valleys that are carved by rivers in areas underlain by insoluble rocks.

Many lakes in central and west-central Florida are the result of sinkhole collapse. However, when it is realized that these lakes represent sinkholes that have occurred during the past 2 to 5 million years, the frequency of their occurrence is not great.

Sinkholes that collapse abruptly occur infrequently under natural conditions. The abrupt collapse-type sinkholes, however, have occurred at increasing rates during the past few decades, not only in west-central Florida, but throughout the world. The cause of this increase in sinkhole occurrence can generally be attributed to activities of man, such as pumping of ground water, dredging or diversion of surface water, or construction of reservoirs and ponds. Man imposes abrupt stresses on land that can induce or hasten development of sinkholes. Induced sinkholes can be a hazard in developed and developing areas of west-central Florida, and their occurrence is expected to continue.

An understanding of sinkholes and their relation to the hydrologic system will become increasingly important as stresses on the system intensify and the likelihood of sinkhole occurrence increases. Thus, in 1979, the U.S. Geological Survey, in cooperation with the Southwest Florida Water Management District, began this study to determine hydrogeologic factors that control sinkhole occurrences in west-central Florida.

## Purpose and Scope

The objectives of the study are to describe hydrogeologic factors that control sinkhole development and to distinguish types of sinkholes common to west-central Florida. An understanding of natural factors in the hydrologic and geologic setting, such as topography, drainage patterns and densities, thickness and type of surficial materials, thickness of confining beds, head differences between water levels in surficial and artesian aquifers, and surface-water and ground-water flow patterns, will provide insight to natural sinkhole development and sinkhole development caused by man's activities. The information is needed to assist in determining the potential for sinkholes to occur and their mode of occurrence.

The study area includes about 10,000 $mi^2$ in west-central Florida (fig. 1). Boundaries of the area are those of the Southwest Florida Water Management District (SWFWMD). The report provides a map of geomorphic units that are classified by sinkhole occurrence, density, and type. Also provided are a tabulation of reported sinkholes, their locations, dates of occurrence, and descriptions, and a discussion of signs warning of sinkhole development.

This report supplements and amplifies the statewide map report "Sinkhole type, development, and distribution in Florida," by Sinclair and Stewart (1985). In particular, the four areas of sinkhole occurrence in the statewide report have been subdivided herein into seven zones and the category of solution sinkholes has been subdivided into limestone-solution and limestone-collapse sinkholes. Zones 1 and 2 herein comprise Area I of the statewide report; zone 3 comprises Area II; zones 4, 5, and 6 comprise Area III; and zone 7 comprises Area IV of the statewide report.

## Description of Area

West-central Florida is characterized by relatively flat, generally swampy lowlands in coastal areas and by gently rolling hills in inland areas. Except for a coastal ridge in central Pinellas County that has altitudes as much as 100 feet above sea level, coastal areas are less than 50 feet in altitude (fig. 2). Cross sections that illustrate the topography are shown in figure 3.

In the southern half of the area, the low-lying coastal plain gradually rises toward the east, butting against sand-covered ridges that have altitudes of more than 150 feet above sea level (figs. 2 through 4). Within the ridge area are numerous sinkhole lakes--circular sinkholes that have filled with water. Surface drainage in the south is relatively well developed.

In the northern half of the area, the low-lying coastal plain also butts against sand ridges trending in a north-northwesterly direction (fig. 4). East of the Brooksville Ridge, the topography is subdued. The northern area has numerous swamps, lakes, and shallow sinkholes. Irregular karst topography and poorly developed surface drainage occur in the northern areas. From the northern part of Pasco County northward, surface drainage, except for the Withlacoochee River, is essentially nonexistent. The only rivers are near the coast and they discharge water from springs. Virtually all springflow is discharge from the Upper Floridan aquifer.

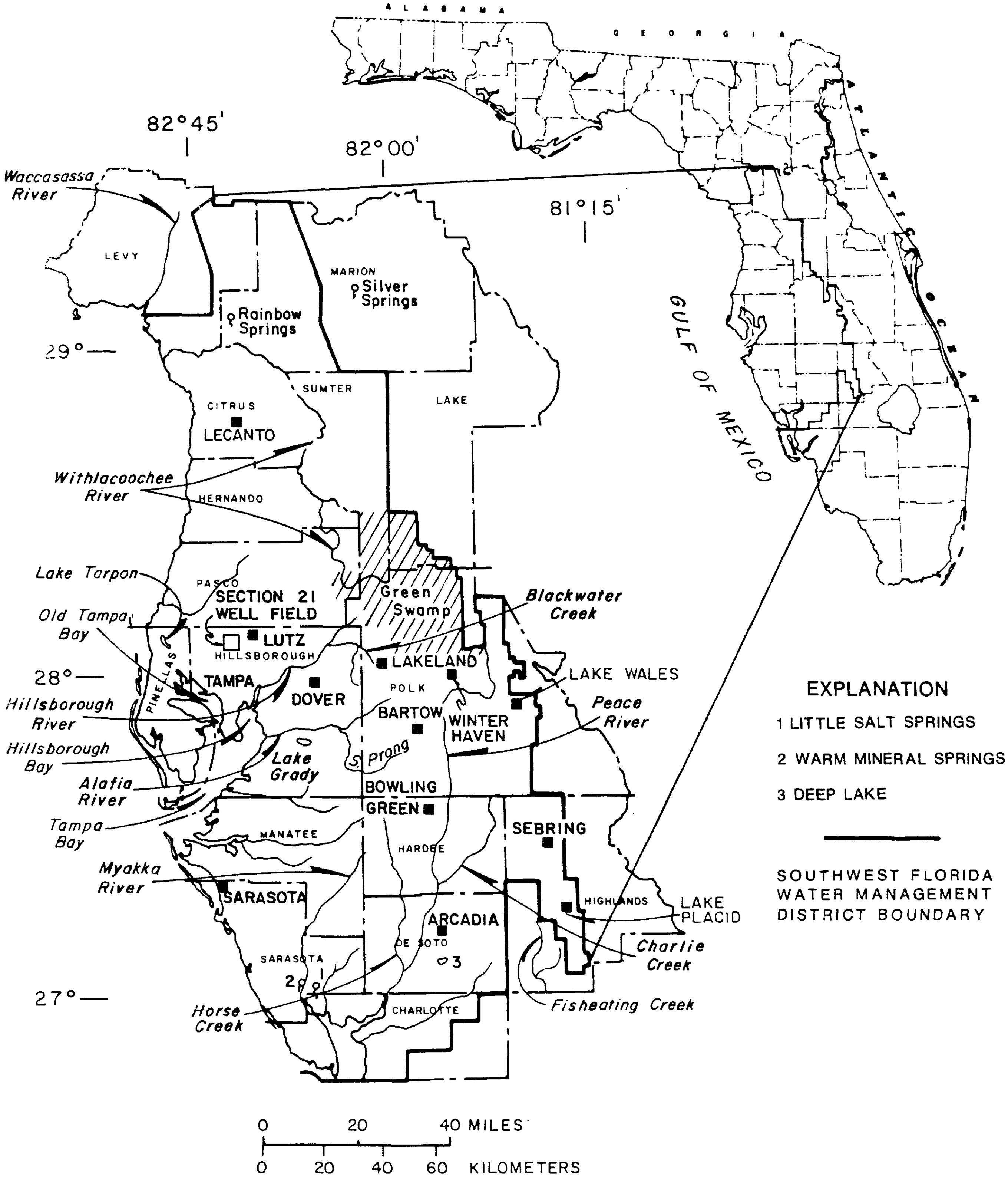


Figure 1.--Location of study area.

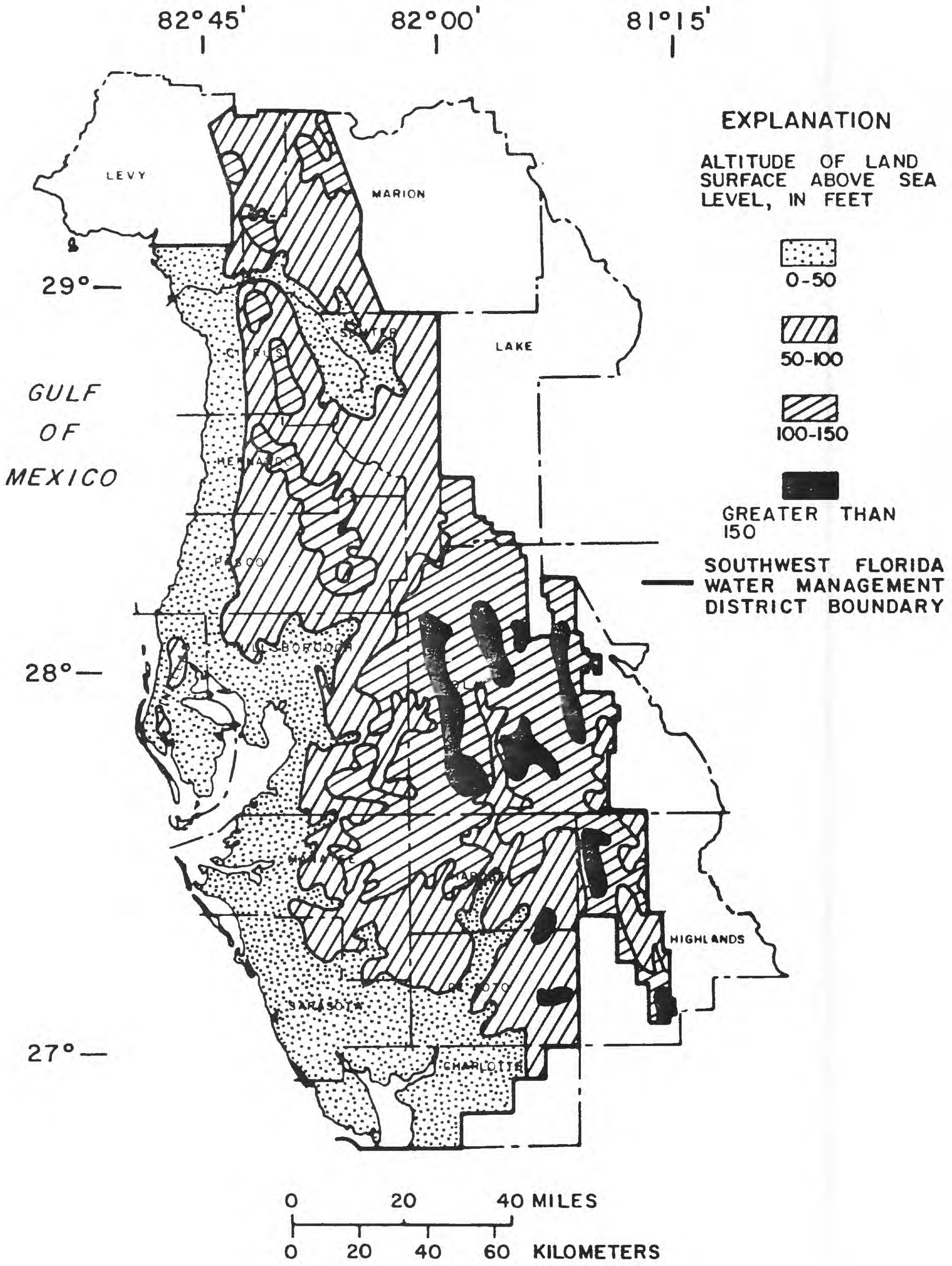


Figure 2.--Topography of west-central Florida.

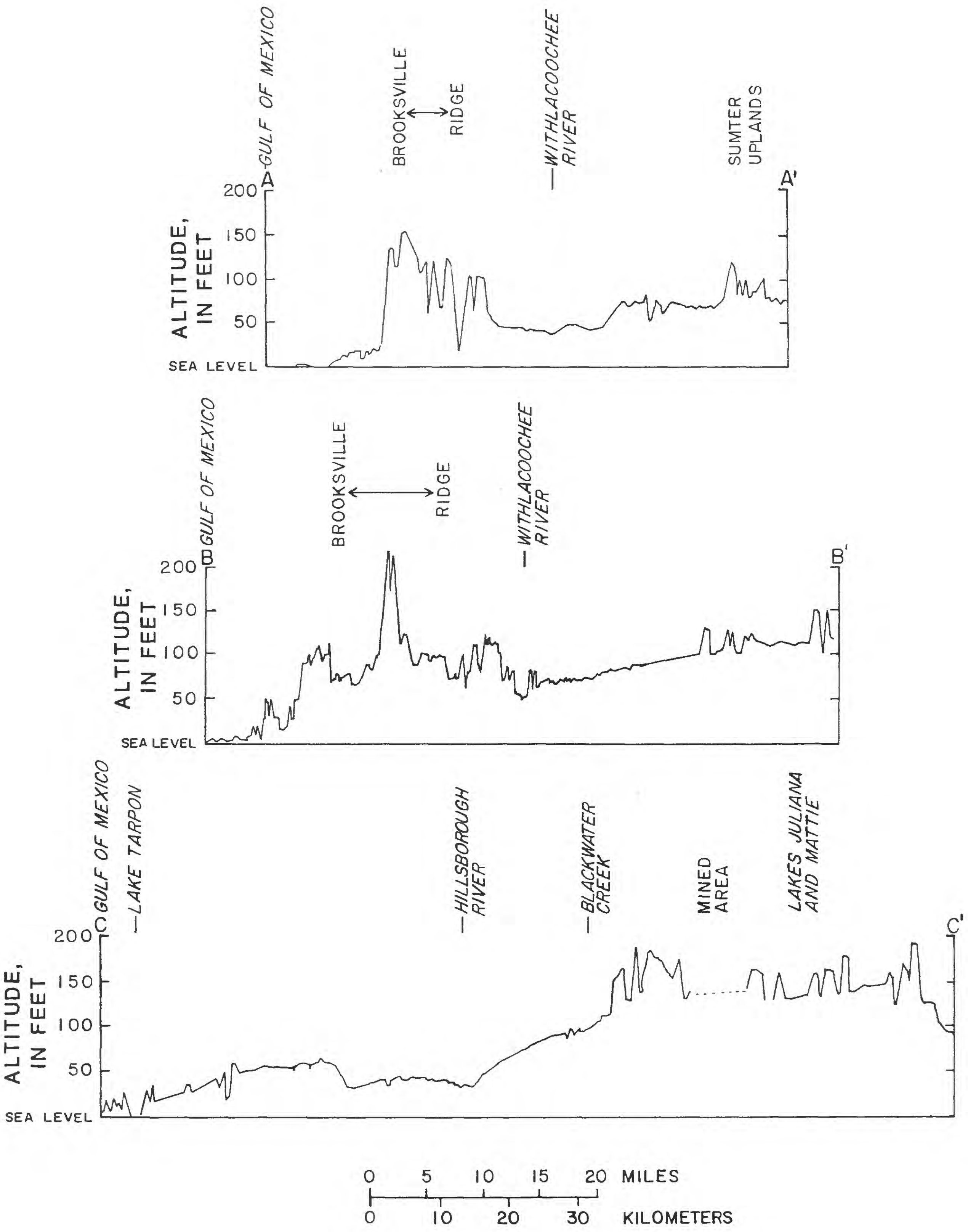
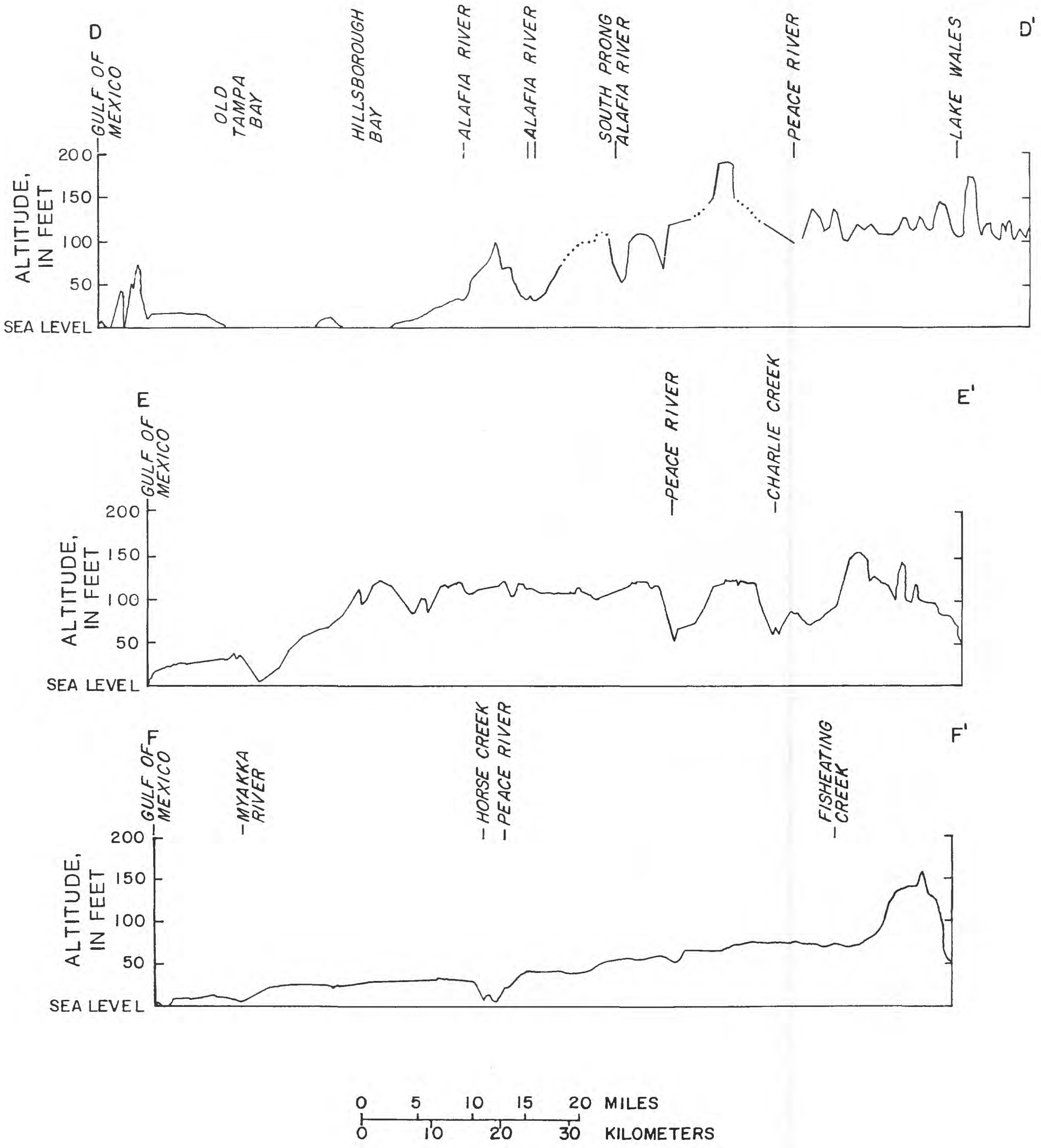


Figure 3.--Topographic sections. (Locations of sections are



shown in figure 4; site locations are shown in figures 1 and 4.)

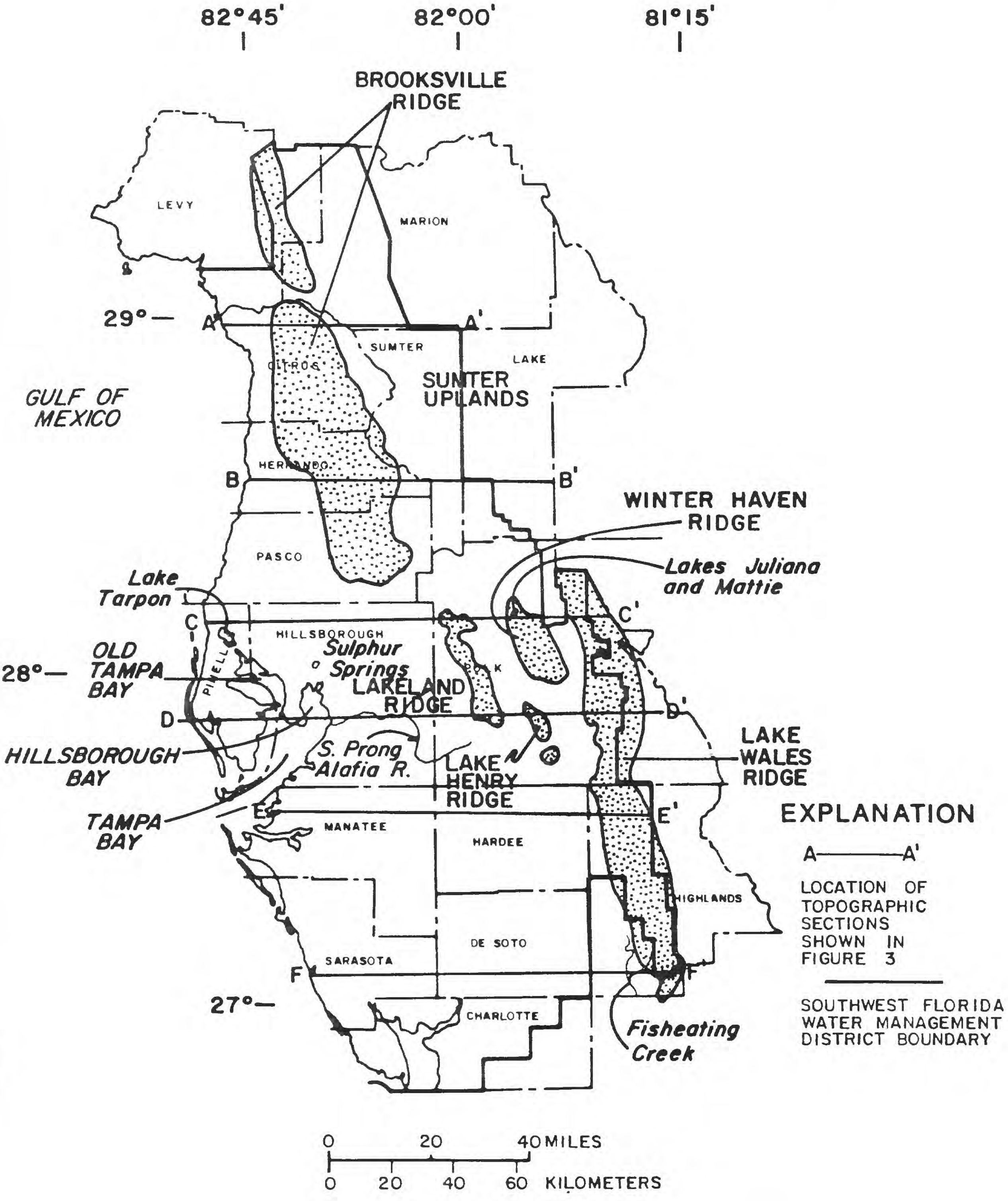


Figure 4.--Locations of ridges in west-central Florida. (Modified from White, 1970.)

## Climate

The climate of west-central Florida is subtropical and is characterized by warm, humid summers and mild winters. Some rainfall normally occurs during each month, but a distinct rainy season extends from June through September and a low rainfall season extends from October through May. About 60 percent of the annual rainfall occurs during the rainy season. Winter rainfall is relatively light because west-central Florida is south of the normal southern limit of winter frontal systems, the causative factor of winter rainfall. Summer rainfall is derived principally from convectional storms that usually occur in the afternoon and early evening and from occasional tropical storms. Spatially, summer rainfall is highly variable; areas only a few miles apart often receive widely differing amounts of rain.

The average annual temperature at Lakeland, which typifies the area, is 72.7°F. Average monthly temperatures range from 61°F in January to 82°F in July and August. Rainfall at Lakeland averages 48.3 inches annually. The amount of rainfall received throughout west-central Florida provides an adequate source of recharge water, a primary need for sinkhole development.

## Previous Investigations

Numerous reports have been written on the geology and hydrology of west-central Florida, but few reports deal primarily with the subject of sinkholes. Some related reports include a report by Back and Hanshaw (1971) that describes the rates of physical and chemical processes in a carbonate aquifer. Sinclair (1982) described sinkhole development resulting from ground-water withdrawals near Tampa. Sinclair (in press) also prepared a general information pamphlet that describes sinkhole development and their occurrence and probability in Florida. Miller and others (1981) described the morphology of sinkholes and lakes in the Withlacoochee River region. Sinclair and Stewart (1985) described sinkhole features in Florida, including descriptions of geology and principles of ground-water movement as related to the creation of sinkholes. Stewart (1968) described the effects of pumping on hydrology in parts of Hillsborough, Pinellas, and Pasco Counties.

Other related reports include that by Ryder (1982) who developed a digital flow model of the area and described its geologic setting. Vernon (1951) provided geologic information for Citrus and Levy Counties. In a report on artesian water in the Tertiary limestone in the Southeastern States, Stringfield (1966) provides data on geologic formations and sinkhole occurrences. White (1970) described the geomorphology of the Florida peninsula. Stewart (1982) described ground-water degradation incidents in west-central Florida, some of which relate to sinkholes.

# GEOLOGY

Limestone underlies the Florida peninsula to depths of several thousand feet. Tertiary limestones and formations (table 1) were deposited much as the limestones of the Bahamas Bank are deposited today. Deposition of each

Table 1.--Hydrogeologic framework

[Modified from Wilson and Gerhart, 1982, table 1; Miller, in press, table 3]

| System | Series | Stratigraphic unit | General lithology | Major lithologic unit | Hydrogeologic unit | Geologic process | Age estimates of boundaries, in million years[1/] |
|---|---|---|---|---|---|---|---|
| Quaternary | Holocene Pleistocene | Surficial sand, terrace sand, phosphorite | Predominantly fine sand; interbedded clay, marl, shell, limestone, phosphorite. | Sand | Surficial aquifer | | |
| Tertiary | Pliocene | Undifferentiated deposits[2/] | Clayey and pebbly sand; clay, marl, shell, phosphatic. | Clastic deposits | Confining bed<br>INTERMEDIATE AQUIFER AND CONFINING UNITS | Fluctuations of sea level with consequent high water tables and deposition in low-lying areas alternating with low water tables and accelerated weathering of soluble rocks. | 2 |
| | Miocene | Hawthorn Formation | Dolomite, sand, clay, and limestone; silty, phosphatic. | Carbonate and clastic deposits | Aquifer | | 5 |
| | | Tampa Limestone | Limestone, sandy, phosphatic, fossiliferous; sand and clay in lower part in some areas. | Carbonate deposits | | Exposure and weathering | 24 |
| | Oligocene | Suwannee Limestone | Limestone, sandy limestone, fossiliferous. | | | Carbonate deposition | |
| | Eocene | Ocala Limestone | Limestone, chalky, foraminiferal, dolomitic near bottom. | | Confining bed | Exposure and weathering | 38 |
| | | Avon Park Formation | Limestone and hard brown dolomite; intergranular evaporite in lower part in some areas. | | FLORIDAN AQUIFER SYSTEM<br>Upper Floridan aquifer | Carbonate deposition | |
| | | Oldsmar Formation | Dolomite and limestone, containing intergranular gypsum in most areas. | Carbonate and evaporite deposits | Middle confining unit<br>Lower Floridan aquifer | | |
| | Paleocene | Cedar Keys Formation | Dolomite and limestone with beds of anhydrite. | | Sub-Floridan confining unit | Exposure and weathering<br>Carbonate deposition | 55<br>63 |

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[1/] Geologic Times Chart, 1984.

[2/] Includes all or parts of Caloosahatchee Marl, Bone Valley Formation, Alachua Formation, and Tamiami Formation.

formation was followed by a period of emergence, erosion, and solution that resulted in development of surface irregularities and solution cavities. Paleokarst surfaces (karst features that were formed in previous geologic times) probably are accordant with each of the periods of emergence and erosion that occurred at the end of deposition of the Avon Park Formation, the Ocala Limestone, and the Suwannee Limestone (table 1).

Clastic sediments that mantle Tertiary limestone were carried from the Appalachian Mountains and the Piedmont, a plateau at the base of the mountains, following the Miocene Epoch and were deposited with limestone. As the depositional environment changed from marine to estuarine and terrestrial in late Tertiary time, clastic sediments became predominant. Descriptions of the formations, starting with the Avon Park Formation, are given in the following sections.

## Tertiary System

Eocene.--The Avon Park Formation (table 1) is composed of fossiliferous limestone and dolomite. The limestone is a moderate brown, dark yellow-brown to dusky yellow-brown, porous and very-fine to medium-grained, and may be crystalline or saccharoidal in texture. The formation is very permeable and cavernous where extensive dissolution has occurred. Its thickness ranges from a few feet in northern areas to more than 800 feet in the south (figs. 5 through 8). The differences in thickness reflect depositional and tectonic effects and postdepositional erosion.

The Ocala Limestone is a shallow-water marine limestone composed of foraminiferal tests, large foraminifera, mollusks, and large echinoids. Lithologically, it is a soft-to-hard, highly fossiliferous limestone that contains minor amounts of dolomite. The Ocala Limestone crops out in parts of Citrus, Levy, and Marion Counties. Where the Ocala Limestone is close to land surface, dissolution of limestone is characterized by caverns and solution pipes. In Levy, Citrus, Marion, Polk, and Sumter Counties, the top of the Ocala Limestone is about 90 feet above sea level. It dips to the south and reaches a maximum thickness of about 600 feet (figs. 5 through 8).

Oligocene.--The Suwannee Limestone is biogenic, predominantly foraminiferal test packstone to grainstone. Interbeds may contain quartz sand, and dolomite is common toward the unit's base from the Tampa Bay area southward. The upper part may contain thin chert lenses and be highly macrofossiliferous.

The Suwannee Limestone consists of relatively pure calcium carbonate. It is exposed locally in southern Citrus and Sumter Counties, most of Hernando County, parts of Pasco County, and in the northeast corner of Hillsborough County. The Suwannee Limestone pinches out in Polk County (section C-C', fig. 6, and sections F-F' and G-G', fig. 8), is absent in Levy County, and crops out in central Citrus County where it caps the topographic highs to form part of the central highlands (White, 1970). The Suwannee Limestone is as much as 300 feet thick in the south (sections D-D' and E-E', fig. 7).

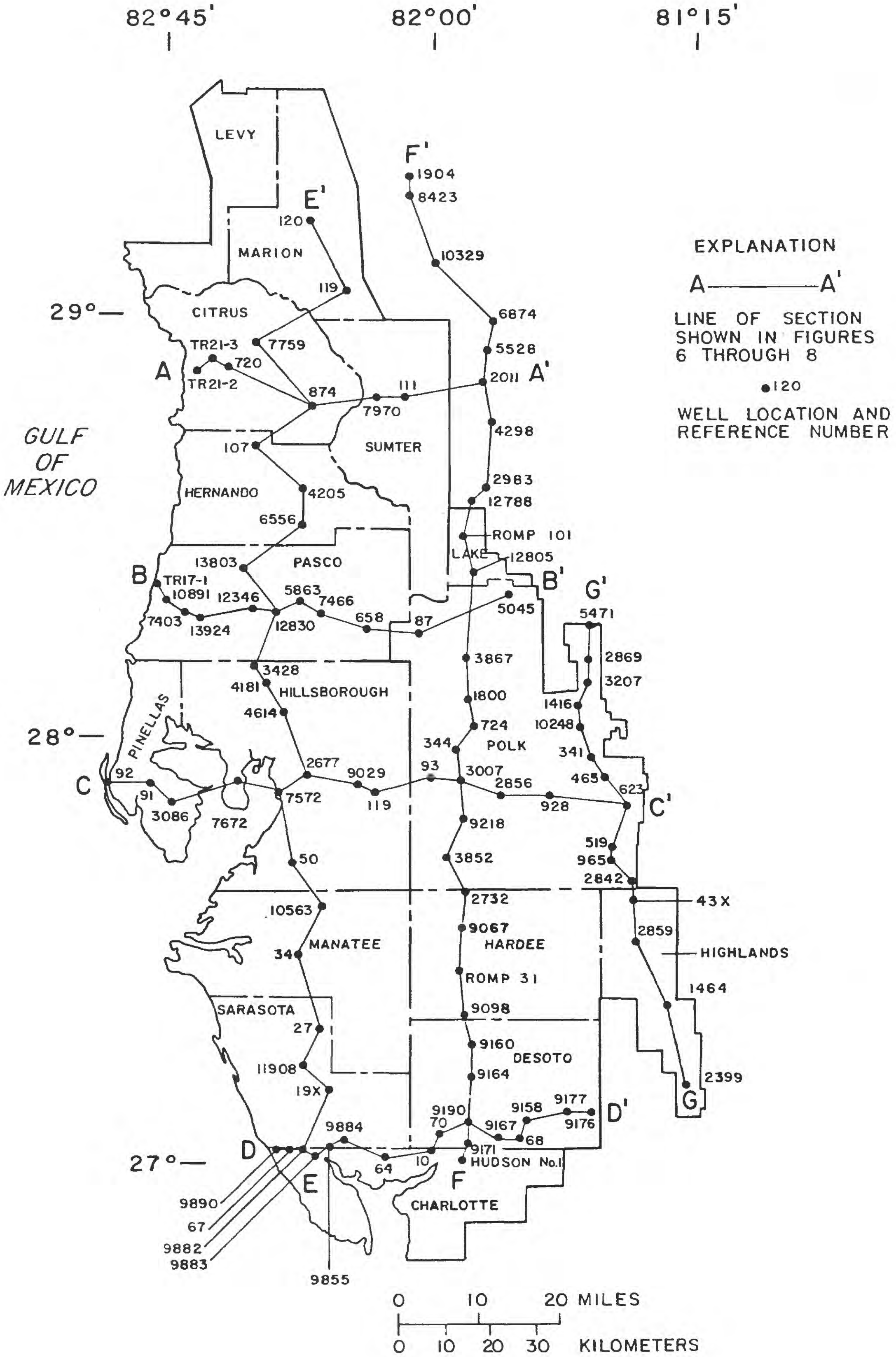


Figure 5.--Locations of geologic sections.

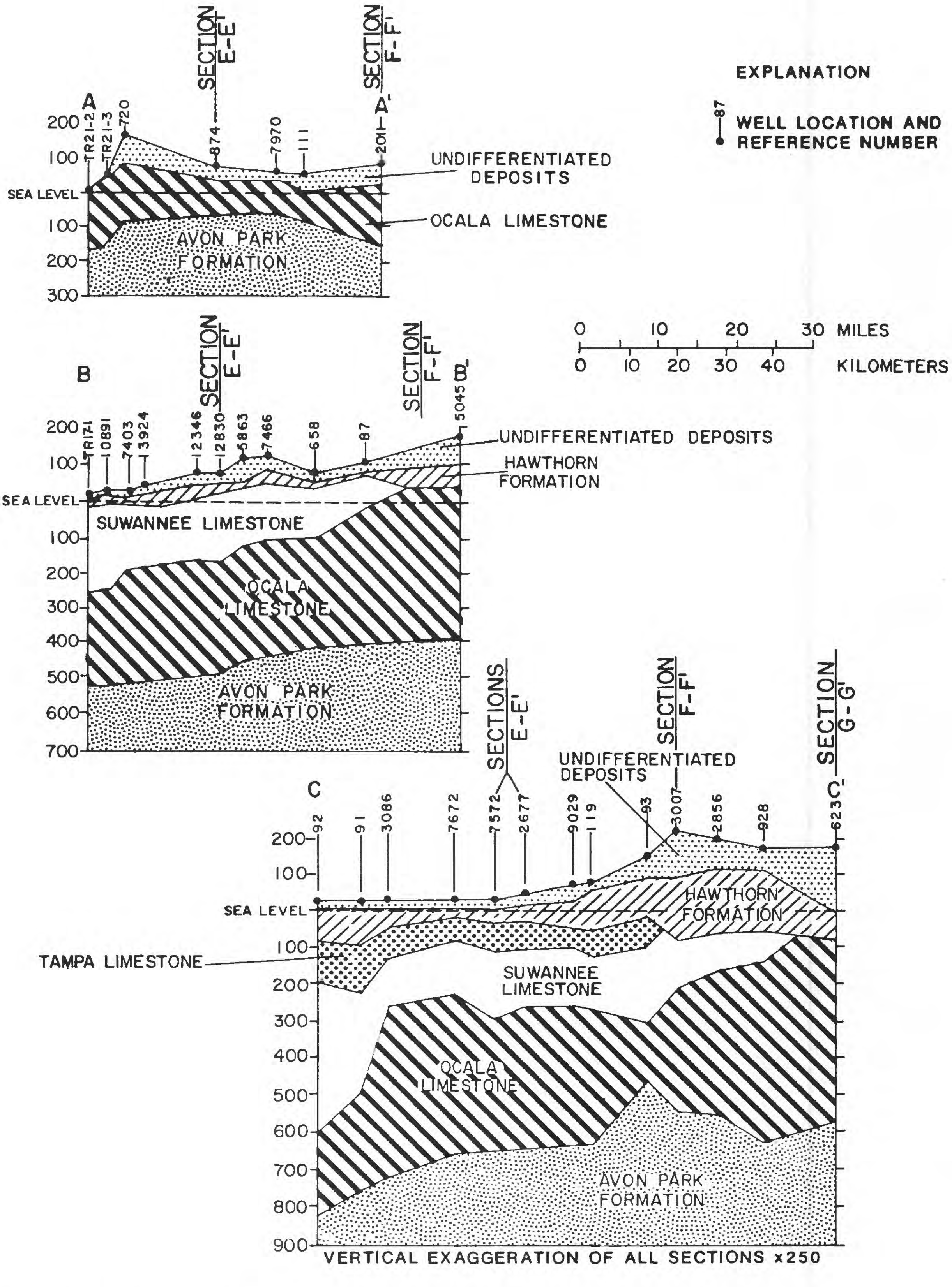
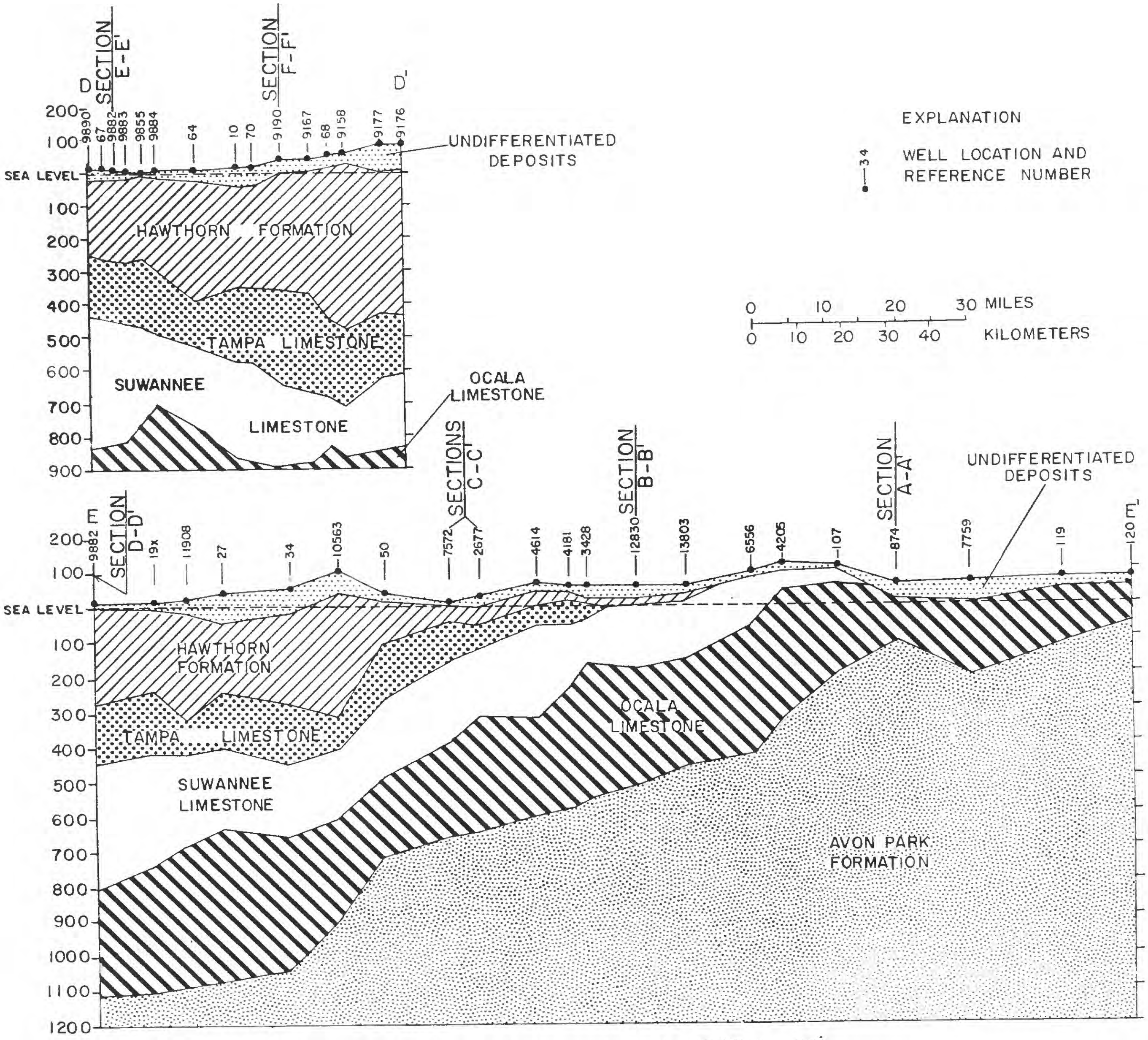


Figure 6.--Geologic sections A-A', B-B', and C-C'. (Locations of sections are shown in figure 5. Modified from Gilboy, 1982.)



VERTICAL EXAGGERATION OF SECTIONS x 250

Figure 7.--Geologic sections D-D' and E-E'. (Locations of sections are shown in figure 5. Modified from Gilboy, 1982.)

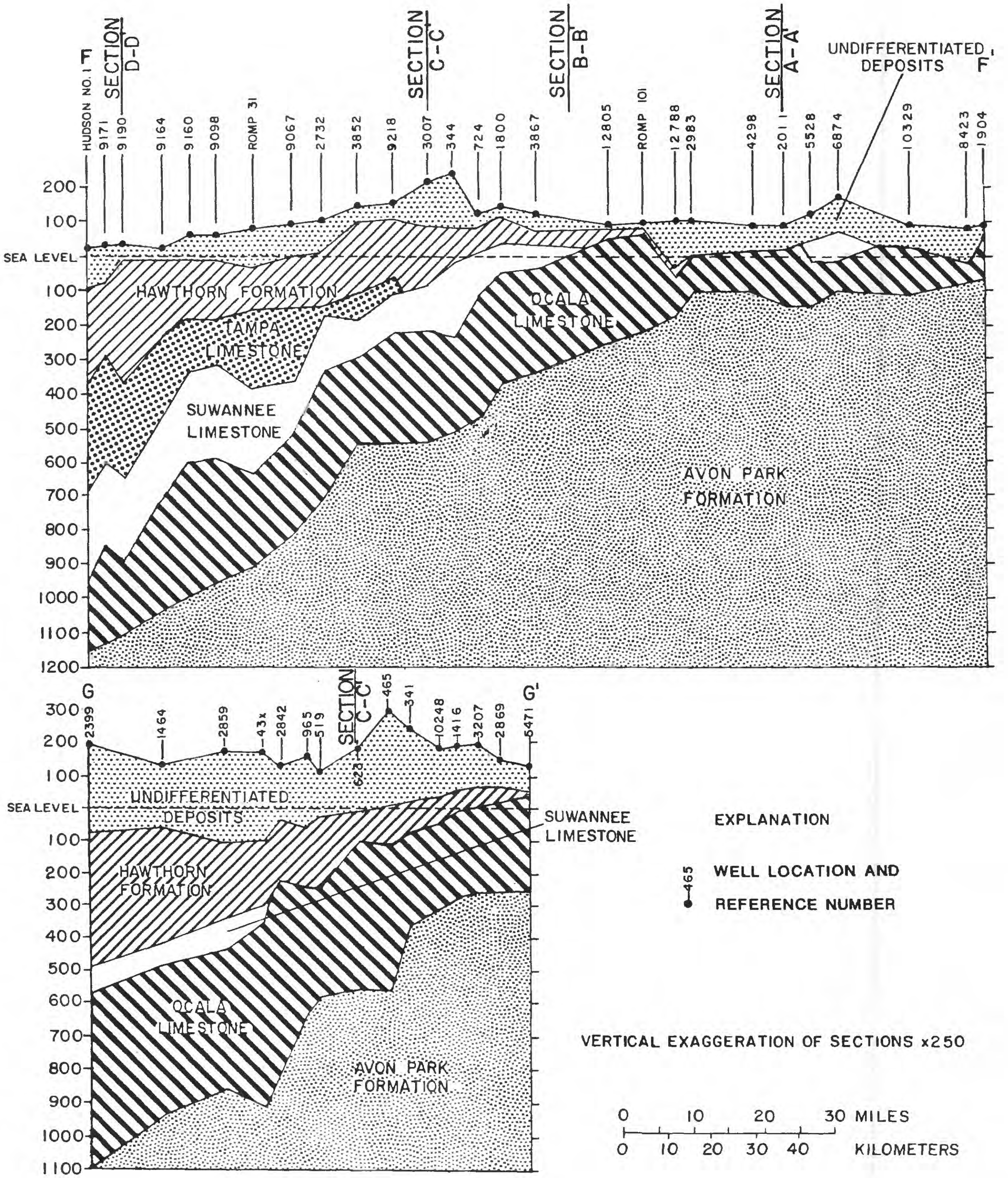


Figure 8.--Geologic sections F-F' and G-G'. (Locations of sections are shown in figure 5. Modified from Gilboy, 1982.)

Miocene.--Miocene sediments are divided into two stratigraphic units, each unit formed as a result of a marine transgression. The two units, from older to younger, are the Tampa Limestone and the Hawthorn Formation (table 1).

A shallow marine environment covered most, if not all, of western peninsular Florida and resulted in deposition of the Tampa Limestone (Carr and Alverson, 1959). The Tampa Limestone consists of limestone and varying amounts of quartz sand and clay embedded in a carbonate matrix. The unit is absent in the north (section A-A', fig. 6), but is as much as 300 feet thick in the south (section D-D', fig. 7). The formation is differentiated from the overlying Hawthorn Formation based on a decrease in or absence of phosphorite and an increase in quartz sand within the rock matrix (King and Wright, 1979). The contact between the Hawthorn Formation and Tampa Limestone is commonly marked by a chert layer at the top of the Tampa Limestone and a weathered, gray, dolomitic limestone. From approximately Sarasota County to southern Hardee County, the lower part of the Hawthorn Formation and Tampa Limestone become lithologically undifferentiable. The Tampa Limestone contains a much higher percentage of phosphorite and clay in southern areas than in Hillsborough County. The Tampa Limestone deposits thin to the north and east of the county. The unit is absent in central Polk County (section C-C', fig. 6) where it grades into a blue-green clay that is devoid of carbonates.

During middle Miocene time, the sea rose and covered most of peninsular Florida except the Ocala uplift area and deposited clastic and carbonate sediments of the Hawthorn Formation. The diverse composition of the Hawthorn sediments reflects depositional environments that include open marine and shallow-water coastal marine. A small percentage of the sediments was derived from fluvial and estuarine processes (Riggs, 1979). Postdepositional reworking of the deposits left residual sand and clay in some places.

The Hawthorn Formation is absent in the north, thickens to the south, and attains a maximum thickness of approximately 600 feet in southern De Soto, Highlands, and Charlotte Counties (figs. 5 through 8). The basal Hawthorn section is composed of carbonate deposits (usually dolomitic) that contain varying amounts of interbedded quartz sand, clay, and phosphate. The middle section consists of interbedded sandy carbonate, clayey sand, and sandy clay. The upper Hawthorn section is predominantly composed of clastic deposits that consist of quartz, phosphate sand and pebbles, and light green to a moderately dark gray clay (Hall, 1983).

The trifold subdivision of the Hawthorn Formation is most apparent in the south. Elsewhere, one or two of these units may be absent, or the upper unit may lie directly over the lowermost unit. In the north, the units become less distinctive and merge to a single unit where a sandy phosphatic clay predominates, or the formation is absent.

Pliocene.--During early Pliocene time, west-central Florida remained emergent, whereas south and central Florida were submerged. The shoreline extended southward through Lake County to Sebring, circled westward through Arcadia and Sarasota and northwest across the Gulf of Mexico (Cathcart, 1966). The Alachua and Bone Valley Formations that contain fossils of early Pliocene vertebrates accumulated as fluvial deltaic deposits. The shell and marl beds, sandy limestone, and calcareous clay of the Tamiami Formation seem to be the result of contemporaneous marine deposition. The Alachua Formation consists of a blue to gray, sandy clay that weathers to yellow-orange or moderate-red due to the presence of iron oxide. The formation generally contains sufficient clay to give it a distinct plasticity, but it also contains significant amounts of quartz sand. This unit is localized, and remnants may exist in the extreme northern and eastern parts of the study area. This unit is typically found in solution cavities in weathered karst surfaces.

The Bone Valley Formation of Pliocene age consists of fine to coarse quartz sand, clay, thin chert sections, phosphate nodules, and vertebrate fossil fragments. It is well represented on structural highs in the Lakeland Ridge area. The Bone Valley Formation extends approximately from Polk and Hillsborough Counties southward into Manatee and Hardee Counties. Its thickness is generally less than 20 feet, but it is 60 feet or more thick in eastern Polk and Hardee Counties (Cathcart and McGreevy, 1959).

The Tamiami Formation is composed principally of white to cream-colored, sandy limestone that grades downward into clay, silt, and very fine sand beds of low permeability. The formation contains abundant oysters and littoral deposits that attest to a shallow marine environment of deposition. The Tamiami Formation may be present in the extreme southern parts of the study area (Hunter and Wise, 1980). The Caloosahatchee Marl overlies the Tamiami Formation and consists of a thin sequence of interbedded clay, calcareous clay, and sand that locally contain broken shelly material (Miller, in press). The upper part of the Caloosahatchee Marl is of Pleistocene age (table 1).

## Quaternary System

Pleistocene and Holocene.--Changes that took place in sea level during the Pleistocene Epoch within the Quaternary System resulted in significant changes in geologic formations that make up the Florida peninsula. Pleistocene and Holocene sediments within west-central Florida consist of unconsolidated to poorly indurated clastics, dominated by quartz sand and shell (marine mollusks predominantly) interbedded with clay and marl. Pleistocene strata include marine and nonmarine beds and may consist of residual lacustrine, fluvial, and eolian deposits. During the Pleistocene Epoch, parts of the Florida peninsula remained relatively stationary, although sea level repeatedly fluctuated in response to glaciation.

Five major stands of low sea level occurred during the Pleistocene Epoch. During each stand, the shoreline receded further seaward. Erosion, subterranean solution, and widespread sinkhole development in the calcareous rocks became prevalent. Subsequent to each period of low sea level, there were associated high-stand periods of deposition that formed five terraces and shorelines (Cooke, 1931). During each of these interglacial periods, coastal features such as spits, bars, and lagoons were formed along the shoreline (Healy, 1975).

Within the northern part of the study area, parts of Citrus, Levy, and Marion Counties have only a veneer of Quaternary sediments overlying the Eocene Ocala Limestone and Avon Park Formation (section A-A', fig. 6, and E-E', fig. 7). These clastic sediments thin westward toward the Gulf Coast. South of Citrus, Levy, and Marion Counties, a number of Pleistocene scarps, terraces, and ridges dot the landscape. The most prominent ridges include the Brooksville, Lakeland, Winter Haven, Lake Henry, and Lake Wales Ridges (fig. 4).

Thickness of the Quaternary deposits tends to increase from north to south. Maximum thicknesses are at the ridges. The Lake Wales Ridge contains the greatest thickness (about 250 feet) of sediments (Bishop, 1956).

### Structural Setting

The area's regional structure incorporates sediments that thicken to the south and southeast. These strata have a gentle homoclinal dip except where they have been modified by local structural conditions. Three structural features of major significance controlled depositional environments of west-central Florida. They are the Peninsular arch, the Ocala uplift, and the south Florida shelf (fig. 9). The Peninsular arch (Applin, 1951) is a large anticlinal fold that affected rock formations throughout the Tertiary System. The arch is the dominant subsurface structural feature of the northern two-thirds of the Florida peninsula. The arch (fig. 9) extends from south-central Georgia to near Lake Okeechobee (Applin and Applin, 1965). Rocks of Tertiary age, predominantly calcareous and overlying the arch, control karst topography in west-central Florida.

It is not clear whether the Ocala uplift is a positive tectonic element or whether Tertiary deposits are draped over a relatively stable basement high. Possibly a combination of the two factors has resulted in thickening of Tertiary sediments away from the two anticlinal crests in the northern part of the peninsula.

The third structural feature, termed the "south Florida shelf" by Applin and Applin (1965), is a broad, relatively flat area composed of rocks of Early Cretaceous and Late Jurassic age. The shelf is southwest of the Peninsular arch and borders the northeast part of the south Florida basin (fig. 9). This shelf extends nearly 200 miles across the Florida peninsula from the Atlantic Coast to Charlotte County. The shelf contains some ancient sinkholes, but there is little current sinkhole activity.

Other structural features may be present that have affected deposition, erosion, and development of karst features. For example, Altschuler and Young (1960) considered the Lakeland Ridge (fig. 4) to be an uplifted block and faults that parallel the east and west sides of the ridge (fig. 9). Vernon (1951) delineated two regional fracture patterns associated with the Ocala uplift. He states that the regional fracturing reflects structural movement during the late Tertiary System. Frequently, stream orientation and sinkhole lineation parallel the fracture patterns. Within the study area, the valley of the Withlacoochee River (fig. 1) reflects this fracture orientation.

## GROUND-WATER HYDROLOGY

The hydrologic system in the southern two-thirds of west-central Florida differs from that in the north. Differences are based on degree of confinement of the hydrologic system, primarily due to pinching out of Miocene formations (section E-E', fig. 7, and F-F', fig. 8). From the central area to the south,

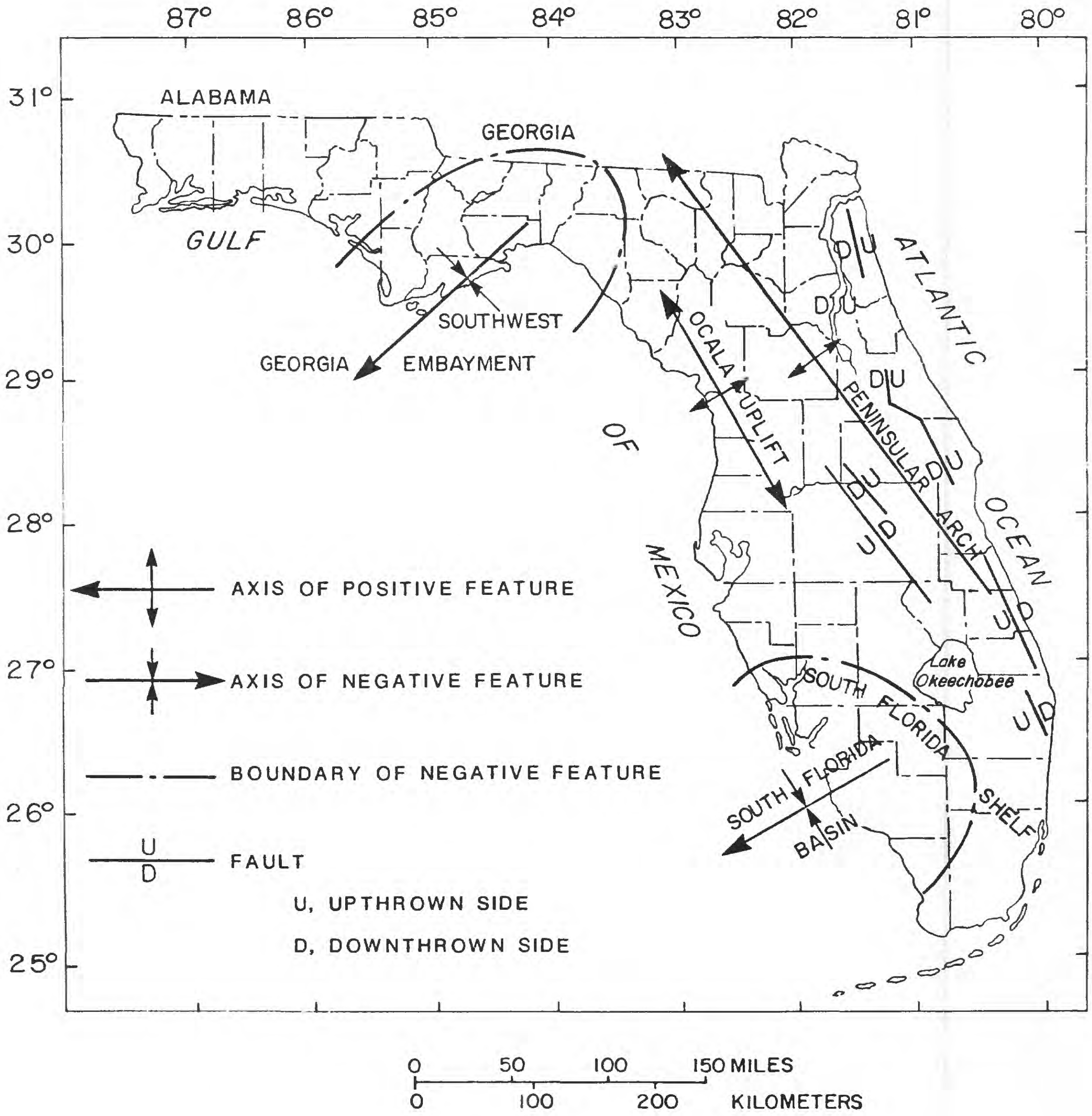


Figure 9.--Structural features in Florida. (Modified from Applin and Applin, 1965; Miller, in press.)

Miocene rocks thicken from a few feet to 600 feet, and the hydrologic system consists of a surficial aquifer, the intermediate aquifer and confining beds, and the Floridan aquifer system. In the north, where Miocene rocks generally are absent, the Floridan aquifer system is unconfined, but may be covered by permeable sand that is 50 or more feet thick.

The principal water-bearing unit is the Floridan aquifer system. As defined by Miller (in press), the Floridan aquifer system comprises:

> "a vertically continuous sequence of carbonate rocks of generally high permeability that are mostly of middle and late Tertiary age, that are hydraulically connected in varying degrees, and whose permeability is, in general, an order to several orders of magnitude greater than that of those rocks that bound the system above and below.
>
> "* * * (in peninsular Florida), less-permeable carbonate units of subregional extent separate the system into two aquifers, herein called the Upper and Lower Floridan aquifers."

Throughout west-central Florida, the freshwater-bearing part of the Floridan aquifer system is the Upper Floridan aquifer. The Upper Floridan aquifer is also the most sinkhole-prone unit in the hydrologic system.

## Recharge and Discharge Areas

The rate of recharge to an aquifer can serve as an indicator of the proximity of the aquifer to the surface, the nature of the overlying sediments, and the relative position of water levels in one aquifer to another. Ryder (1982) defined areas and rates of recharge to and discharge from the Upper Floridan aquifer in west-central Florida (fig. 10). The areas range from those of discharge to areas of recharge of 15 inches or more per year. As noted earlier, the sediments overlying the Upper Floridan aquifer thicken to the south (figs. 7 and 8). The influence of the overlying sediments in retarding recharge to the Upper Floridan aquifer can be seen in areas south of Hillsborough and Polk Counties where recharge rates are relatively low.

The areas that have high recharge rates occur in the north and are indicative of well-drained sands that are in contact with the limestone and areas where permeable limestone is at or near land surface. Areas that have low to moderate recharge rates are generally covered with a discontinuous to thick mantle of silt or clay that slows recharge. Also, some areas where recharge rates are low may be nearly or completely saturated, such as the Green Swamp (fig. 1), and recharge is retarded because of slow ground-water movement.

Discharge areas occur where the potentiometric surface of the Upper Floridan aquifer is at or above land surface and flow is upward. Such areas occur along the coast, at springs and gaining rivers, and along the western edge of the Green Swamp.

Areas of high recharge and high discharge generally correspond to areas where solution channels are well developed in the limestone. In high recharge areas, chemically agressive water readily dissolves limestone. As the water

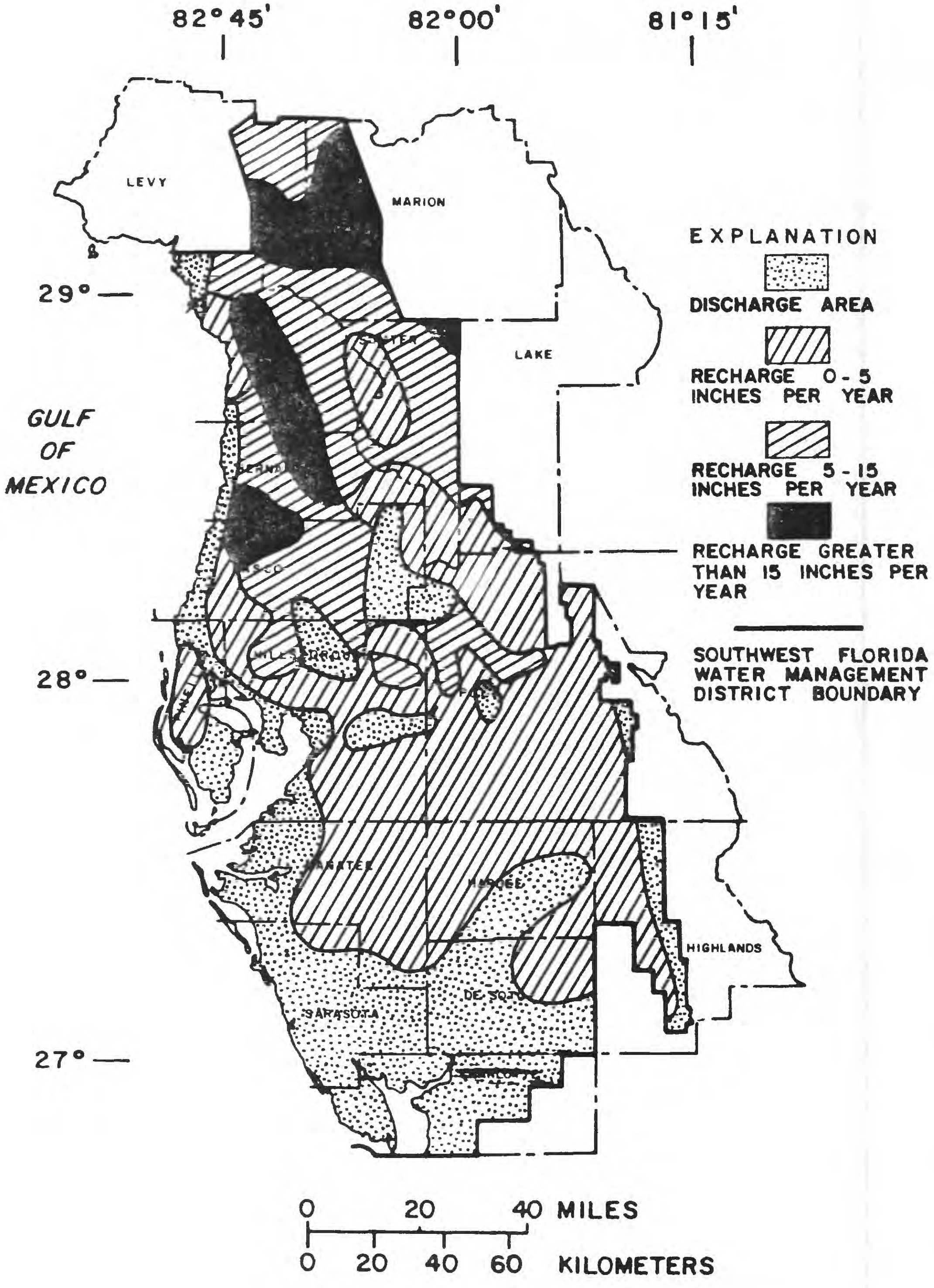


Figure 10.--Distribution of Upper Floridan aquifer recharge and discharge under natural conditions, excluding springflow. (Modified from Ryder, 1982.)

moves downgradient, the rate of dissolution is reduced as retention time within the aquifer increases. In the northern part of the area, the ground-water flow system is relatively shallow and springs discharge much of the water soon after it is recharged. Stewart and Mills (1984), on the basis of dye tests, estimated ground-water velocities to be as high as 9,200 ft/d in an area north of Tampa.

In areas of low recharge and low discharge, ground-water movement is sluggish and retention times may be hundreds or thousands of years. The deep flow system in the south produces highly mineralized water, but sinkhole development is slight.

## Thickness of Cover Material

Although west-central Florida is underlain by thousands of feet of limestone and dolomite that are susceptible to dissolution by ground water, most of the area is covered by a mantle of insoluble sand and clay that control the ultimate route of water that percolates into the materials. In areas where limestone is exposed at land surface, or is thinly covered, rainfall infiltrates directly to the water table through conduits that have been opened and enlarged by dissolution. Where limestone is covered by permeable sand, however thick, rain water is largely held where it falls and percolates downward through the sand into the limestone.

Surface runoff is intermittent where rainfall moves directly into the aquifers. Streams and rivers are widely separated, and valleys that were developed are poorly defined. Conversely, areas where limestone is covered by thick (more than 100 feet) and impermeable clay layers, downward movement of water is retarded or impeded, and well-defined stream channels receive surface runoff and drain a high water table through closely spaced networks of tributaries.

The approximate thickness of the surficial deposits and the confining bed overlying the Upper Floridan aquifer (table 1) are shown in figures 11 and 12, respectively. The surficial deposits include sand, clayey sand, shell, and shelly marl above the confining beds. The surficial deposits consist of Holocene sand, Pleistocene marine terrace sand, unconsolidated parts of the Pleistocene and Pliocene Caloosahatchee Marl, and the Pliocene Alachua and Bone Valley Formations. Throughout large areas in the north, the total thickness of cover material is less than 25 feet. These areas reportedly have very few sinkholes, and those that occur generally are shallow and broad and develop over fairly long periods of time.

The confining bed (fig. 12) is shown as a single unit, although it is composed of various lithologic deposits--mostly clay, sandy clay, marl, clayey sand, limestone, and dolomite. Principal stratigraphic components include: (1) Miocene to Holocene beds of clay, sandy clay, and marl, undifferentiated with respect to age, that underlie the surficial aquifer; (2) the Miocene Hawthorn Formation comprised mainly of phosphatic clays and poorly indurated limestone and dolomite lenses; and (3) the unconsolidated sections of the underlying Miocene Tampa Limestone that occurs in much of Polk, Hardee, De Soto, and Charlotte Counties and consists of clay and clayey sand. Figure 13 is a composite of figures 11 and 12 that shows the total thickness of overburden.

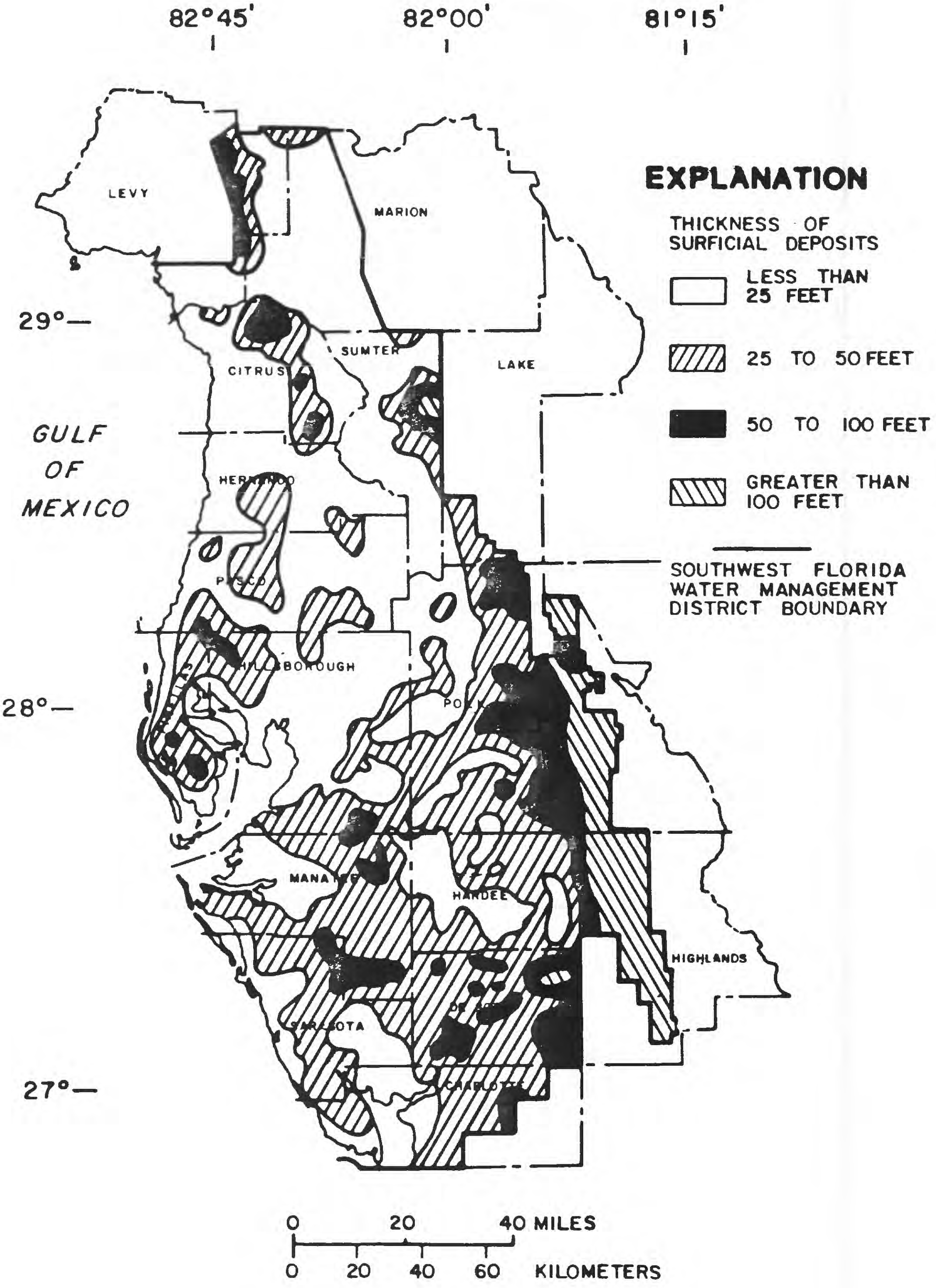


Figure 11.--Generalized thickness of the surficial deposits overlying the confining bed. (From Wolansky, Spechler, and Buono, 1979.)

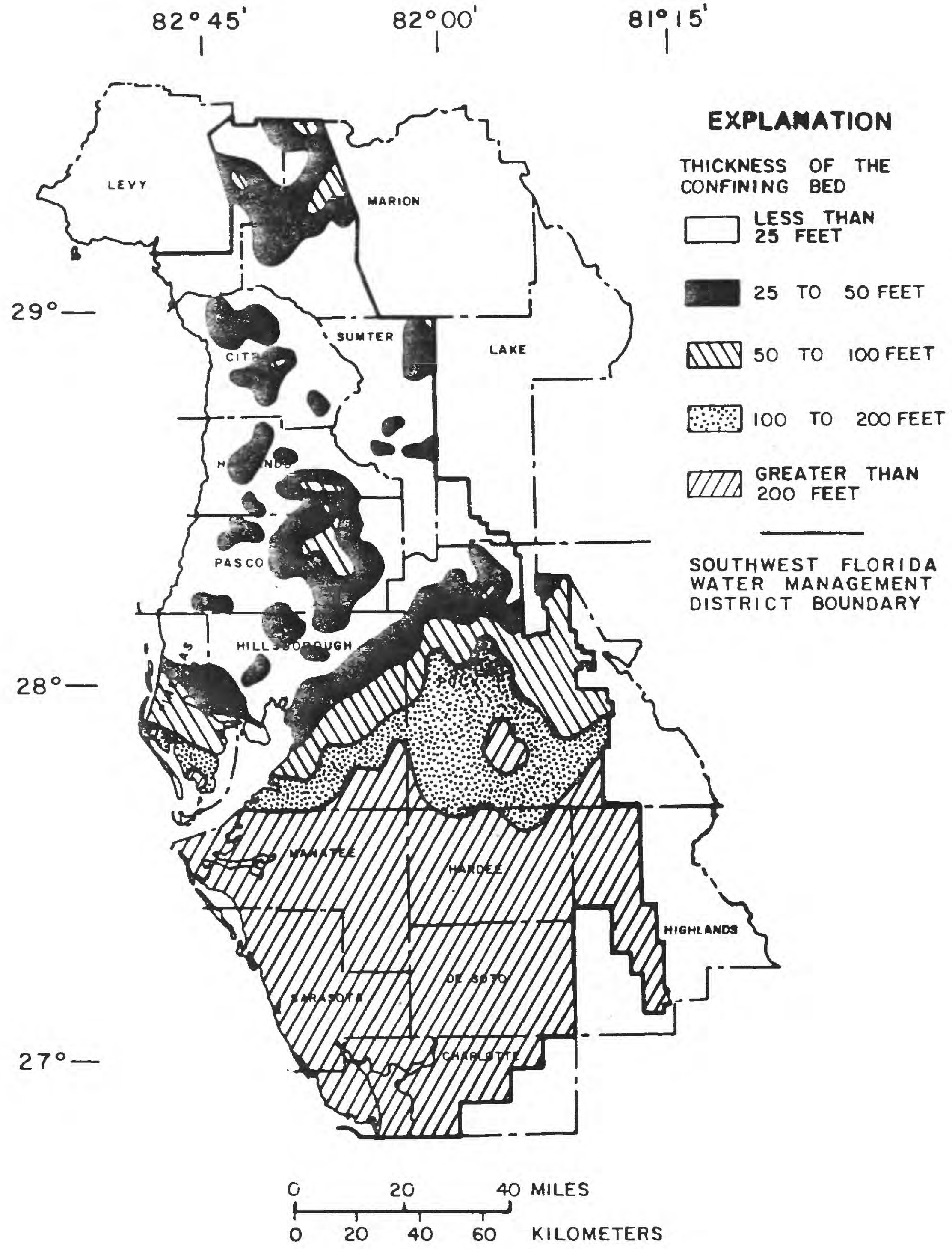


Figure 12.--Generalized thickness of the confining bed overlying the Upper Floridan aquifer. (Modified from Buono and others, 1979.)

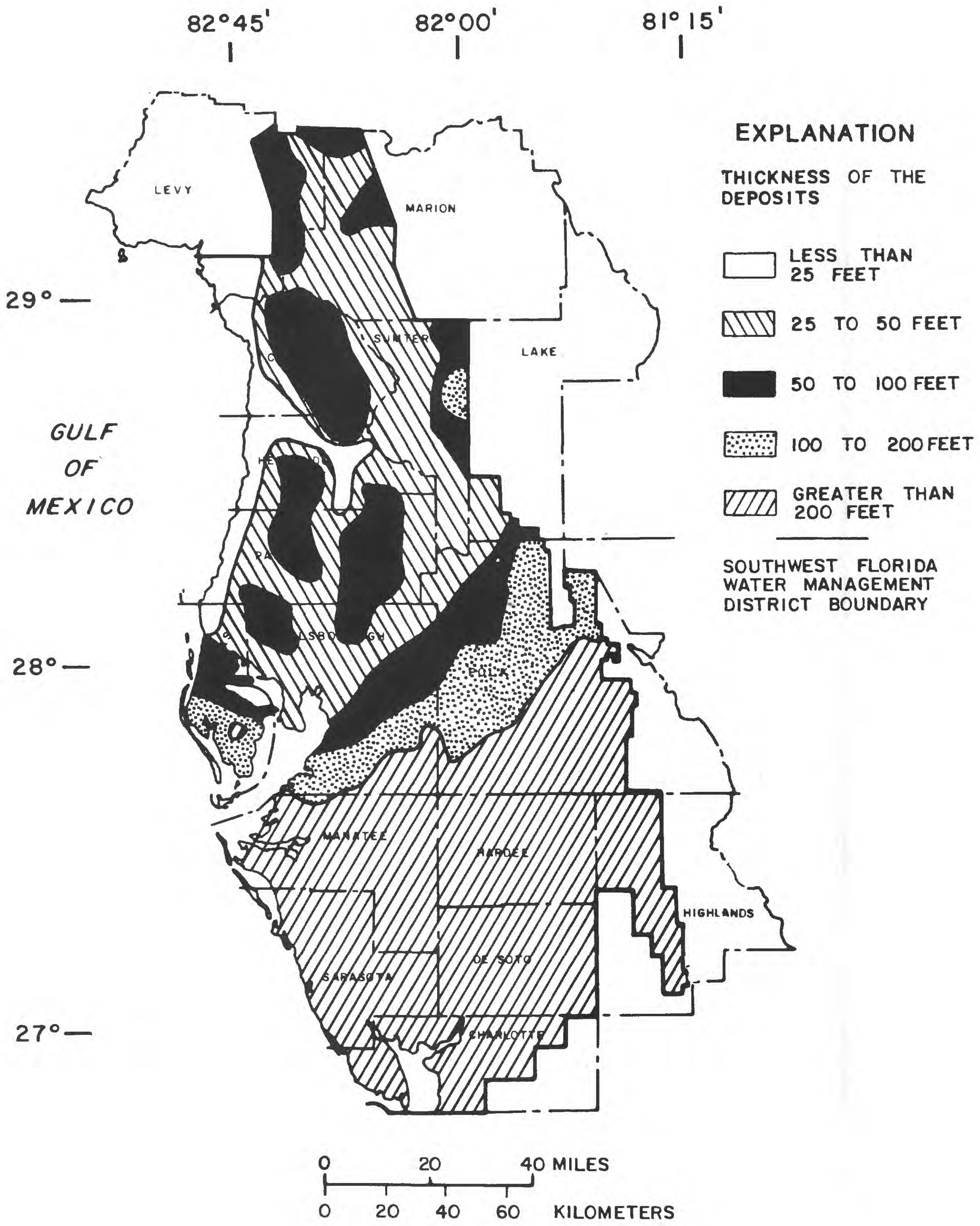


Figure 13.--Generalized thickness of the unconsolidated deposits overlying the Upper Floridan aquifer. (Modified from Buono and others, 1979; Wolansky, Spechler, and Buono, 1979; Gilboy, 1982.)

In some areas in the north, such as at the Brooksville Ridge, limestone is covered by a layer of materials (predominantly sand 50 to 100 feet thick) that are relatively incohesive and permeable. Where the cover is permeable and confining beds are absent, water infiltrates directly to the water table, which may be in the cover or in the underlying limestone. The areas reportedly have very few sinkholes.

Cover material in the central area ranges from 25 to 200 feet or more in thickness. The clay confining bed provides a degree of cohesiveness to the cover material that bridges developing solution cavities. This area reportedly has the greatest number of sinkhole occurrences in west-central Florida.

The southern area has a thick confining bed (more than 200 feet) that limits ground-water circulation and development of solution cavities in the carbonate rocks. Where cavities do form, the confining sediments have adequate bearing strength to bridge cavities of moderate size. Carbonate layers also occur within the clastic confining unit. Where these layers are permeable enough to permit circulation of ground water, they too are subject to dissolution and subsequent sinkhole development. However, the area is generally one of infrequent sinkhole collapse.

## Water-Level Fluctuations in Aquifers

### Surficial Aquifer

The surficial aquifer is unconfined, that is, its water surface or water table is under atmospheric pressure. Water levels in the aquifer respond rapidly to recharge and discharge and, if the water table is close to land surface, to evapotranspiration. Fluctuations of water levels in wells that tap the surficial aquifer are illustrated in figure 14. Seasonal and long-term fluctuations of water levels vary with location. In general, fluctuations are greatest in the highland areas and least in discharge areas near the coast.

Recharge to the surficial aquifer occurs throughout the year and is at a maximum during the wet season (fig. 14). The surficial aquifer is the principal source of recharge to underlying aquifers throughout much of the study area. Where the water table in the surficial aquifer is higher than the potentiometric surface in underlying aquifers, recharge to the lower aquifers occurs. In coastal and other low-lying areas, the head gradient between the aquifers is reversed, and flow is upward from the lower aquifers to the surficial aquifer.

### Upper Floridan Aquifer

The Upper Floridan aquifer is confined by a clay or sandy clay that occurs at the base of the surficial aquifer or intermediate aquifer and confining bed system (table 1), except in the north where limestone is overlain by sand. Where confined, the potentiometric surface of the Upper Floridan aquifer may rise above the top of the limestone. Water levels in wells that tap the

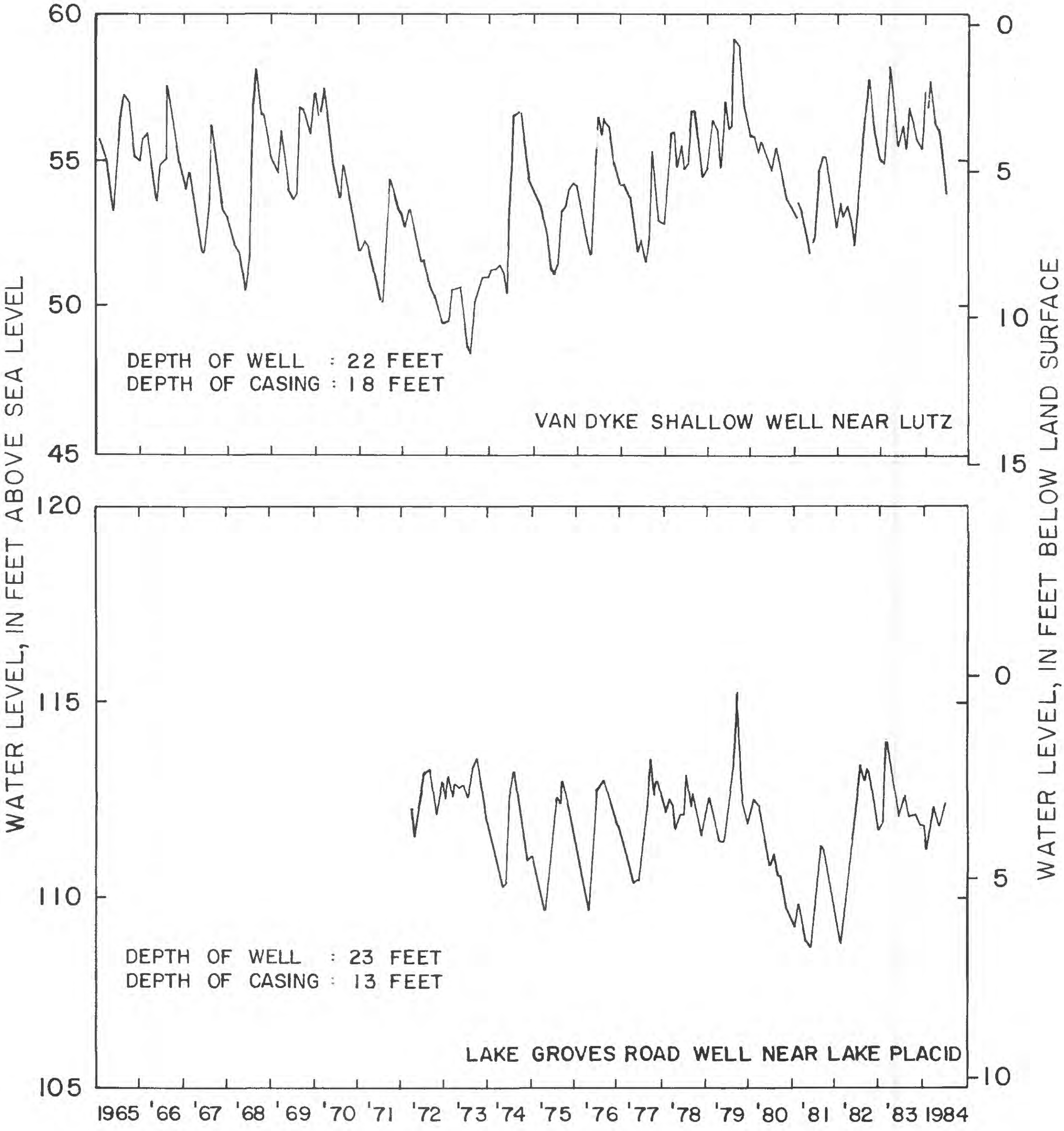


Figure 14.--Month-end water levels in surficial aquifer wells near Lutz and Lake Placid, 1965-84. (General locations of wells are shown in figure 1.)

confined aquifer rise slowly in response to recharge during the wet season (fig. 15). The response to rainfall is dampened by the confining beds and overlying deposits. Hydrograph analysis of artesian wells is difficult because water levels are affected within relatively short times by pumping even at great distances. Water levels in wells thus reflect rises due to cessation of pumping and recharge and declines due to pumping and natural discharge. Differences of as much as 40 feet have been recorded between the annual high and low water levels in western Polk County, a major center of ground-water withdrawal (fig. 16). Fluctuations in the potentiometric surface in wells relatively unaffected by ground-water withdrawals, except occasionally for irrigation and frost-freeze protection, are shown in figure 17. The well near Dover is in the confined part of the aquifer and the well near Lecanto is in the unconfined part.

## Head Differences Between Aquifers

Water provides a hydrostatic pressure that exerts a downward force or an upward buoyant force on material overlying a cavity. The relative levels of water in the multiple aquifer system, therefore, are an important factor in sinkhole development.

In the central part of the study area, the water table in the surficial aquifer is higher than the potentiometric surfaces of underlying aquifers. The areas of downward head are more widespread during the dry season and there are greater differences in head between the water table and the potentiometric surface because of large ground-water withdrawals from the underlying aquifers.

In the south, wells completed in the Upper Floridan aquifer flow, indicating that the area is one of buoyant pressure. In the north, the Upper Floridan aquifer is unconfined and pressure, as such, does not affect sinkhole development. In the north and south, sinkhole development is less active than in the central area where downward hydrostatic pressures prevail.

## Directions of Ground-Water Flow

The configuration of the water table of the surficial aquifer is a subdued expression of land surface. The water table is higher in the inland ridge areas than near coastal areas. Regionally, the direction of ground-water movement in the surficial aquifer is to the west, toward the Gulf of Mexico. However, regional flow patterns are interrupted by local areas of discharge that reduce the significance of the regional pattern. Discharge from the surficial aquifer occurs in streams, lakes, and swampy areas.

Movement of water in the Upper Floridan aquifer is better defined areally than movement of water in the surficial aquifer. The potentiometric surface of the Upper Floridan aquifer shows a pressure gradient from recharge areas (highs) to discharge areas (lows) (figs. 18 and 19). The topography of the land surface is reflected only by the discharge areas, such as the valley of the Withlacoochee River. The potentiometric surface of the Upper Floridan aquifer is highest in the Green Swamp area in the northern part of Polk County (figs. 18 and 19). The regional direction of water movement from this and other potentiometric-surface highs is northwest or southwest. Although the pattern of ground-water movement is fairly consistent, minor changes are caused by heavy pumping. Water levels are generally at their annual highs in September (fig. 18) and at their annual lows in May (fig. 19).

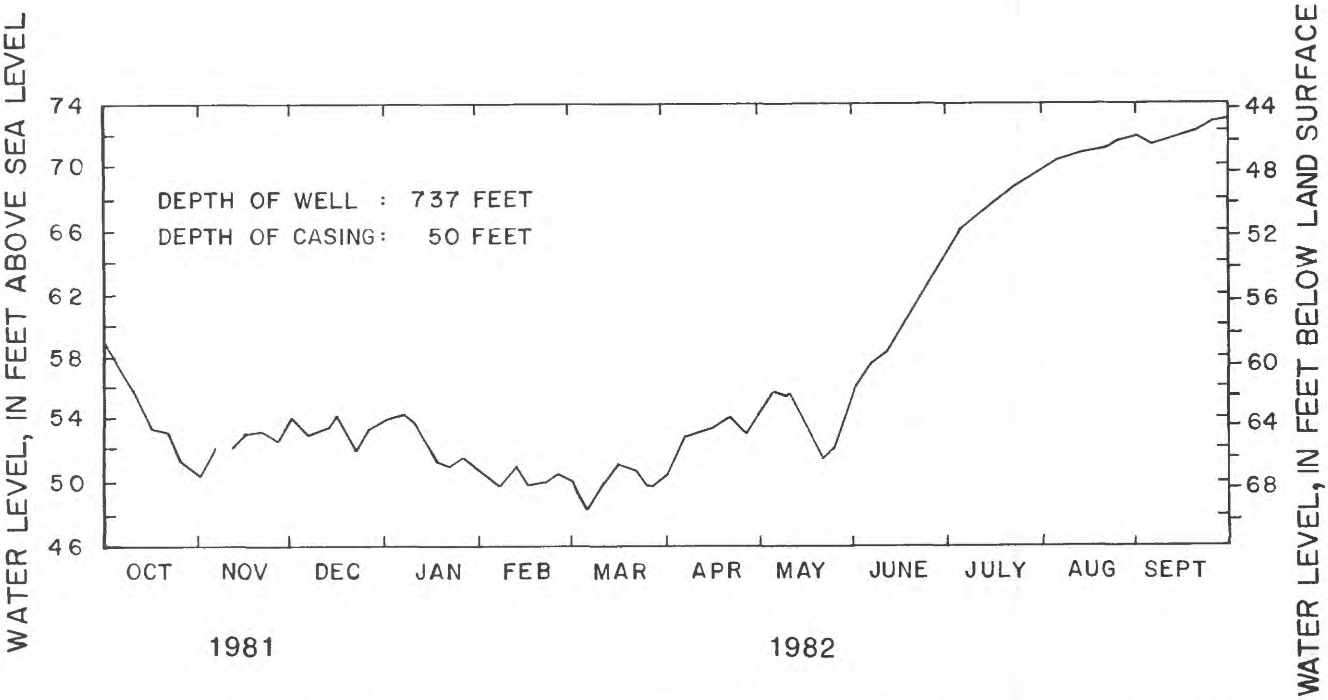


Figure 15.--Water levels in the Maddox well near Bowling Green, 1981-82. (General location of well is shown in figure 1.)

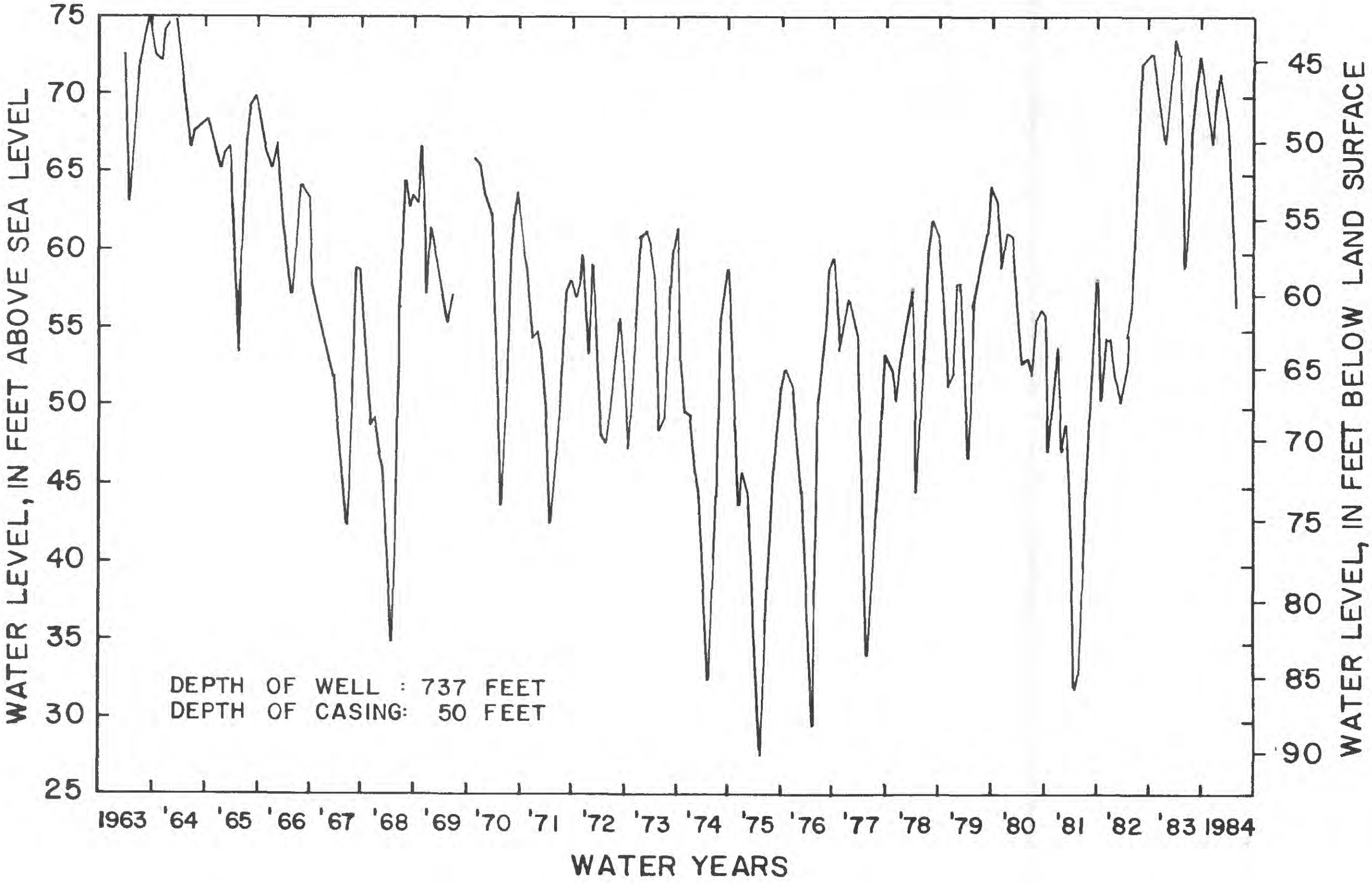


Figure 16.--Month-end water levels in the Maddox well near Bowling Green, 1963-84. (General location of well is shown in figure 1.)

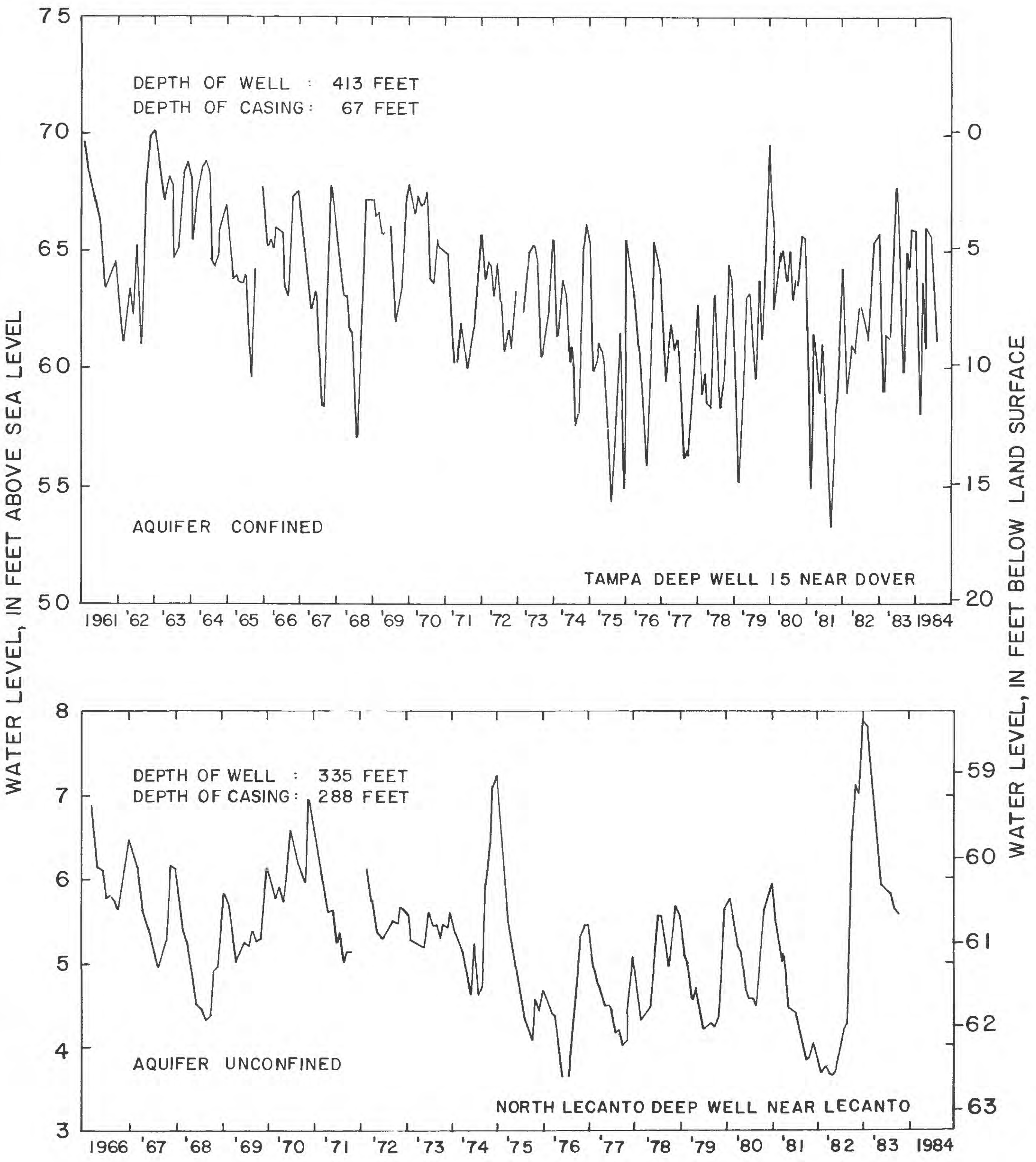


Figure 17.--Month-end water levels in two wells in the Floridan aquifer system, 1961-84. (General locations of wells are shown in figure 1.)

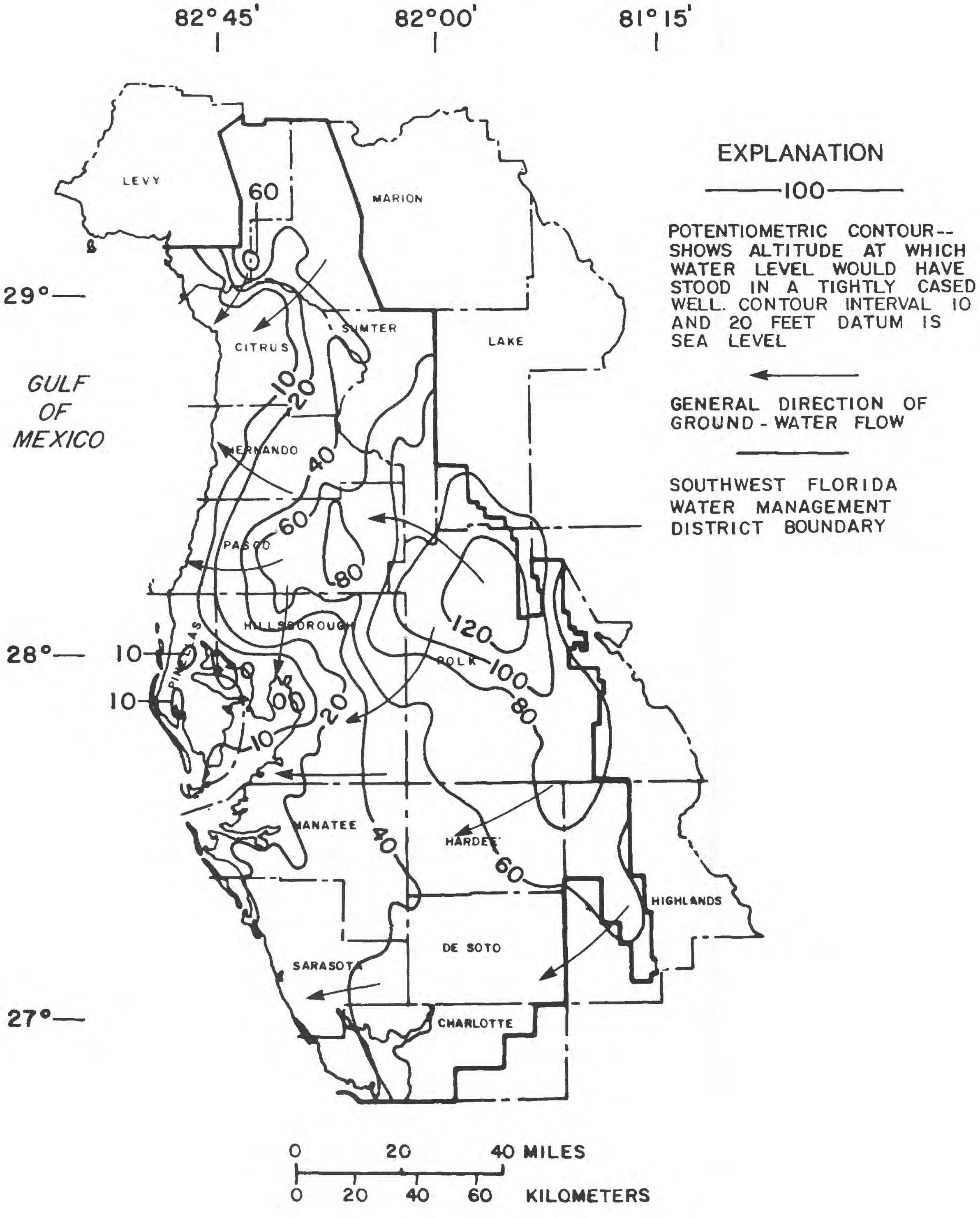


Figure 18.--Potentiometric surface of the Upper Floridan aquifer, September 1979. (Modified from Yobbi and others, 1979.)

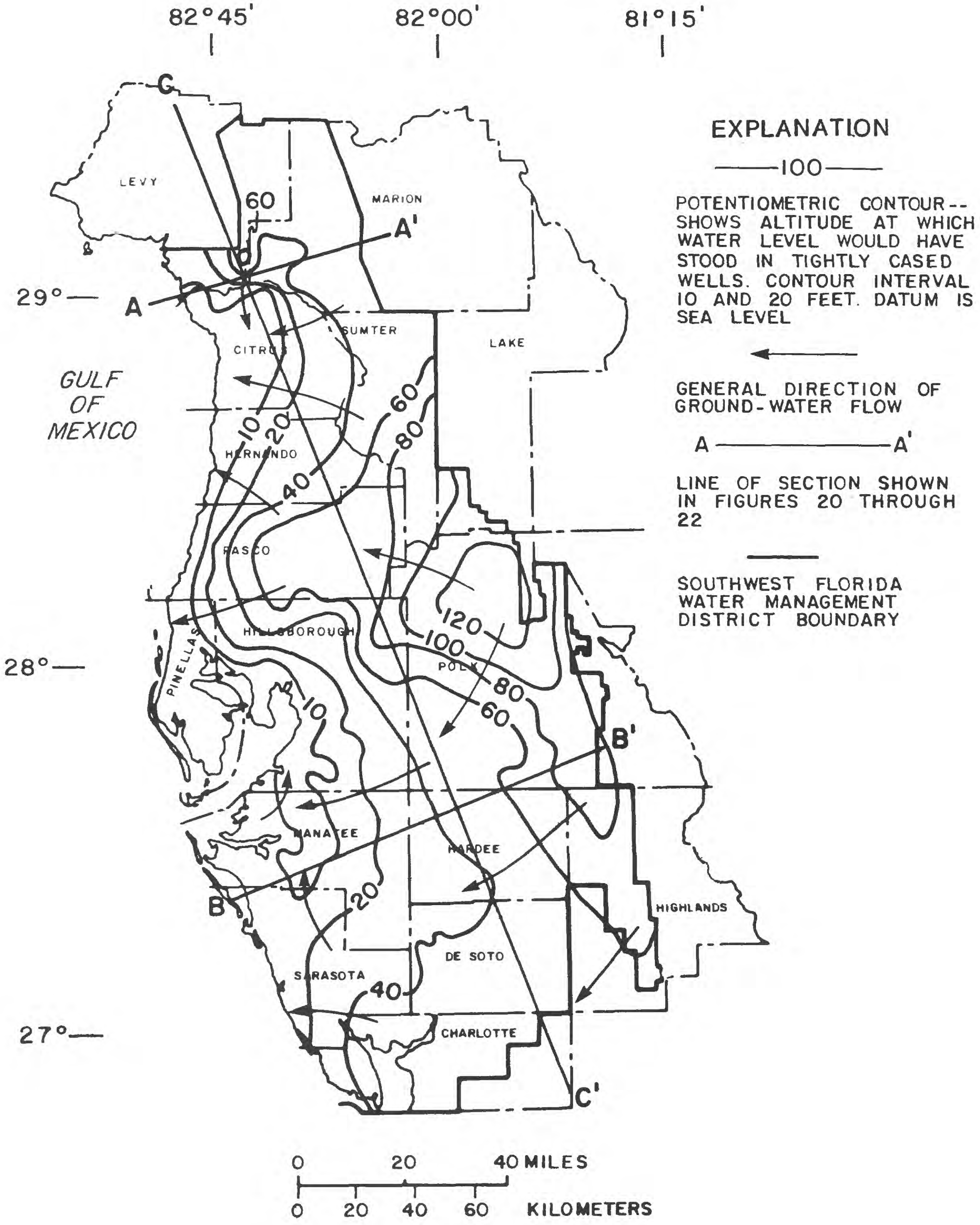


Figure 19.--Potentiometric surface of the Upper Floridan aquifer, May 1979. (Modified from Wolansky, Mills, Woodham, and Laughlin, 1979.)

The unconfined flow system along an east-west hydrogeologic section in the north is shown in figure 20 (section A-A'). The unconfined or semiconfined conditions enable a relatively high rate of recharge to occur (fig. 10). Water enters the Upper Floridan aquifer, travels relatively short distances through well-developed dissolution channels, and discharges at large springs. Figure 20 shows that the aquifer base, or top of the intergranular evaporites, drops from about 600 feet below sea level to about 1,800 feet below sea level in the eastern part of the section. However, water-quality data and a reduction in permeability and porosity of the lower part of the Avon Park Formation suggests that the flow is very sluggish in the deeper zones compared to the shallow flow system (Faulkner, 1973; Ryder, in press).

The east-west hydrogeologic section (B-B') in figure 21 represents the confined flow system in the southern areas. Within most of the eastern half of the section, water moves downward from the surficial aquifer through a confining bed and into an intermediate aquifer and confining unit. A relatively small amount of water returns to the surface in topographically low areas, such as the Peace River valley. Most water moves downward through a confining bed and into the Upper Floridan aquifer where flow is westward toward the Gulf of Mexico. Locally, particularly in the ridge area a few miles north of the eastern edge of the section, sinkholes may breach the overlying deposits and penetrate the Upper Floridan aquifer. The sinkholes may be occupied by lakes or by permeable sands and are sites for relatively high rates of recharge to the Upper Floridan aquifer. Along the coastal margin and in the Gulf, there is a reversal of gradient and water flows upward through the confining beds.

In contrast to the hydrogeologic sections in figures 20 and 21, the north-south section (C-C') in figure 22 is generally perpendicular to flow paths within the aquifer systems. Flow is generally westward, out of the plane of the section, except for some local discharge areas near the top of the intermediate aquifer and the Upper Floridan aquifer. Figure 22 shows from north to south: (1) thickening of the confining beds and a transition from generally unconfined to confined conditions in the Upper Floridan aquifer, (2) thickening of the intermediate aquifer, (3) an increase in importance of the highly permeable zone in the Avon Park Formation (solution channels in the Ocala Limestone having less significance), and (4) thickening of the Upper Floridan aquifer.

## KARST DEVELOPMENT

The term karst (Slavic kras) means, literally, a bleak, waterless place. The area is waterless because the limestone terrane permits precipitation to drain internally through conduits that have been developed by solution. Solution development in limestone, as expressed at land surface, gives karst terrane the unique morphology that distinguishes it from landforms created by erosion of clastic rocks. Chemical corrosion and internal drainage are the active processes rather than physical erosion and surface runoff. Monroe (1970) describes karst as "* * * A terrain generally underlain by limestone, in which the topography is chiefly formed by the dissolving of rock, and which is commonly characterized by karren, closed depressions, subterranean drainage, and caves."

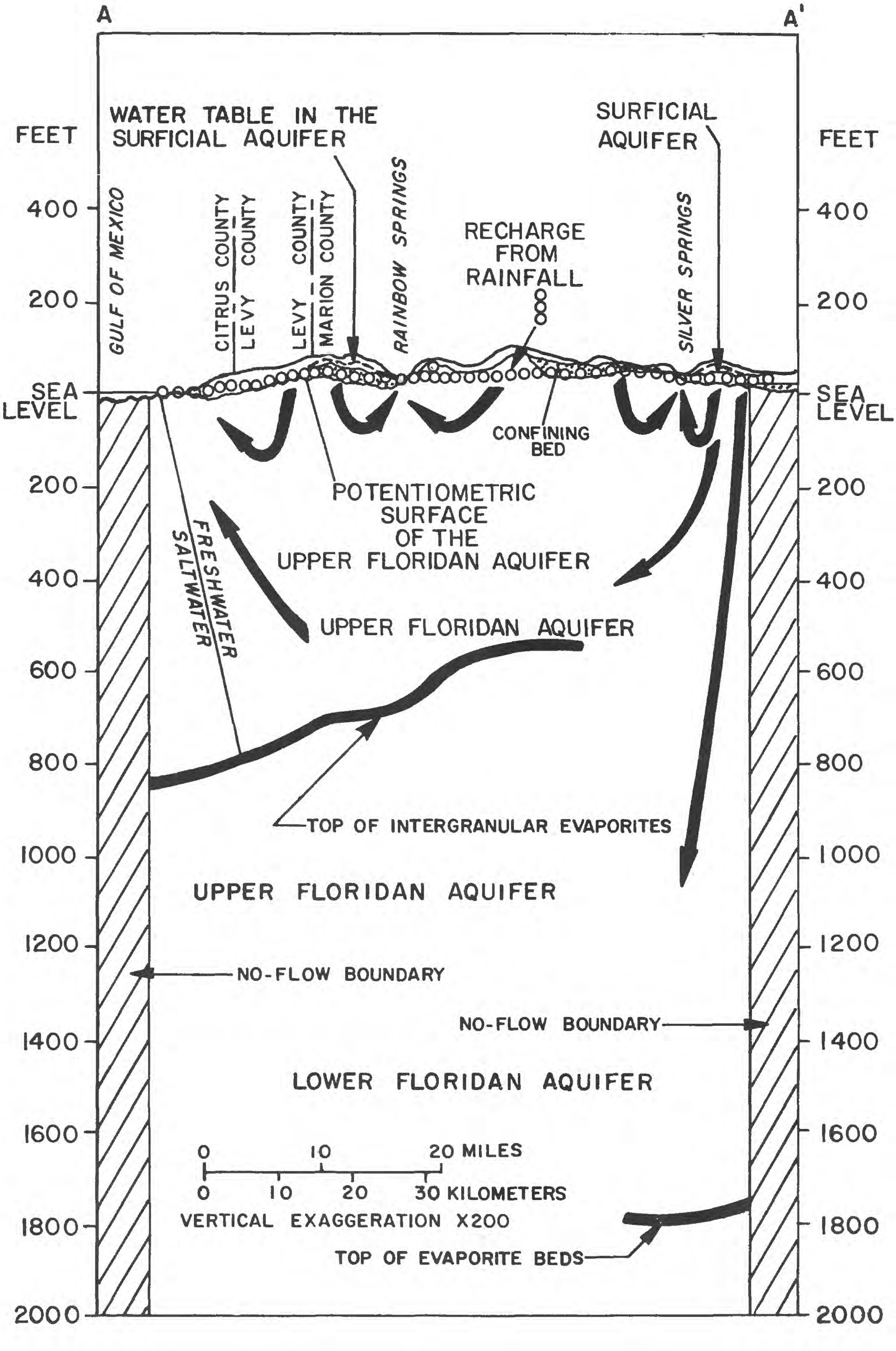


Figure 20.--Generalized hydrogeologic section A-A' showing flow patterns. (Line of section is shown in figure 19; from Ryder, in press; site locations are shown in figure 1.)

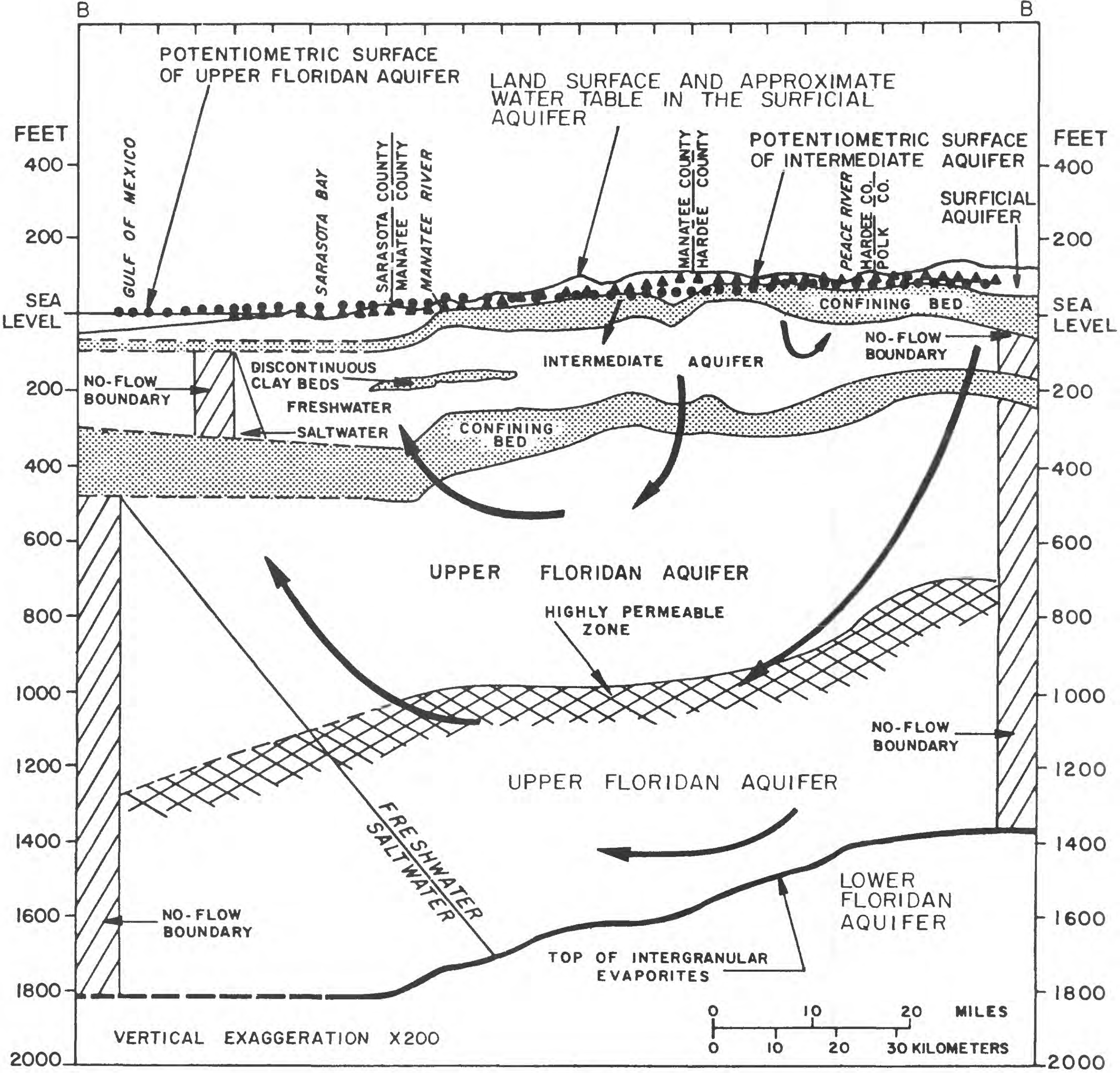


Figure 21.--Generalized hydrogeologic section B-B' showing flow patterns. (Line of section is shown in figure 19; modified from Ryder, in press; site locations are shown in figure 1.)

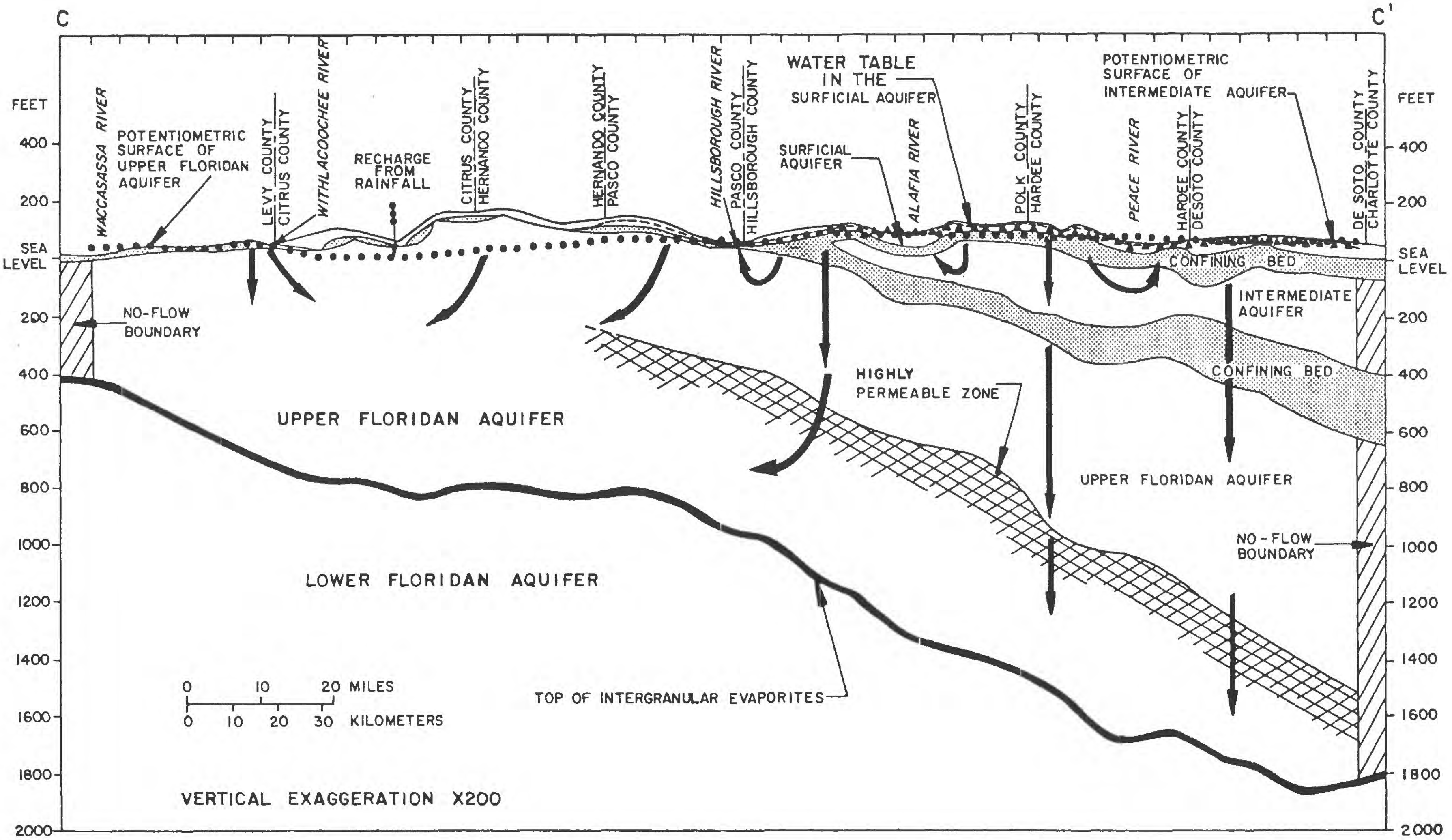


Figure 22.--Generalized hydrogeologic section C-C' showing flow patterns. (Line of section is shown in figure 19; modified from Ryder, in press; site locations are shown in figure 1.)

West-central Florida is not a bleak, waterless place, but many features of its landscape are due to dissolution of limestone bedrock and are properly termed karst features. Where limestone is exposed, karst features are obvious. Throughout most of west-central Florida, however, the limestone is covered with an overburden of sand and sandy clay. The effects of karst processes on the underlying limestone become apparent when the unconsolidated sand and clay subside or collapse into solution cavities. Landforms of this nature are designated "mantled karst"; the karst processes are reflected at land surface. The term "buried karst" is applied to terrane where the overburden is thick and has enough bearing strength to lessen subsidence or collapse. In these terranes, dissolution activity within the underlying limestone may not become apparent at land surface.

The Florida peninsula is largely developed on Tertiary limestone that locally has been uplifted and differentially dissolved. The result is a pattern of physiographic features that have generally low relief. Geologic structure and stratigraphy are primary controls on karst development. White (1970) characterized structurally high areas, such as the northern third of the study area, as "dead zone" karst that contains many steep-walled sinkholes, abandoned springheads, dry stream courses, intermittent lakes, and dry beds of former shallow lakes that are now prairies. South of this area, the limestone bedrock dips downward and is overlain by several hundred feet of clastic strata. Broad, shallow sinkhole lakes are common in lowland areas and small deep sinkhole lakes that apparently represent a complex geologic history occur in the ridge areas.

Karst development in west-central Florida is controlled by lithology and water movement, dissolution by chemically aggressive water, aquifer material, and sea levels. Sweeting (1973) described the difference between karst and nonkarst areas as follows:

> "As a result of the solution of the rock, drainage in limestones sinks into the ground and does not become integrated into surface rivers, whereas in nonkarst areas the surface water becomes organized and systematized into valleys to form a connected network. The surface and underground relief features in limestones are shaped in a vertical sense. The parts of the surface where the water sinks into the ground become isolated from one another, so that the relief forms appear unconnected and disparate; hollows or pits are formed where the drainage sinks into the ground, giving the landscape a pitted character. Thus the landforms of limestone areas and the processes which give rise to them are so distinctive that they are now known universally as karst landforms and karst processes."

## Lithology and Water Movement

The lithology or physical properties of carbonate rock control the amount of rock surface that is exposed to chemical corrosion and the way water moves through the rock. The thickness of rock beds, clay content, texture, grain size, and brittleness determine whether flow is diffused through the many primary openings or is channeled through the few secondary openings. Very few limestones retain their primary openings by the time they are lithified.

Ground-water flow, therefore, is commonly often through secondary openings that have developed along joints, faults, bedding planes, and erosional surfaces. The most common of these secondary features are joints that were formed by tensional or compressional stresses and bedding planes that mark stages of deposition and were susceptible to chemical corrosion. Faults, especially if surrounded by a zone of fractured rock, commonly form conduits for water movement. If the rock is highly pulverized or clays occur along the fault plane, faults may act as barriers to water flow. Erosional surfaces are the least common of the principal types of secondary openings, but many are favorable for ground-water flow.

The amount of rock surface exposed to corrosion is small in relation to the volume of rock. Thus, dissolution of the rock is more apt to develop a few large conduits. When reefs and reef debris lithify, they usually form rock that has numerous voids and passages. Flow through this type of rock is diffused, and the rock surface exposed to corrosion is large in relation to volume. Numerous small, interconnected conduits are developed, and the rock generally has the appearance of Swiss cheese, but major conduits are rare.

When calcareous sediment lithifies, it forms a dense, essentially impervious rock, and water movement is confined to bedding planes, erosional surfaces, joints, and other physical features. Soluble materials that comprise the total surface area of the rock are removed, but insoluble materials remain and may accumulate in the openings. In addition, material from adjacent areas may be carried into the solution-formed openings. Dissolution by circulating water is primarily along conduit walls. The conduits, thus, rapidly enlarge and become major openings through which water moves freely.

## Dissolution of Aquifer Materials

The Floridan aquifer system is composed of approximately 65 percent calcite, 34 percent dolomite, and minor amounts of gypsum (Back and Hanshaw, 1971). Calcite and dolomite are the dominant minerals and are of major importance in terms of dissolution and sinkhole development. However, gypsum is highly soluble and contributes to sinkhole development in some areas.

The geochemistry of calcite, dolomite, and gypsum is relatively straightforward. These minerals have relatively simple structures, and processes of dissolution involve rapid reactions even in dilute solutions. Thus, quantitative rules of chemical equilibrium are particularly effective as a basis for predicting rates of limestone dissolution and land subsidence.

The dominant factor that determines the ability of recharge water to dissolve calcite and dolomite is acidity of the water. Also, temperature, and to a lesser degree pressure, affect solubility rates. If recharge water has high ionic strength and low concentrations of calcium, magnesium, and carbonate, its ability to dissolve these minerals is enhanced.

Rain water, the primary source for recharge water, is naturally acidic. If rain water is in equilibrium with atmospheric carbon dioxide, it has a pH of about 5.6 units. The pH of rain water may be lowered by air pollution, thus enhancing the ability of rain water to react with aquifer materials. However, air pollution has been of little significance in terms of dissolution and development of sinkholes that occur over geologic time. Acidic gases, such as sulfur dioxide, hydrogen sulfide, and oxides of nitrogen, may also contribute to the acidity of rain water.

The major source of acidity in natural ground water is carbon dioxide from bacterial decomposition of organic matter in the soil zone. The amount of carbon dioxide in the soil zone may be several hundred times that in rain water (Stumm and Morgan, 1970). This results in ground water that has a pH of about 4 units and, thus, enhances dissolution of limestone. Chemical reactions that are related to dissolution of carbon dioxide in water and subsequent dissolution of limestone minerals are as follows:

$$\underset{\text{(gaseous carbon dioxide)}}{CO_2\text{ (gas)}} \rightleftharpoons \underset{\text{(aqueous carbon dioxide)}}{CO_2\text{ (aqueous)}} \tag{1}$$

$$\underset{\text{(aqueous carbon dioxide)}}{CO_2\text{ (aqueous)}} + \underset{\text{(water)}}{H_2O} \rightleftharpoons \underset{\text{(carbonic acid)}}{H_2CO_3} \tag{2}$$

$$\underset{\text{(carbonic acid)}}{H_2CO_3} + \underset{\text{(calcite)}}{CaCO_3} \rightleftharpoons \underset{\text{(calcium ion)}}{Ca^{++}} + \underset{\text{(bicarbonate ion)}}{2HCO_3^{-}} \tag{3}$$

$$\underset{\text{(carbonic acid)}}{2H_2CO_3} + \underset{\text{(dolomite)}}{CaMg(CO_3)_2} \rightleftharpoons \underset{\text{(calcium ion)}}{Ca^{++}} + \underset{\text{(magnesium ion)}}{Mg^{++}} + \underset{\text{(bicarbonate ion)}}{4HCO_3^{-}} \tag{4}$$

Most dissolved carbon dioxide remains in the unhydrated form $CO_2$ (aqueous) and does not form carbonic acid ($H_2CO_3$). The ratio of $CO_2$ (aqueous) to $H_2CO_3$ is 650 to 1 (Stumm and Morgan, 1970).

Because calcite dissolution is the predominant chemical cause of sinkhole occurrence in the study area, special attention will be given to the calcite dissolution process. Recharge water that contains carbon dioxide dissolves calcite to produce two bicarbonate ions and one calcium ion for each carbon dioxide molecule that reacts. A small amount of carbonate ions will also be dissolved until equilibrium with calcite is reached. Because initial concentrations of carbon dioxide in recharge water and degree of undersaturation are generally unknown, another approach to calculate the rate of calcite dissolution and cavity formation is desirable. Alkalinity provides a measure of the amount of calcite that has dissolved without knowledge of initial carbon dioxide concentrations or the degree of undersaturation. Alkalinity of water from a limestone aquifer can come only from dissolution of carbonates, such as calcite or dolomite, rather than from carbon dioxide, which is an acid. Although carbon dioxide permits more alkalinity, all alkalinity comes from the carbonate rock whether it occurs as two bicarbonate ions because of reaction with carbon dioxide or as one carbonate ion that is unreacted with carbon dioxide.

The volume of calcite that is dissolved in a pure calcite aquifer is described by the following equation:

$$V_c = 3.70\text{x}10^{-7} \text{ x recharge x alkalinity} \qquad (5)$$

where

$V_c$ = volume of dissolved calcite, in cubic inches per square inch of surface area;

recharge = recharge rate, in inches per year; and

alkalinity = alkalinity, as $CaCO_3$, in recharge water as a result of dissolution of calcite, in milligrams per liter.

For a pure dolomite aquifer, the coefficient in equation 5 would be $3.21\text{x}10^{-7}$.

Equation 5 can be used to estimate the rate of cavity formation when used with average recharge rate, concentration of alkalinity near the bottom of the zone where sinkhole formation occurs, and an estimate of how concentrated ground-water flows are in solution channels or fractures as compared to average recharge rates for an area. For example, if the average annual recharge rate is 5 inches and the alkalinity is 200 mg/L as $CaCO_3$, from equation 5: $3.70\text{x}10^{-7}$ x 5 x 200 = $3.70\text{x}10^{-4}$ $\text{in}^3$ of calcite will dissolve beneath each square inch of land surface each year.

If the area near a fracture receives 10 times the average recharge because of concentration of ground-water flow, 10 times as much calcite ($3.70\text{x}10^{-3}$ $\text{in}^3$) could dissolve each year under each square inch of land surface. This rate of dissolution would result in development of a 1-foot deep cavity in about 3,200 years [12 ÷ ($3.70\text{x}10^{-3}$)].

In natural ground water, the solubility of gypsum is independent of pH. The capacity of ground water to dissolve gypsum is controlled by concentrations of calcium and sulfate ions, ionic strength, temperature, and pressure. The dissolution of gypsum is described by the following equation:

$$\underset{\text{(gypsum)}}{CaSO_4 \cdot 2H_2O} \rightleftharpoons \underset{\text{(calcium ion)}}{Ca^{++}} + \underset{\text{(sulfate ion)}}{SO_4^{--}} + \underset{\text{(water)}}{2H_2O} \qquad (6)$$

The dissolution of gypsum can be described by the following equation:

$$V_g = 7.73\text{x}10^{-7} \text{ x recharge x } SO_4 \qquad (7)$$

where

$V_g$ = volume of gypsum dissolved, in cubic inches per square inch of land surface;

recharge = recharge rate, in inches per year; and

$SO_4$ = concentration of sulfate in recharge water, in milligrams per liter.

This equation does not account for sulfate reduction by bacteria.

Back and Hanshaw (1971) describe a method of estimating from a chemical analysis for calcium, magnesium, and sulfate the amount of calcite, dolomite, and gypsum that would have dissolved to produce a 1984 water sample from the Floridan aquifer system, assuming that saline water has not mixed with recharge water. Their equations were used to derive an equation that could be used to estimate the volume of calcite, dolomite, and gypsum that has dissolved. The equation is as follows:

$$V_{c,d,g} = [(9.213\text{x}10^{-7} \text{ x Ca}) + (1.122\text{x}10^{-6} \text{ x Mg}) + (3.88\text{x}10^{-7} \text{ x } SO_4)] \text{ x recharge} \quad (8)$$

where

$V_{c,d,g}$ = volume of calcite, dolomite, and gypsum dissolved, in cubic inches per square inch of land surface;

recharge = recharge rate, in inches per year; and

Ca, Mg, and $SO_4$ = concentrations, in milligrams per liter.

The equations for dissolution of carbonates and gypsum do not account for changes in solubility that are caused by changes in temperature and pressure. Solubility of carbonates is related to solubility of $CO_2$, which is inversely proportional to changes in temperature and directly proportional to changes in pressure. Gypsum is a mineral whose solubility increases with increasing temperature and pressure.

The following example uses equation 8 and a typical water sample for the Bartow area to estimate the quantity of material dissolved under each square inch of land surface per year. The concentrations of calcium, magnesium, and sulfate in the water sample are 51, 22, and 3.9 mg/L, respectively (Miller and Sutcliffe, 1982). The annual recharge rate for the area is about 5 inches. Substituting these values in equation 8 results in the following:

$$\begin{aligned} V_{c,d,g} &= [(9.213\text{x}10^{-7} \text{ x } 51) + (1.122\text{x}10^{-6} \text{ x } 22) + (3.88\text{x}10^{-7} \text{ x } 3.9)] \text{ x } 5 \\ &= 3.66\text{x}10^{-4} \text{ in}^3/\text{yr}. \end{aligned}$$

Thus, $3.66\text{x}10^{-4}$ $\text{in}^3$ of material would dissolve under each square inch of land surface per year. At this rate, it would take about 33,000 years ($12 \div 3.66\text{x}10^{-4}$) to dissolve a 1-foot deep cavity. Because ground-water flow is concentrated in faults and fractures, however, recharge and dissolution would also be concentrated. If this focused flow resulted in a 10-fold increase in recharge at the joints and fractures, it would take only about 3,300 years to develop a 1-foot cavity in such areas.

Sinclair (1982) used a similar analysis to predict the rate that limestone is removed within a $3\text{-mi}^2$ cone of depression at a well field in Hillsborough County. At the 1978 rate of pumpage, 1 foot of limestone would dissolve throughout the area of influence in about 1,700 years. Thus, the rate of limestone removal caused by pumping is two or more times greater than the natural rate of removal indicated for the Bartow area.

## Sea Levels

Fluctuations of sea level with respect to the land surface have been an important factor in the development of karst of west-central Florida. Periods of submergence and deposition of limestone have alternated with periods of land exposure and erosion and dissolution of carbonate rocks.

The most recent changes of sea level were in response to climatic changes during periods of glaciation in the Pleistocene Epoch. Seawater was retained on land in continental glaciers and sea level was as much as 400 feet lower than its present (1984) level. The Gulf Coast of Florida was at least 300 miles west of its present position. Many of the karst features of the limestone are related to Pleistocene sea stands and ground-water levels.

During periods of low sea level, ground-water levels were correspondingly low and water-table conditions probably prevailed in much of the limestone underlying the present peninsula. Perched water tables probably were present in the surficial sand where the sand was separated from the limestone by clay. Ground-water circulation and karst development were most active at the surface of the water table. The lower sea level lowered the base level toward which surface runoff and ground water would flow and affected rates of recharge, levels of the water table, and even directions of ground-water flow in some areas. Conduits and cavern systems likely developed at the base altitude established by sea level.

The effect of high sea levels was to fill existing karst features with sand and clay by wave action and coastal currents. Sediments associated with this inundation were principally silica sand and clay deposits in the northern areas. Calcareous reefs and reef-associated sediments were deposited from near the Alafia River southward.

Many beaches and terraces have been defined in west-central Florida, but recent studies suggest that the terraces and beaches above about 100 feet are probably pre-Pleistocene or, perhaps, structural in genesis. Along the ridge areas and where the land surface is above 100 feet in altitude, sinkholes and sinkhole lakes are well developed, fairly large, and may be in a mature stage of development. The ridges, for example, probably have not been inundated by the sea since Miocene time or about 5 million years ago. The many large sinkhole lakes and internally drained depressions in the central ridges attest to a long, uninterrupted period of weathering, solution, and subsidence of limestone bedrock.

Most of the topography below an altitude of 100 feet is relatively subdued. The valley of the Green Swamp and the Withlacoochee River (fig. 1), for example, was inundated several times during the Pleistocene Epoch. Coastal currents and wave action developed a relatively flat surface on the surficial fill within that area even though the bedrock surface buried beneath the sand and clay is very irregular.

Ground-water circulation that occurred during the highest stands of sea level probably was confined to the ridges and adjacent areas. Movement of ground water probably was sluggish because of the relatively flat gradient and lack of head to move the water. Solution of limestone was greatest at and immediately below the top of the limestone where most recharge of corrosive water occurred.

## WARNING SIGNS

Sinkholes induced by man's activities can be expected to increase in frequency and are particularly hazardous because many occur in populated areas (Sinclair, in press). Although the occurrence of sinkholes can be abrupt, there are signs that warn of possible collapse, such as:

1. Slumping or sagging--slanting fence posts or other objects; doors and windows that fail to close properly.
2. Structural failure--cracks in walls, floors, and pavement; and cracks in the ground surface.
3. Ponding--ponding of rainfall where it has not ponded previously.
4. Vegetative stress--wilting of small areas of vegetation because of lowered water table caused by drainage through a developing sinkhole.
5. Turbidity in well water--turbid water in nearby wells during early stages of sinkhole development.

Surface erosion by rivers is well understood, visible, and subject to some control by man, but subsurface erosion is difficult to trace and the prediction of potential collapse is difficult or impossible. Buildings, bridges, and other structures can generally be designed in a manner that will mitigate damage. However, reliable methods for the prevention of or prediction of exact time and location of sinkhole occurrence have not been developed. Aerial photography, geophysical surveys, and test-well drilling are time-consuming and expensive approaches to detection of cavities at depth, but have not proven to be consistently effective in detecting cavities.

## TYPES AND FEATURES OF SINKHOLES

Types of sinkholes that are common to west-central Florida include: (1) limestone solution, (2) limestone collapse, (3) cover subsidence, and (4) cover collapse (Sinclair, in press). Limestone-solution and limestone-collapse sinkholes usually occur in areas where limestone is bare or thinly covered, but may also occur where cover materials are thick. Cover-subsidence and cover-collapse sinkholes usually occur in areas where there is a thick cover of material overlying the limestone. Descriptions of sinkhole types and factors that affect their occurrence are summarized in table 2.

### Sinkholes in Areas of Bare or Thinly Covered Limestone

Throughout much of the northern part of west-central Florida, cover material overlying limestone is less than 25 feet thick (fig. 13). Generally, the cover material is very permeable, and the effect, in terms of solution development of the limestone, is similar to that of bare limestone exposed to weathering. Solution of limestone and sinkhole development are greatest at the surface and in near-surface joints and fractures and generally decrease with depth.

Table 2.--Principal features of the major types of sinkholes

[From Sinclair, in press]

| | Sinkhole type | | | |
|---|---|---|---|---|
| | Limestone solution | Limestone collapse | Cover subsidence | Cover collapse |
| Cover material | Limestone bare or thinly covered. | Limestone bare to deeply buried by cover material. | Incohesive, permeable sand, as much as 50 feet or more thick. | Generally 5 to 100+ feet thick. Incohesive, permeable sand grading downward to clayey sand with relatively cohesive, poorly permeable clay overlying limestone. |
| Ground-water levels | Water table generally below top of limestone. | | Water table may be in sand or below top of limestone. | Water table in cover sand perched above and leaking through poorly permeable clay. Artesian water level in limestone generally below water table but above limestone surface. |
| Sinkhole development | Imperceptibly slow subsidence of land surface by removal of limestone in solution. | Cavities develop only at depth beneath limestone surface where they enlarge by upward collapse of the roof, layer by layer, until the limestone roof is too thin to support itself and collapses abruptly; a relatively rare occurrence in terms of landscape development. Sinkhole size controlled by bearing strength of limestone roof and depth of cavity. | Imperceptibly slow subsidence of land surface. Only very small cavities are likely to form at limestone surface because incohesive sand moves continuously or spasmodically downward to occupy space formerly held by dissolved limestone. | Solution-enlarged joints at limestone surface are bridged by overlying cohesive clay until bearing strength of clay is exceeded. Cavity moves upward by roof spalling until it appears abruptly at land surface. Sinkhole size controlled by bearing strength of clay, usually related to clay thickness. |
| Activities that commonly trigger sinkholes | Declines in ground-water levels, particularly abrupt declines and fluctuations due to pumping from wells, are the most common factors that trigger collapse.<br>Impoundments, such as reservoirs and holding ponds, may load the land surface and provide a source of water that percolates downward, eroding cover material into solution cavities. Diversion of surface drainage by roads or paving of large areas that concentrates runoff may also accelerate internal erosion.<br>Static loads (buildings) and vibratory and harmonic loads (heavy equipment, trains) may be sufficient to trigger collapse of cavities at shallow depth. | | | |
| Effects of activities | Slight. | Slight. Collapse may be induced where water table is above limestone surface. | Small-scale piping commonly induced. | Collapse commonly induced. |

## Limestone-Solution Sinkholes

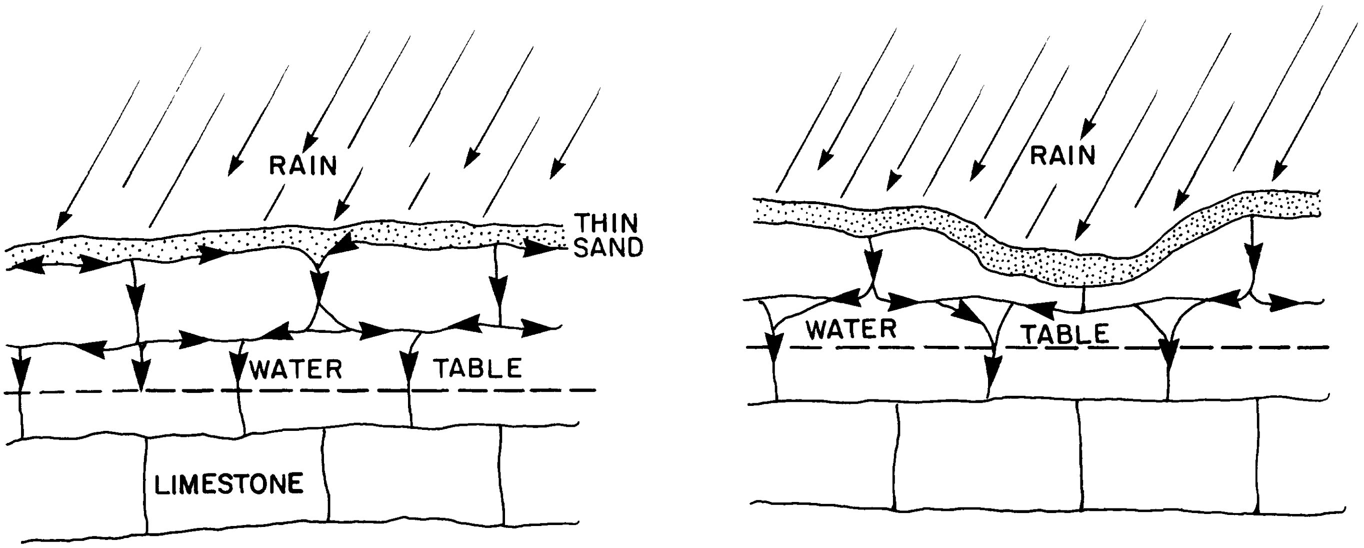
In areas where limestone is covered by thin layers (less than 25 feet) of soil or overburden, solution of the limestone is most active at the limestone surface. The most common type of sinkhole in these areas results from subsidence that occurs at roughly the same rate as the dissolving of the rock. Dissolved limestone and insoluble residue are carried along enlarged fractures as solution of limestone progresses. At many places, actual voids do not form because subsidence occurs gradually as the limestone dissolves. The result is a gradual lowering of the land surface and development of depressions that collect more surface runoff as the depression's perimeter expands (fig. 23). This type of sinkhole commonly forms as a funnel-shaped depression. The slope of its sides is determined by the rate of subsidence relative to the rate that surface material is transported into the depression. Surface runoff may carry sand and clay particles into the depression and form a relatively impermeable clay seal in its center. If percolation is restricted by the clay seal, a marsh or intermittent lake generally forms in the depression. Limestone solution and subsequent land subsidence are common in karst areas. The process produces an undulating topography throughout much of the northern part of west-central Florida, particularly in the northern part of the area.

## Limestone-Collapse Sinkholes

The most obvious type of sinkhole occurs where a solution cavity expands in size until the limestone roof collapses (fig. 24). Collapse is generally abrupt and at times catastrophic. Limestone-collapse sinkholes may occur in any area of soluble rock regardless of the depth of the rock. However, they occur most often in areas where limestone is at or near land surface and where the water table is below the limestone surface. Ground-water circulation is most vigorous at, and just below, the water table where solution of limestone is accelerated. Other causes of accelerated solution at certain depths may be the occurrence of bedding planes in the limestone or changes in rock composition that concentrate the flow of water.

Limestone is commonly exposed in the vertical or overhanging walls of collapse sinkholes. The walls are usually irregular in shape because of joints and fractures in the rock. Surface drainage and accumulation of sediment will, eventually, smooth the sides and reduce their slopes until they are not distinguishable from other types of sinkholes.

Although limestone-collapse sinkholes provide dramatic local topography, roof collapse is relatively uncommon. Dissolution at the limestone surface and in near-surface joints is more likely the dominant process in landscape development. Thus, limestone-collapse sinkholes are relatively uncommon in west-central Florida, except for a coastal strip along Pasco, Hernando, and Citrus Counties and a small area in Levy and Marion Counties in the extreme northern part.

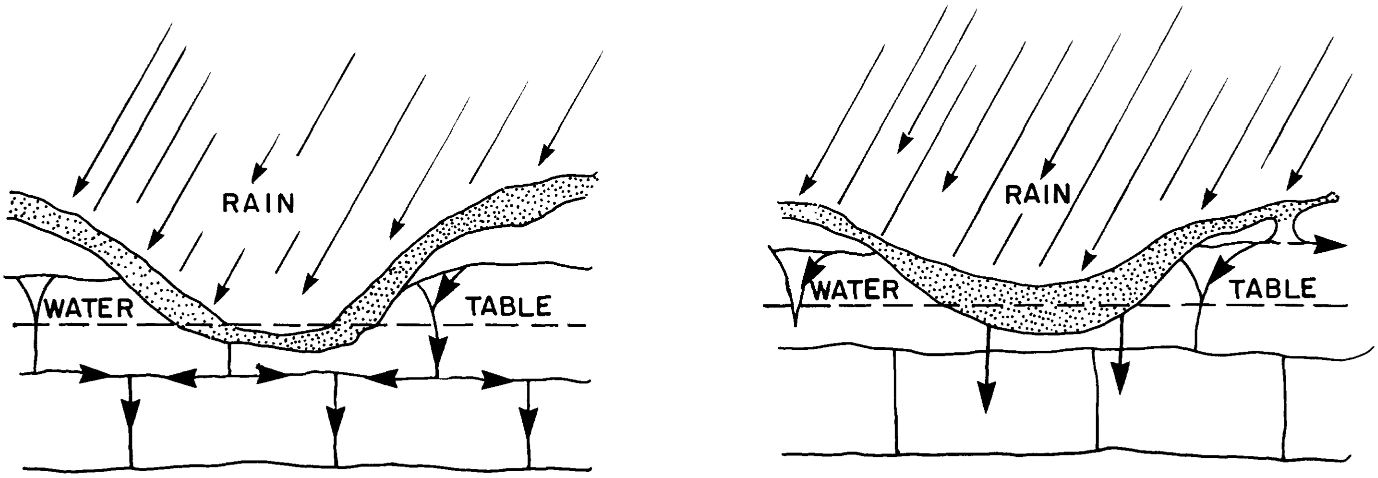


a.

Rainwater percolates through joints in limestone to the water table. Highly transmissive joints dissolve faster than others.

b.

Differential solution of bedrock is expressed by a depression at land surface that funnels water to the enlarged joints.



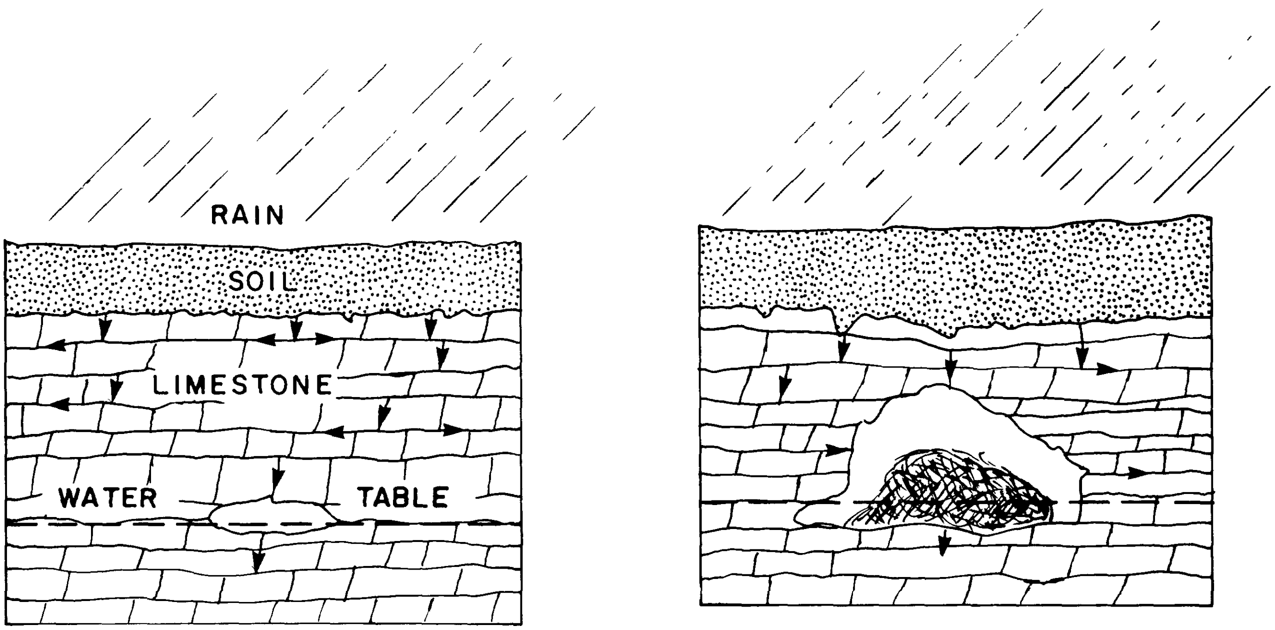
c.

Sinkhole intersects the water table. Rate of dissolution is greatly reduced and may be less than surrounding area.

d.

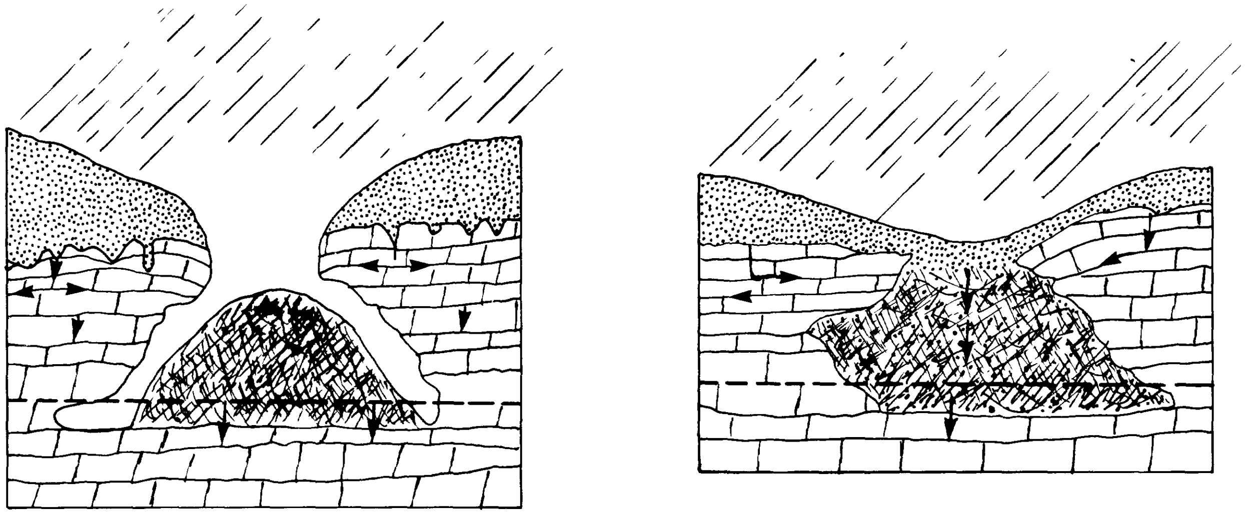
Sinkhole is expressed as a shallow sand-filled depression because of clay and clayey sand filling and subsidence of surrounding limestone.

Figure 23.--Stages in development of a limestone-solution sinkhole. (Arrows indicate direction of water movement.)



a. Solution cavity develops along joint or other plane of weakness at the water table.

b. Roof collapses, most likely at joint intersection. Undercutting of cave walls by diverted ground water.



c. Roof collapse reaches land surface. Undercutting continues.

d. Soil washes into depression and obscures its origin. Breakdown and cave roof cemented by recrystallized limestone.

Figure 24.--Stages in development of a limestone-collapse sinkhole. (From Sinclair, in press. Arrows indicate direction of water movement.)

## Sinkholes in Areas of Thickly Covered Limestone

The thickness and composition of unconsolidated material that mantles limestone controls, to a large degree, the shape and size of sinkholes. A thick layer (more than 50 feet) of dense clay may have sufficient bearing strength to bridge a limestone cavity of considerable size (more than 50 feet in diameter). When the clay finally fails, the resulting sinkhole will be relatively large and will probably form abruptly.

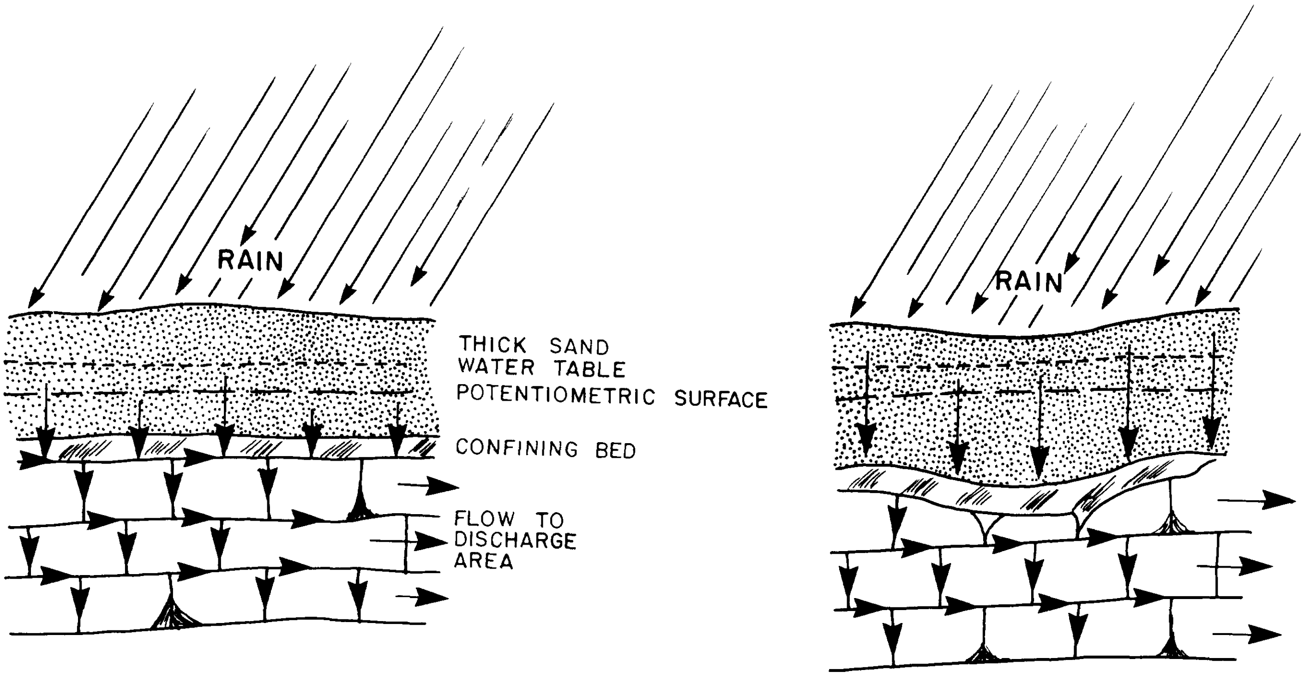
Where limestone is buried beneath a sufficient thickness (more than 100 feet) of unconsolidated material, sinkholes are less common. If the overburden consists of incohesive sand, an upward-migrating cavity will be dissipated by a general lessening of density of cover material over a large area, and the result will be a relatively extensive subsidence of the land surface that occurs over time. Generally, subsidence of this type may go unnoticed for several years. If the overburden is clay, its low permeability may impede downward movement of ground water and retard development of solution cavities in the underlying limestone. For this reason, areas underlain by thick layers of relatively impermeable clay generally are not affected by sinkholes.

### Cover-Subsidence Sinkholes

In areas where the limestone is covered by materials that are relatively incohesive and permeable, sinkholes develop by subsidence (fig. 25). The water table in the surficial aquifer is above the potentiometric surface of the Floridan aquifer, and head differences between the aquifers largely determine the rate of downward movement of water into the underlying limestone. Dissolution of the limestone is greatest during the early development of a sinkhole and is smallest after the sinkhole intersects the potentiometric surface (fig. 25d). Under these conditions, individual grains of sand move downward in sequence, replacing limestone that has dissolved. Areas where sand cover is as much as 50 to 100 feet thick may develop cover-subsidence sinkholes that are only a few feet in diameter and depth. Their small size and mode of occurrence are due to the fact that cavities in the limestone cannot develop to appreciable size before they are filled with sand. The thousands of cypress heads in west-central Florida occupy depressions formed by cover-subsidence sinkholes.

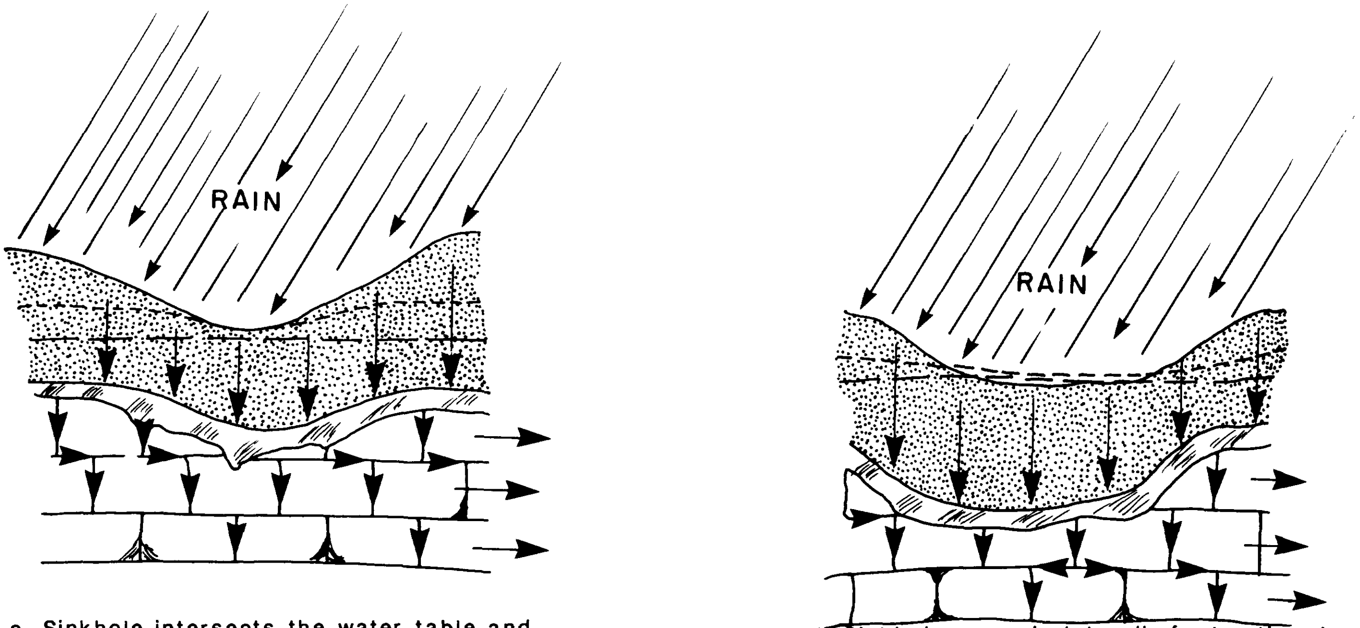
### Cover-Collapse Sinkholes

Throughout much of west-central Florida, the sand cover becomes increasingly clayey with depth and a layer of dense, impermeable clay commonly overlies the limestone surface. The clay component provides a degree of cohesiveness to the cover material that allows it to bridge a developing cavity in the limestone. The result of failure of the bridge is a cover-collapse sinkhole whose dimensions are related to the size of the cavity and the bearing strength of the clay. Cover-collapse sinkholes form by the same general mechanism as cover-subsidence sinkholes. The distinction between the two types of sinkholes is whether the cover subsides slowly or collapses abruptly. The rate of cover subsidence is controlled by the degree of cohesion or bearing strength of the cover material.



a. Rainwater percolates through incohesive deposits to underlying limestone. Highly transmissive joints dissolve faster than others.

b. Differential solution of bedrock is expressed by a depression at land surface that funnels water to the enlarged joints.



c. Sinkhole intersects the water table and cypress trees begin to grow. Rate of dissolution is reduced because there is less head difference between the water table and potentiometric surface and, thus, less percolation.

d. Sinkhole spreads laterally faster than it subsides. A cypress dome forms with old trees in the center and young trees on the perimeter.

Figure 25.--Stages in development of a cover-subsidence sinkhole. (Arrows indicate direction of water movement.)

An example of stages in the development of a small cover-collapse sinkhole near Tampa, where the limestone is covered by about 4 feet of clay and 30 feet of sand, is shown in figure 26. The geology is typical of much of west-central Florida where clay separates the surficial sand from the limestone below. Solution cavities develop near and at the top of the limestone where acidic water leaks downward through the clay (fig. 26a). The clay layer overlying the limestone may bridge the cavity for a considerable time by virtue of its cohesive strength, but eventually the clay will collapse as material continues to fall from the cavity roof (fig. 26b). The cavity then develops rapidly upward by piping as the relatively loose sand flows downward. This process is acceleated by water that percolates through the sand and the breach in the clay to the limestone cavity. The photograph at the top of figure 26c was taken in 1971, shortly after the sinkhole appeared. The top of figure 26d shows the same sinkhole in 1981. During the 10-year period, the only visible change that occurred was surface material eroded into the depression.

Where clay fills the limestone cavity, downward movement of water through the cavity may be diverted because the clay is less permeable than the surrounding limestone. Where the clay layer does not completely fill the cavity, downward movement of water from the upper sand is enhanced by disrution of the clay layer and by increased surface drainage into the expanding depression at land surface. The sinkhole may then be further enlarged by additional collapse or subsidence.

The thickness and composition of unconsolidated material that covers the limestone have an important effect on the shape and size of land-surface collapse. A thick layer (more than 50 feet) of dense clay may have sufficient strength to bridge a large-diameter cavity whose limestone roof has collapsed into a solutionally enlarged joint in the limestone. When the clay layer finally fails, the resulting cover-collapse sinkhole will be relatively large and will probably form abruptly. The width of the cavity at the limestone surface may not be as great as that in the clay, or as great as the diameter at land surface. The limestone cavity may be a deep, small-diameter conduit through which debris is transported by gravity and ground-water flow. The size of the sinkhole at land surface is proportional to the thickness and bearing strength of the cover material and the volume of the underlying cavity.

Collapse of cavernous passages may occur at considerable depth (50 to 200 feet) beneath overlying rock formations. The overlying rock layers may (1) collapse at the same time as the roof of the cave, (2) may bridge the cavity before eventually collapsing, or (3) if the rock is not too brittle, may sag or slowly settle into the cavity. In the first two instances, sinkholes appear abruptly at land surface. If the rock sags or settles, sinkholes form by gradual subsidence rather than by abrupt collapse. Cover-collapse sinkholes occur most frequently in the midsection areas of west-central Florida. They commonly occur in the ridge areas, but have also occurred as a result of pumping in areas of Hillsborough and Pasco Counties.

## Induced Sinkholes

Induced sinkholes are caused by man's activities, whereas natural sinkholes are not related to man's activities (Newton, 1976). Induced sinkholes consist of two types: those that result from water-level declines caused by ground-water withdrawals and those that result from construction. Induced sinkholes are common in developing areas of west-central Florida. Their occurrence can be expected to continue as the area develops.

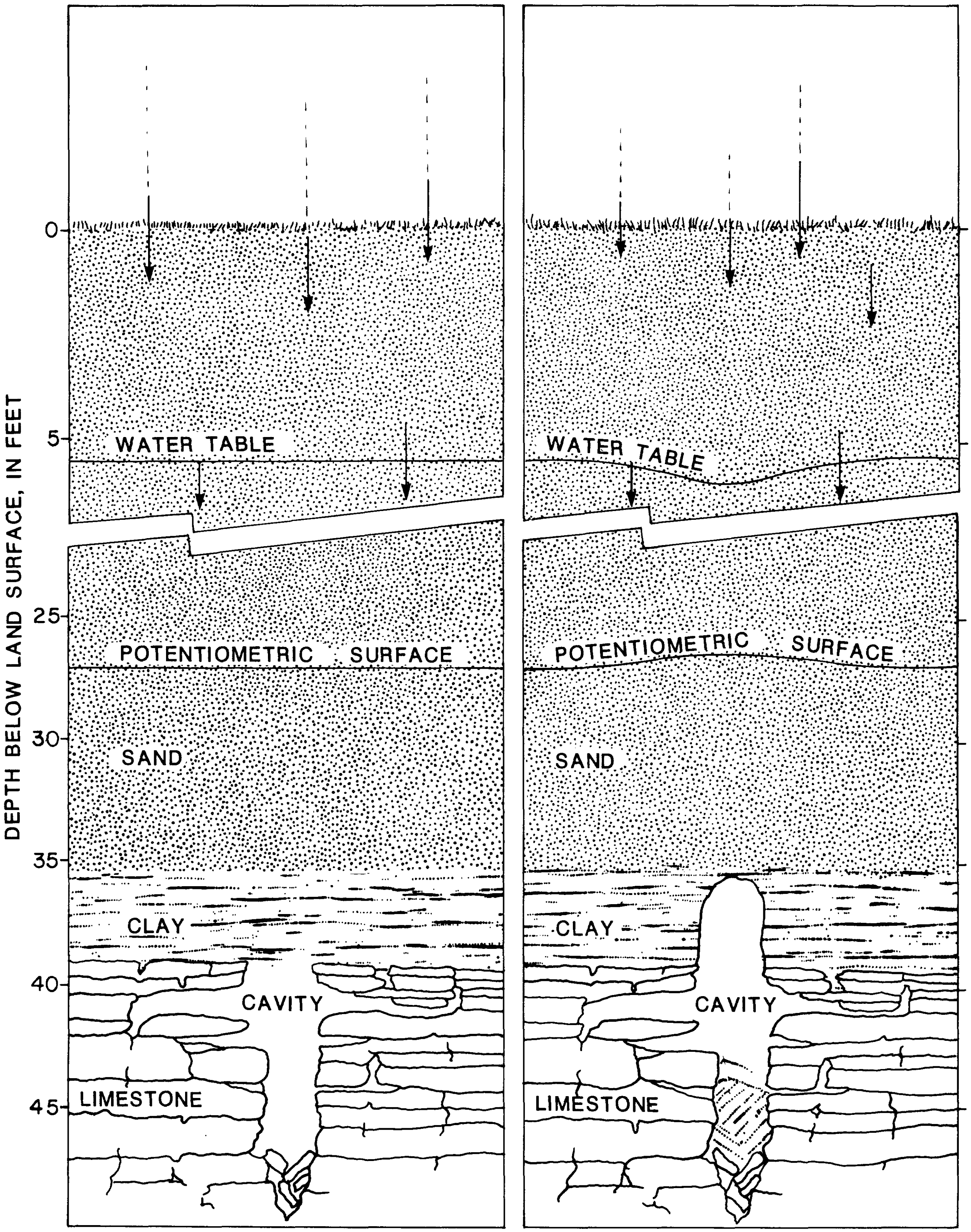
## Sinkhole Collapse Related to Ground-Water Withdrawals

The Upper Floridan aquifer is recharged primarily by direct infiltration or downward leakage from overlying aquifers. This occurs in areas where the water table or potentiometric surface of the overlying aquifers is higher than the potentiometric surface of the Upper Floridan aquifer and where confining beds that separate the aquifers are thin, discontinuous, or breached by sinkholes, faults, or other openings. In areas where the Upper Floridan aquifer is confined, recharge increases when the aquifer is pumped. The increase in recharge by leakage is directly proportional to the head differences between aquifers caused by pumping. That is, the greater the head difference, the greater the leakage through the confining bed into the Upper Floridan aquifer. Ground-water withdrawals can accelerate sinkhole development, particularly during dry periods when water levels in the Upper Floridan aquifer are low. Lowering of water levels by pumping results in loss of the water's buoyant support of unconsolidated material that overlies cavities in limestone. If the competency of the overlying layer is exceeded because of the increased weight, the effect is a collapse of the material into the limestone cavity.

Stewart (1968) documented a sinkhole that developed because of pumpage at the Section 21 well field north of Tampa (fig. 27). The limestone in the well-field area is overlain by a dense, relatively impermeable clay layer that averages about 4 feet in thickness (fig. 26). The clay is overlain by about 30 feet of sand. The area is a Pleistocene terrace whose main topographic relief is that caused by development of sinkholes.

Records of pumpage and water levels in the Section 21 well field are shown in figure 27. Prior to early 1964, pumpage was about 4 Mgal/d, and the head difference between the water table and the potentiometric surface was about 10 feet. By May of 1964, pumpage in the well field had increased to nearly 15 Mgal/d. The pumping caused the head difference between water levels in the surficial aquifer and the Upper Floridan aquifer to increase from about 10 to 15 feet. Thus, stresses across the confining clay layer increased. In areas where cavities were near critical conditions, that is, approaching the point where their roofs would collapse under natural conditions, the sudden increase of downward pressure hastened roof collapse. During the period of pumping from February through May 1964, 64 new sinkholes were reported within a 1-mile radius of the well field (Sinclair, 1982).

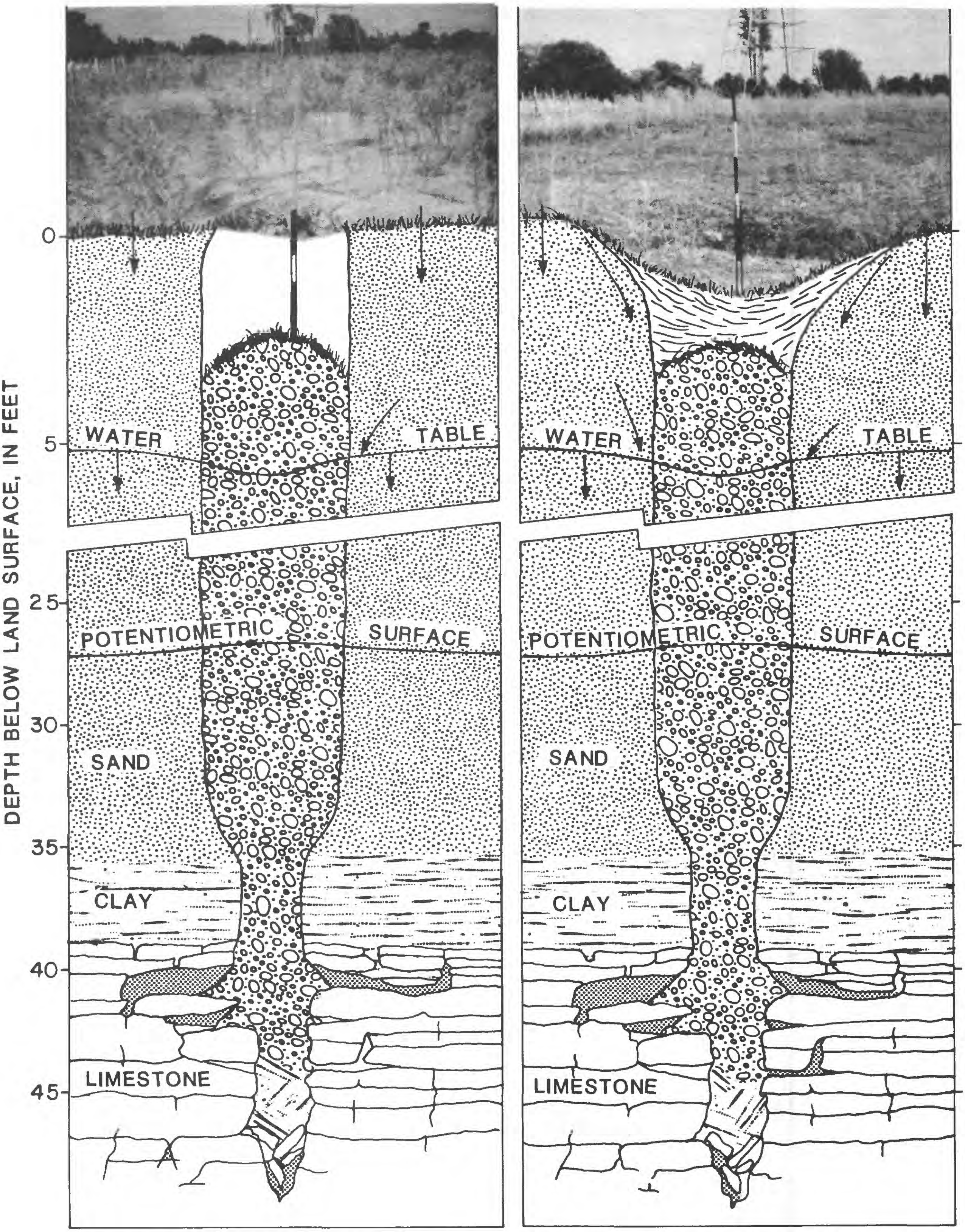
An example of the effects of large ground-water withdrawals from the Upper Floridan aquifer on sinkhole development was also documented in a 7-$\text{mi}^2$ area near Dover (fig. 1) in eastern Hillsborough County (Hall, L. E., and Metcalfe, S. J., Hydrologists, Hillsborough County, written commun., 1977). During the period January 17-24, 1977, air temperatures dropped to about 25°F, and to protect strawberry crops from freezing, growers spray irrigated throughout the freeze period. The intensive irrigation caused withdrawals of several



a. Cavity dissolved in limestone by percolating ground water.
Time: Centuries.

b. Collapse of overlying clay into cavity by spalling.
Time: Months - years.

Figure 26.--Stages in development of a cover-collapse



c. Piping of cohesionless sand into cavity.
Time: Hours - days.

d. Modification of sinkhole by surface erosion.
Time: Ten years.

sinkhole. (From Sinclair, in press.)

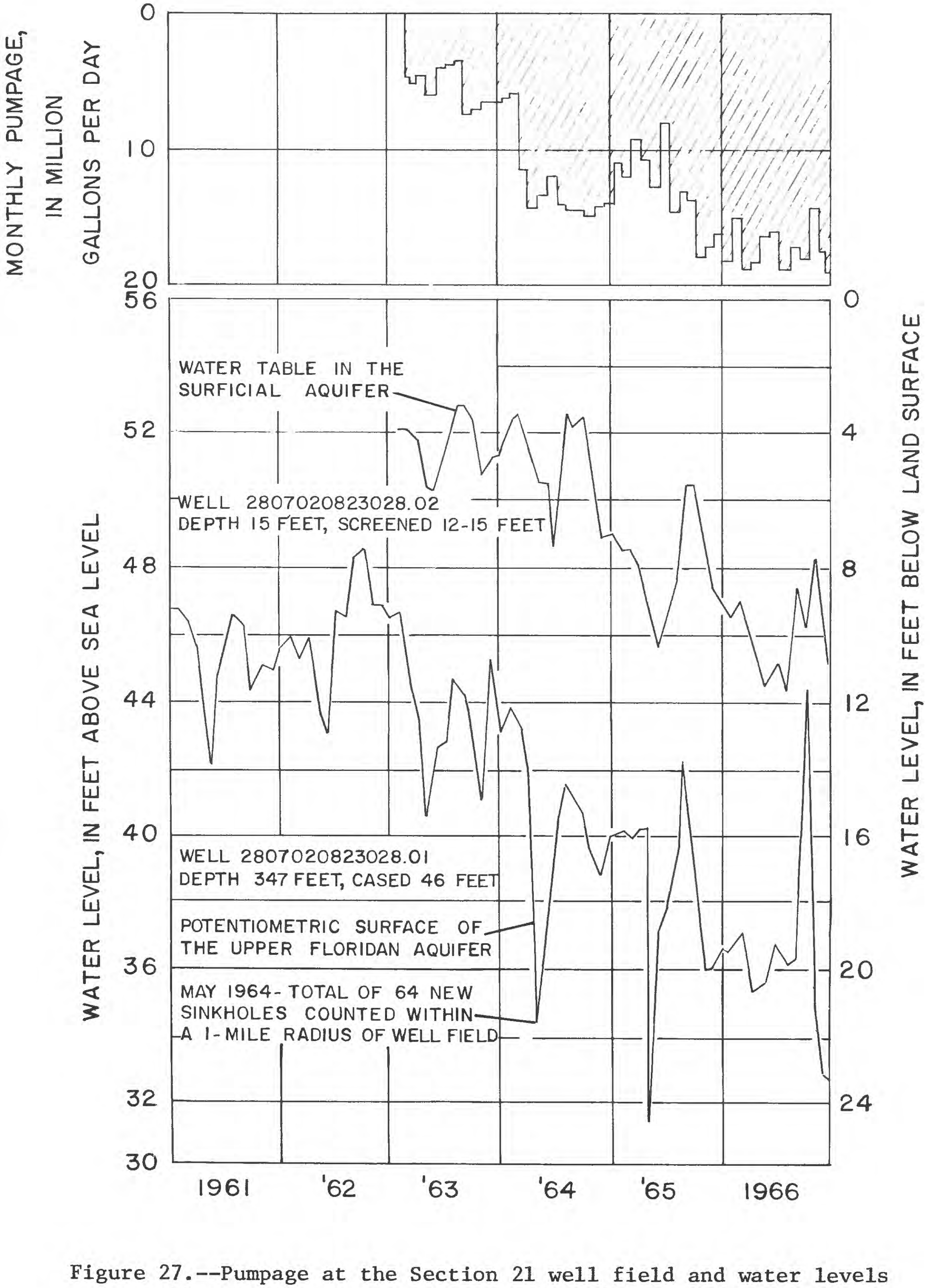


Figure 27.--Pumpage at the Section 21 well field and water levels in shallow and deep observation wells, 1961-66. (Modified from Stewart, 1968.)

million gallons of ground water per day and caused a large decline in the potentiometric surface throughout the area. The reduction in buoyancy caused by drawdown in the potentiometric surface, coupled with the decrease in cohesive strength and the increased load at the surface caused by the irrigation, triggered the occurrence of 22 sinkholes in the area.

In December 1983, air temperatures at Dover were lower than those in January 1977 and again the crops were spray irrigated to prevent freezing. However, the heavy pumping of ground water did not produce a rash of sinkholes such as those that occurred in 1977. The lack of sinkhole occurrences in 1983 probably was due to the fact that stress on the aquifer system was about the same as in 1977 and, therefore, was not sufficient to induce development of new sinkholes. Sinkholes that could result under that level of stress had occurred during the 1977 event, so the potential for additional sinkholes to occur was greatly lessened.

## Sinkholes Related to Construction

Ponding of water by construction of dams and reservoirs and diversion of surface water by other activities, such as highway construction, have also been responsible for triggering the collapse of sinkholes. Impoundment of water in reservoirs and artificial lakes may contribute to sinkhole development by raising ground-water levels, loading the land surface, and providing a source of percolating water that may flow through and erode zones of weakness in carbonate rocks or overlying sediments.

The bed of Lake Grady (fig. 1), a manmade lake in south-central Hillsborough County, is shown in figure 28. Two years after the 200-acre lake was formed, abnormal declines in its level indicated that it was losing water (Stewart, 1982). Water in neighboring wells that tapped the Upper Floridan aquifer became turbid about a month before a sinkhole opened and drained the lake. The sinkhole was subsequently partially excavated and filled with wire mesh, cement, and clay. The plugged sinkhole was then isolated from the lake basin by an earthen dike and the lake refilled.

In highway construction, removal of surficial materials and vegetation may expose openings that connect with the underlying limestone or it may change the natural drainage pattern of an area. Exposed openings provide direct access for surface water to move downward into the aquifers and increase dissolution of the limestone. Changes in the natural drainage pattern generally result in concentrating surface runoff into ditches or ponds to remove the excess water. The discharge of large concentrated volumes of water may cause erosion of surficial materials that overlie cavities in the limestone and hasten development of sinkholes. Several sinkholes have occurred on highways in the study area, particularly in Hillsborough and Polk Counties. Generally, the sinkholes ranged in diameter from about 5 to 25 feet and averaged about 15 feet in depth.

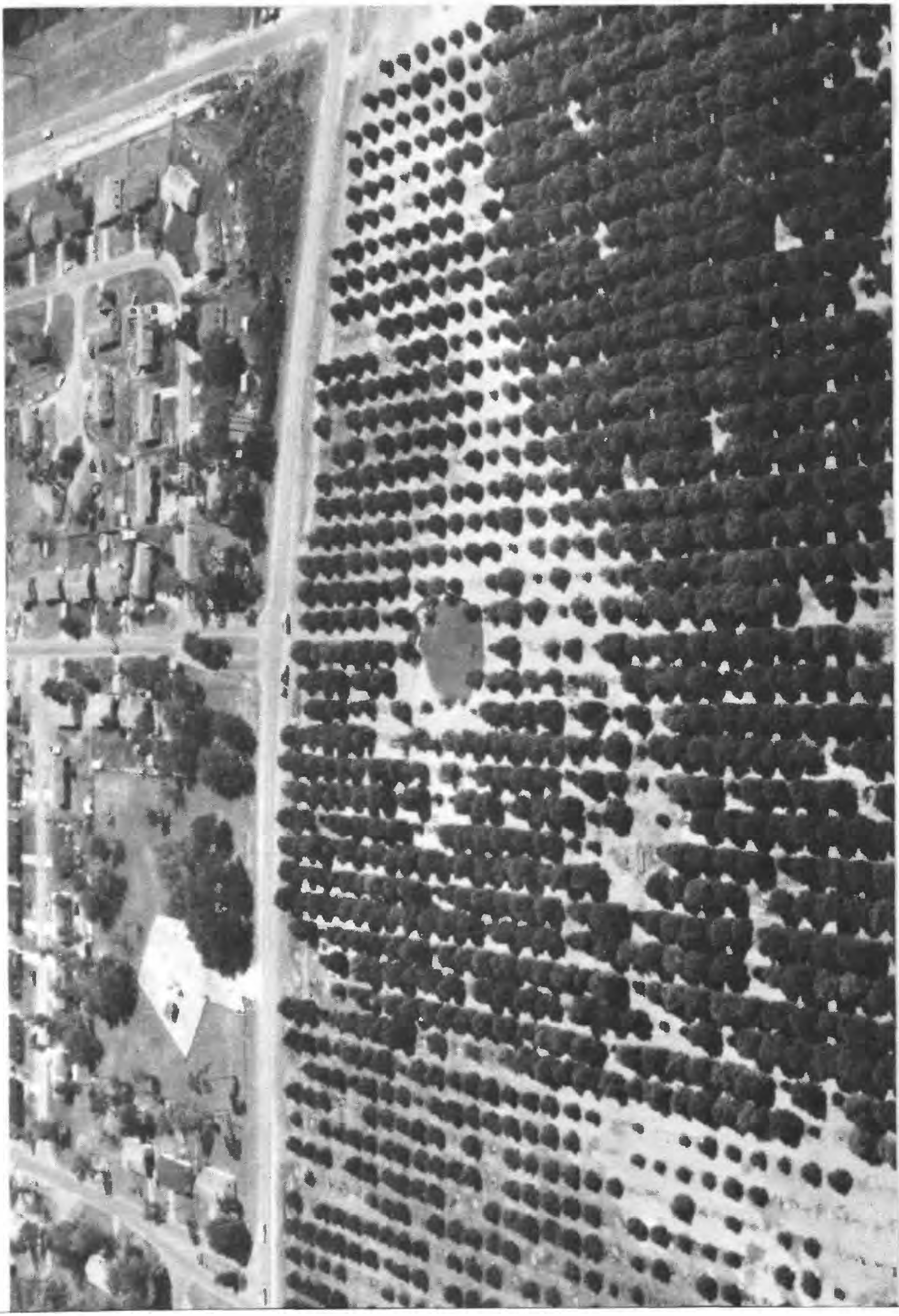


Figure 28.--Bed of former Lake Grady near Tampa drained by a cover-collapse sinkhole, May 1974. (Photograph by J. W. Stewart, U.S. Geological Survey.)

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p. 56

The photographs on pages 56 and 64 were switched inadvertently.

The photograph on page 56, which shows an aerial view of a sinkhole near Winter Haven, should have appeared on page 64 with the caption, "Sinkhole

# OCCURRENCE OF SINKHOLES

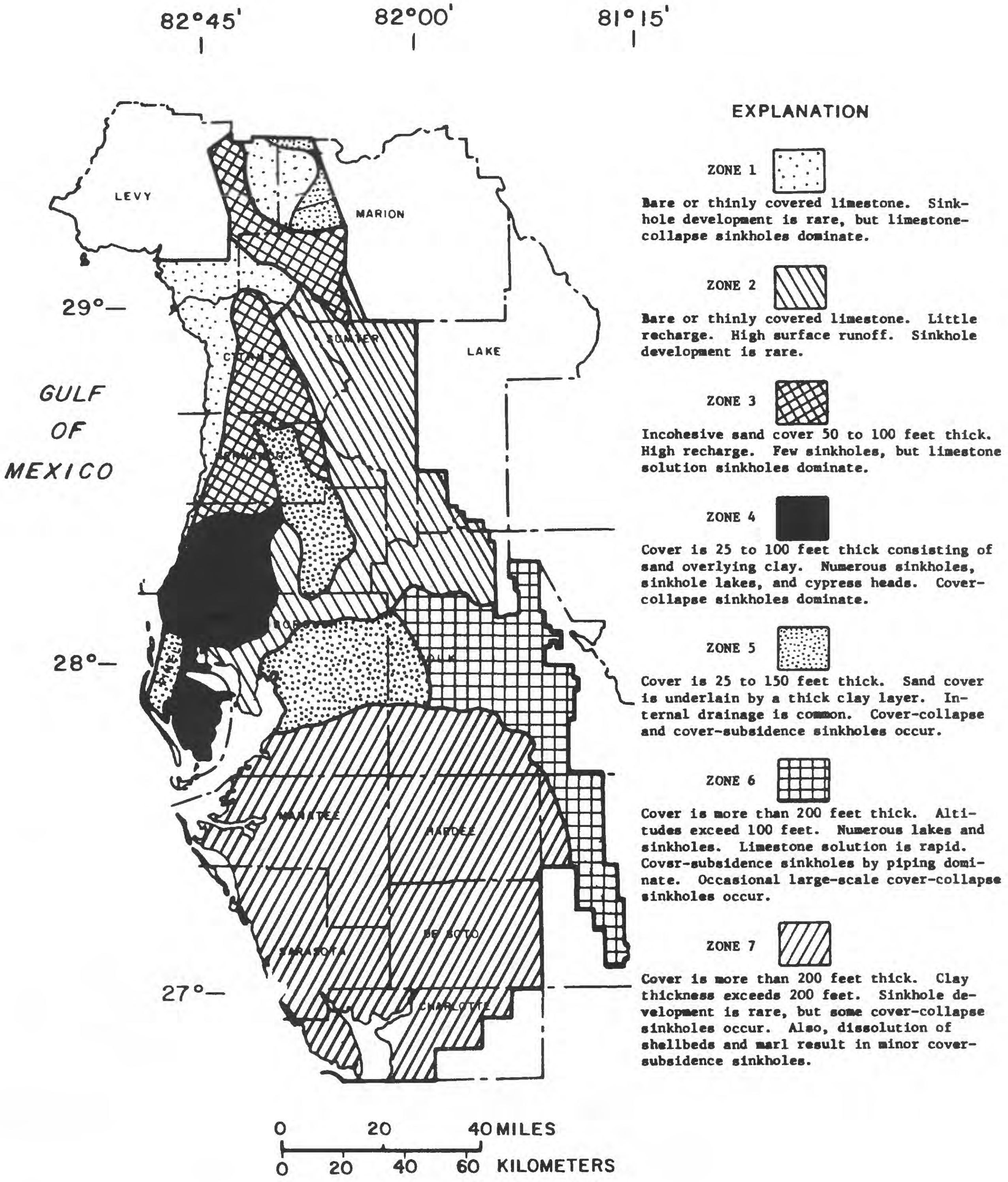
## Sinkhole-Type Areas

The areas shown in figure 29 illustrate zones of different sinkhole type and their relationship to different types of geology, landscape, and geomorphology. Zone 1 consists of a coastal strip below an altitude of about 25 to 30 feet and a small area in the extreme north. The altitude along the coast marks a relatively long stand of sea level that created beaches from about the Hillsborough-Pasco County line northward. To the east of these beaches, on the terrace, the mantle of sand and sandy clay is relatively thin and limestone bedrock is near land surface. Joint and fracture patterns in the limestone are evident in the occurrence of linear stream segments in the area. Sinkholes in zone 1 are generally formed by the collapse of limestone roofs over conduits that have expanded beyond their roof-support capacity. Because of the very low ground-water gradient and relatively noncorrosive water, sinkhole development in zone 1 is not rapid, even in terms of geologic time, except perhaps in the vicinity of springs. Most sinkholes in zone 1 are limestone-collapse sinkholes where a limestone roof has failed because of loading of the land surface, ground vibration, ground-water withdrawals, or other development activities.

Zone 2 is a large area comprising the Green Swamp and the Withlacoochee and Hillsborough River basins. The area consists of bare to thinly covered limestone. Because the area is one of dense stream patterns, it suggests that much of the rainfall that is not lost to evapotranspiration runs off as streamflow. Small amounts of rainfall are available for infiltration, and aquifer recharge, though variable, is generally small (fig. 10). Most of the area was flooded by high sea levels several times during the Pleistocene Epoch. The land surface was altered by long-shore currents and wave action so that karst features within the limestone are filled and relatively inactive. At many places in zone 2, limestone is at land surface and caves do occur, but for the most part, the water table is at or near land surface. Ground-water circulation is impeded to a great extent by material of low permeability that filled the limestone conduits. Thus, sinkhole development in zone 2 is relatively rare.

Zone 3 has essentially no surface runoff, although rainfall is plentiful. Recharge to zone 3 is probably the highest in west-central Florida (fig. 10). It is also an area of relatively corrosive water in the Upper Floridan aquifer, and corrosion of limestone is taking place relatively rapidly. Zone 3 comprises a sand mantle 50 to 150 feet thick that blankets limestone. The zone occurs along the Brooksville Ridge and the terrace east of the ridge in Marion County (fig. 4). Because of the incohesive nature of the sand, sinkhole development in the area proceeds by way of gradual subsidence rather than abrupt collapse. As the limestone surface below the sand mantle is dissolved and removed in solution, sand grains move downward to occupy the created space. Generally, this movement is transmitted to land surface over a long period of time. However, piping may occur after a limestone roof collapses, and an open sinkhole may appear at land surface.

Zone 4 comprises areas in parts of Hillsborough, Pasco, and Pinellas Counties covered by Pleistocene sand and clay deposits that range in thickness from 25 to 100 feet. Where the underlying limestone was dissolved, a residuum



EXPLANATION

ZONE 1 ░

Bare or thinly covered limestone. Sinkhole development is rare, but limestone-collapse sinkholes dominate.

ZONE 2 ▧

Bare or thinly covered limestone. Little recharge. High surface runoff. Sinkhole development is rare.

ZONE 3 ▩

Incohesive sand cover 50 to 100 feet thick. High recharge. Few sinkholes, but limestone solution sinkholes dominate.

ZONE 4 ■

Cover is 25 to 100 feet thick consisting of sand overlying clay. Numerous sinkholes, sinkhole lakes, and cypress heads. Cover-collapse sinkholes dominate.

ZONE 5 ▒

Cover is 25 to 150 feet thick. Sand cover is underlain by a thick clay layer. Internal drainage is common. Cover-collapse and cover-subsidence sinkholes occur.

ZONE 6 ▦

Cover is more than 200 feet thick. Altitudes exceed 100 feet. Numerous lakes and sinkholes. Limestone solution is rapid. Cover-subsidence sinkholes by piping dominate. Occasional large-scale cover-collapse sinkholes occur.

ZONE 7 ▨

Cover is more than 200 feet thick. Clay thickness exceeds 200 feet. Sinkhole development is rare, but some cover-collapse sinkholes occur. Also, dissolution of shellbeds and marl result in minor cover-subsidence sinkholes.

Figure 29.--Zones of different sinkhole types.

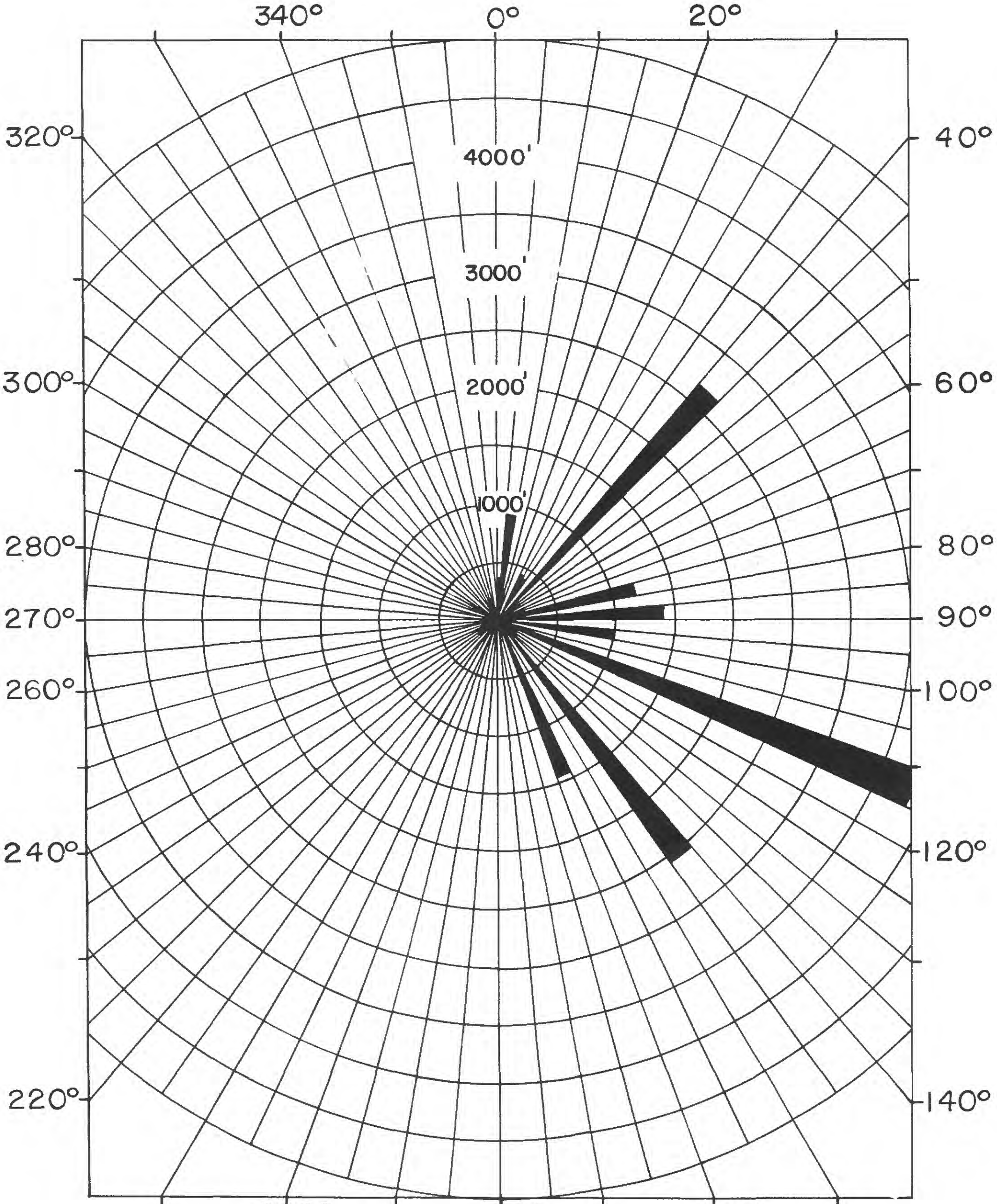
of sandy clay was left that grades down to a weathered limestone surface. This sandy clay forms a confining bed that restricts the downward movement of water from the surficial aquifer to the Upper Floridan aquifer. Many sinkholes, sinkhole lakes, and cypress heads occur in zone 4. The cypress heads form in depressions that intersect the water table and are more obvious indications of sinkholes than land-surface depressions, such as those that occur in zone 3. Lakes in zone 4 are commonly irregular in outline because of the coalescence of many small sinkholes. Figure 30 is a Rose diagram of the composite along the long axes of sinkholes in the Section 21 well-field area (fig. 31) that is in zone 4. The small sinkholes that are included in the Rose diagram could have been oriented in any direction because most small sinkholes in zone 4 are round. Along fractures, the sinkholes develop laterally and increase in size as they coalesce. In general, the long axes of many sinkholes in Section 21 fall in the range of 40 to 45 degrees and 110 and 115 degrees. Lineations of stream channels in the area also correspond somewhat roughly to lineations of sinkholes and sinkhole features. The sinkholes in zone 4 are generally the cover-collapse type.

The effects of development on the occurrence of sinkholes have been well documented in zone 4 because of the number of large well fields in the area (Stewart, 1968; Sinclair, 1974). Development of sinkholes in this zone, where the geology is relatively well known, can probably be predicted as well as anywhere in west-central Florida.

Zone 5 comprises the southern end of the Brooksville Ridge, northwestern Pinellas County, and an area that extends from about Tampa eastward to the Lakeland Ridge. Land-surface altitudes in most of the areas are relatively high, and surficial sands are underlain by a thick section (25 to 100 feet) of impermeable clay. Much of the rainfall flows through short intermittent streams to the Gulf or to lakes. The lakes increase in size during the rainy season and some disappear when intermittent sinkholes develop in lake bottoms and water drains internally to the Upper Floridan aquifer. This process is best shown in the southern Brooksville Ridge area because of its high altitude and rapid ground-water movement. The process is also typical of east-central Hillsborough County where the limestone is overlain by 25 to 150 feet of sand and sandy clay. Most streams in the area are perennial. Internal drainage is common, and sinkholes occur by cover collapse and cover subsidence.

Zone 6 is in the eastern part of the study area and includes parts of Polk and Highlands Counties. It is a region of ridges often referred to as the Lake Region. Cover material is greater than 200 feet thick with 100 feet or more of clay. Ridges in zone 6 include the Winter Haven Ridge, Lake Henry Ridge, and Lake Wales Ridge (fig. 4). The altitudes of the ridges are 100 feet or more above sea level. These ridges are primarily erosional remnants, but may be structural as proposed for the Lakeland Ridge. The ridges are apparently bordered by beaches and terraces of pre-Pleistocene age. Lakes and sinkholes along the ridges are relatively large and well developed. This may be because the area has not been innundated since Miocene time.

The ridge area is one of moderate recharge (fig. 10) of relatively corrosive water. Because of circulation of corrosive water, solution of bedrock is as rapid as any area in west-central Florida.



EXPLANATION

LENGTH IS CUMULATIVE LENGTH OF LONG AXIS OF SINKS WITHIN A 5 DEGREE ARC.

Figure 30.--Lineation of sinkholes within the Section 21 well-field area near Tampa.

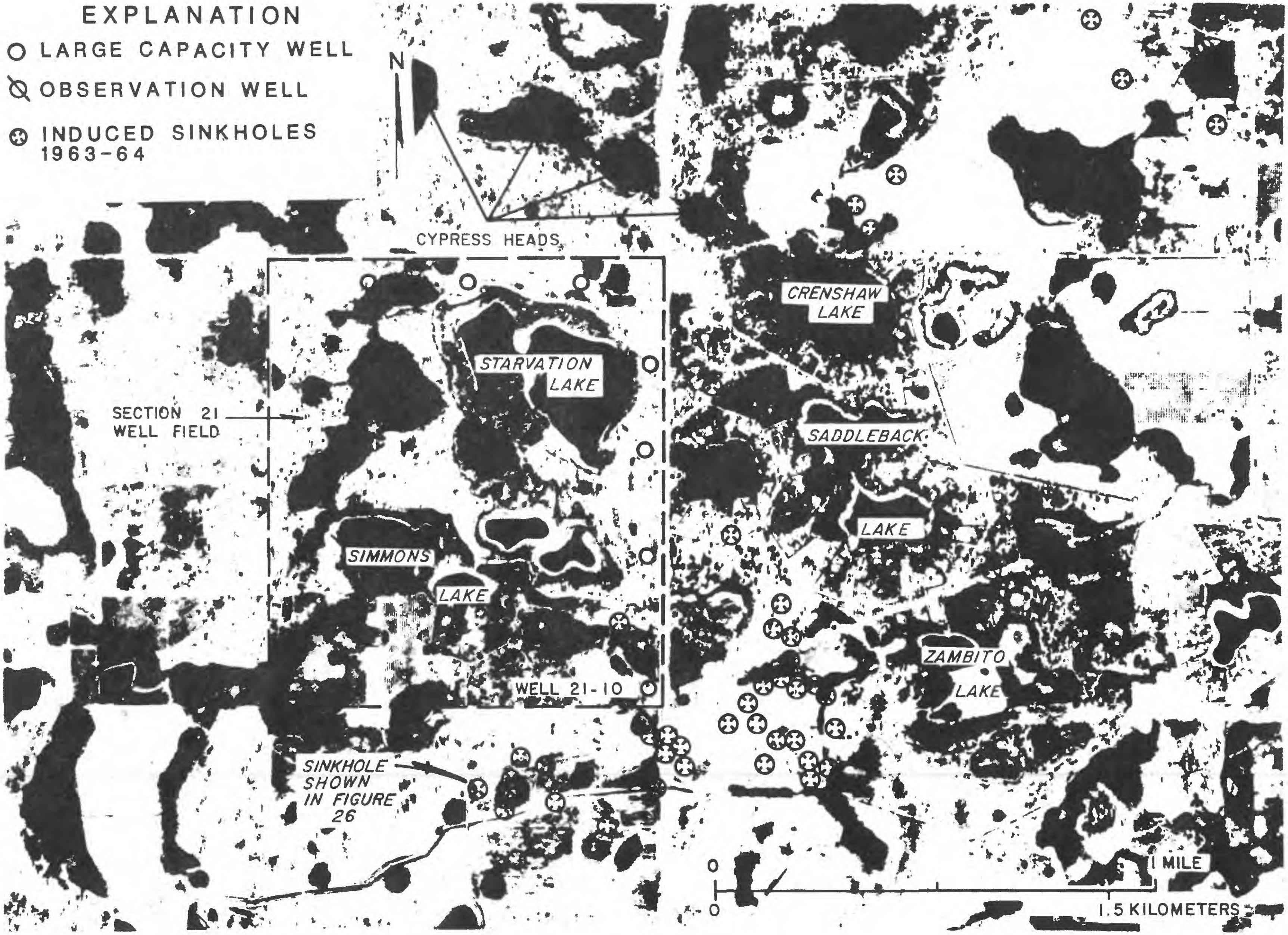


Figure 31.--Section 21 well-field area near Tampa. (Modified from Sinclair, 1982.)

The occurrence of small diameter vertical pipes in the overburden is illustrated by the bottom contours of Lake Eloise at Winter Haven (fig. 32). The small circular depressions in the lake bottom at the south end of the lake are presumed to be relatively recent, small diameter, piping type sinkholes. Although development of small diameter pipes in the overburden is probably the most common erosive process in zone 6, large-scale cover-collapse sinkholes also occur. Figure 33 is an aerial photograph of a sinkhole that occurred in an orange grove near Winter Haven in the summer of 1981 following a year-long period of drought. The sinkhole is about 120 feet in diameter and 30 feet deep. The sinkhole appeared at the same time as several nearby sinkholes and is presumed to have been caused by limestone collapse rather than by piping in the overburden. Thus, cover-subsidence sinkholes, largely by piping, dominate in zone 6, but cover-collapse sinkholes also occur.

Polk County's Department of Public Safety routinely monitors and documents sinkhole occurrences. Figure 34 is a map of the county that shows locations of reported sinkholes. Most of the sinkholes are within zone 6. Also shown in figure 34 is the topography of the county. Sinkholes are concentrated along the east flank of the Lakeland Ridge that, according to Altschuler and Young (1960), is an uplifted block. Presumably, the fault traces on either side of the uplifted ridge are marked by sinkholes. Analysis of driller's well logs indicates that the Lakeland Ridge is a bedrock high and that a bedrock low occurs immediately to the east of it and a less well-defined bedrock low occurs to the west of it. This fracture area was probably of major importance in accelerating corrosion of limestone and subsequent collapse of land surface.

Figure 35 shows major lineations along which sinkholes have occurred in Polk County. Lineations seem to aline with surface indications of underlying structural features, such as gaps through the Winter Haven and Lake Henry Ridges. Additional lineations are alined with gaps in the Lake Wales Ridge. From comparisons of topographic features, structure contours, apparent lineations, and surface-water features, it becomes apparent that geology and geologic structure affect the occurrence of sinkholes.

Zone 7 includes all or parts of eight counties in the lower third of the study area. The cover material in zone 7 is more than 200 feet thick and consists of cohesive sediments, discontinuous carbonate beds, and clay. Areas, such as zone 7, where the clay is as much as 200 feet thick may be considered to be essentially free from sinkhole development. However, shell beds and marl within the Pleistocene section near land surface and limestone in the Hawthorn Formation are probably dissolving. Thus, the small circular depressions commonly observed on topographic maps of zone 7 are probably cover-subsidence sinkholes resulting from very small collapse into underlying calcareous units.

Paleokarst features, such as Warm Mineral Spring, Little Salt Spring, and Deep Lake, occur in the southern part of zone 7 (fig. 1) and are examples of large solution cavities that formed below the confining clay. In the vicinity of Deep Lake, the deposits of the Hawthorn Formation are as much as 500 feet thick (fig. 8). Deep Lake has a maximum depth of about 300 feet. The cross section of Deep Lake (fig. 36) illustrates a classic example of a cover-collapse sinkhole and a breakout dome where overlying beds are collapsing into a large cavity at considerable depth. The debris pile at the base of the lake is largely clay. Deep Lake developed in response to collapse into deep and apparently large-scale solution cavities in the Upper Floridan aquifer below the Hawthorn Formation.

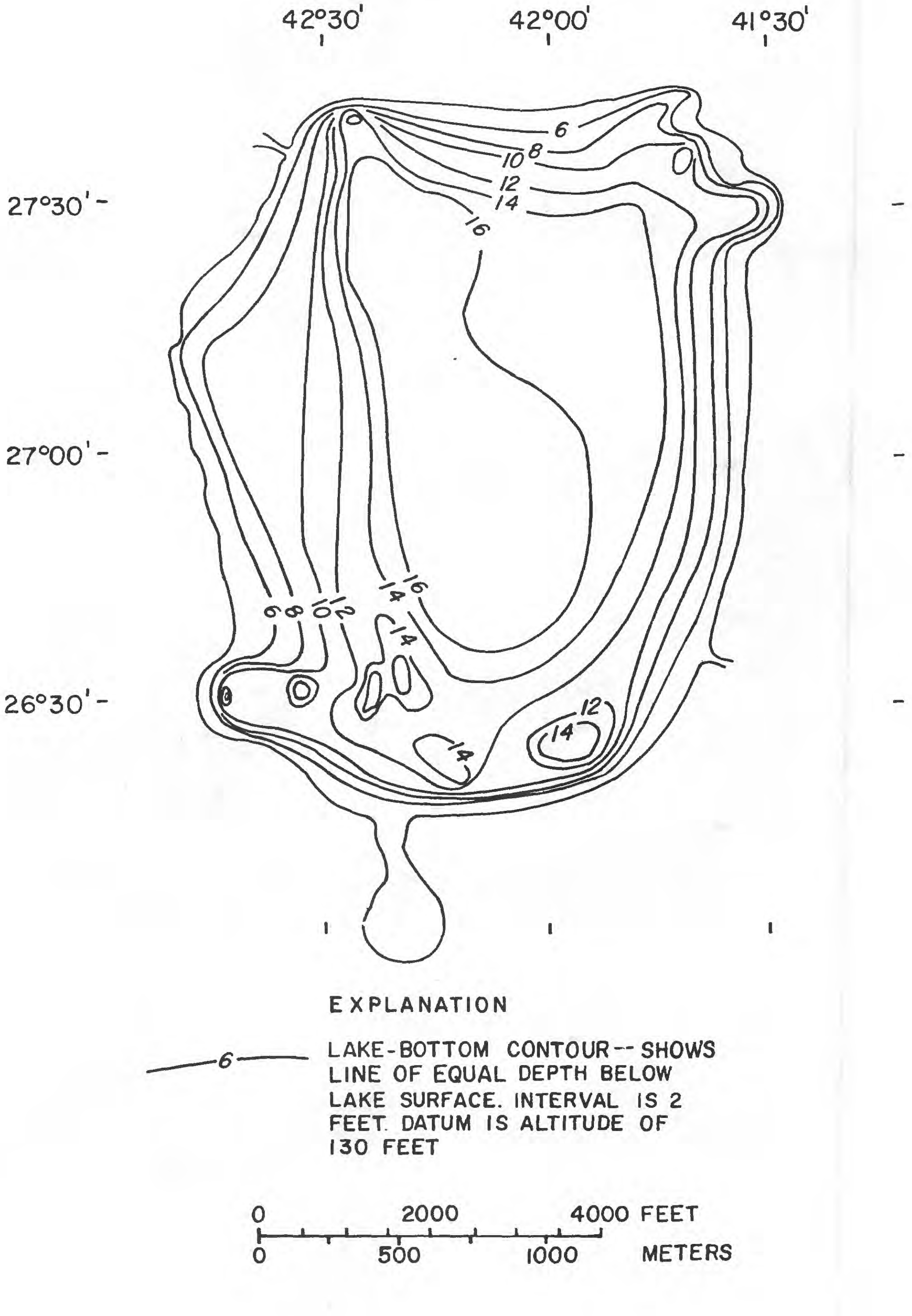


Figure 32.--Bottom topography of Lake Eloise at Winter Haven. (From Sinclair and Reichenbaugh, 1981.)

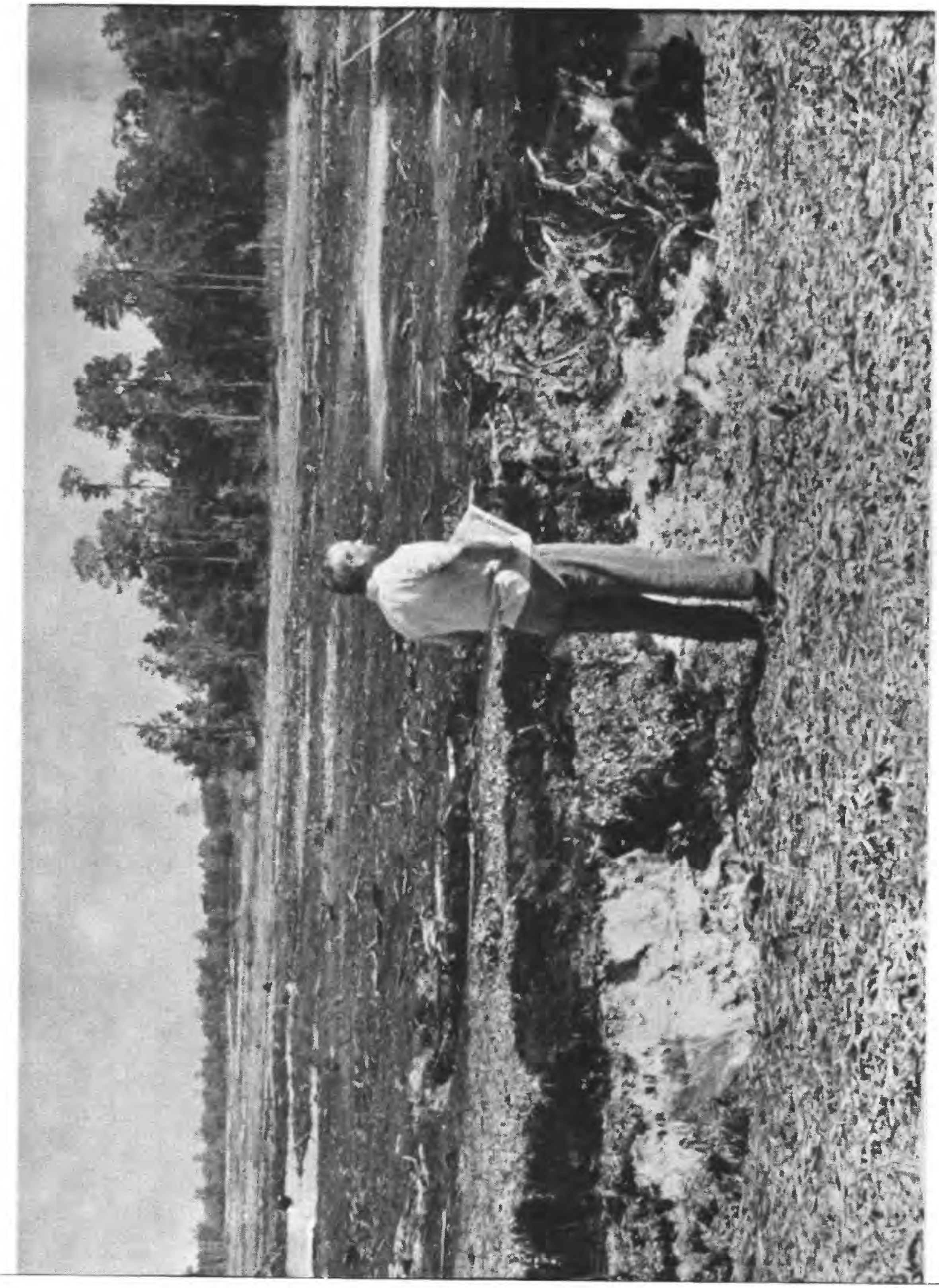
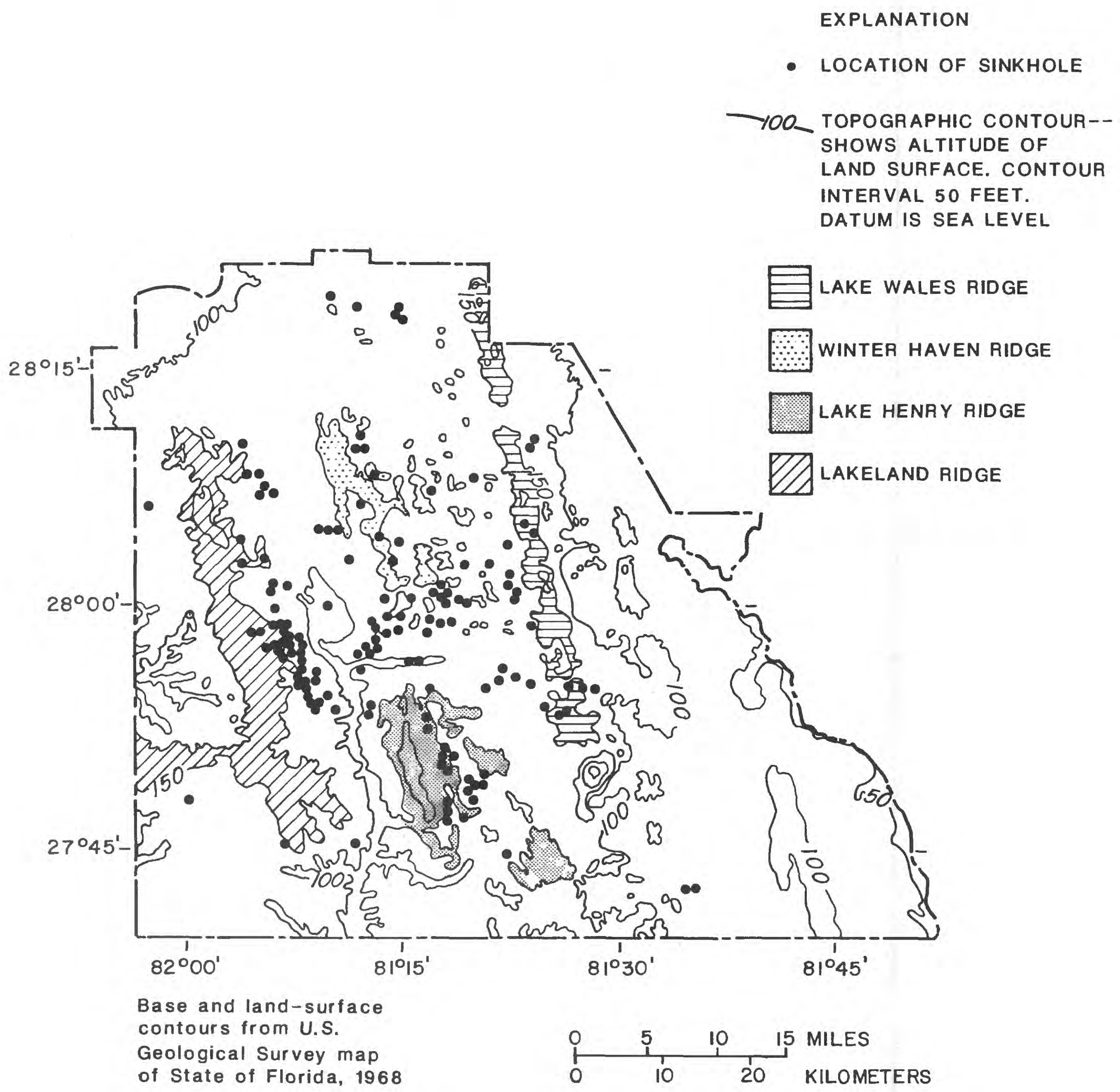


Figure 33.--Sinkhole near Winter Haven.

p. 64

The photographs on pages 64 and 56 were switched inadvertently.

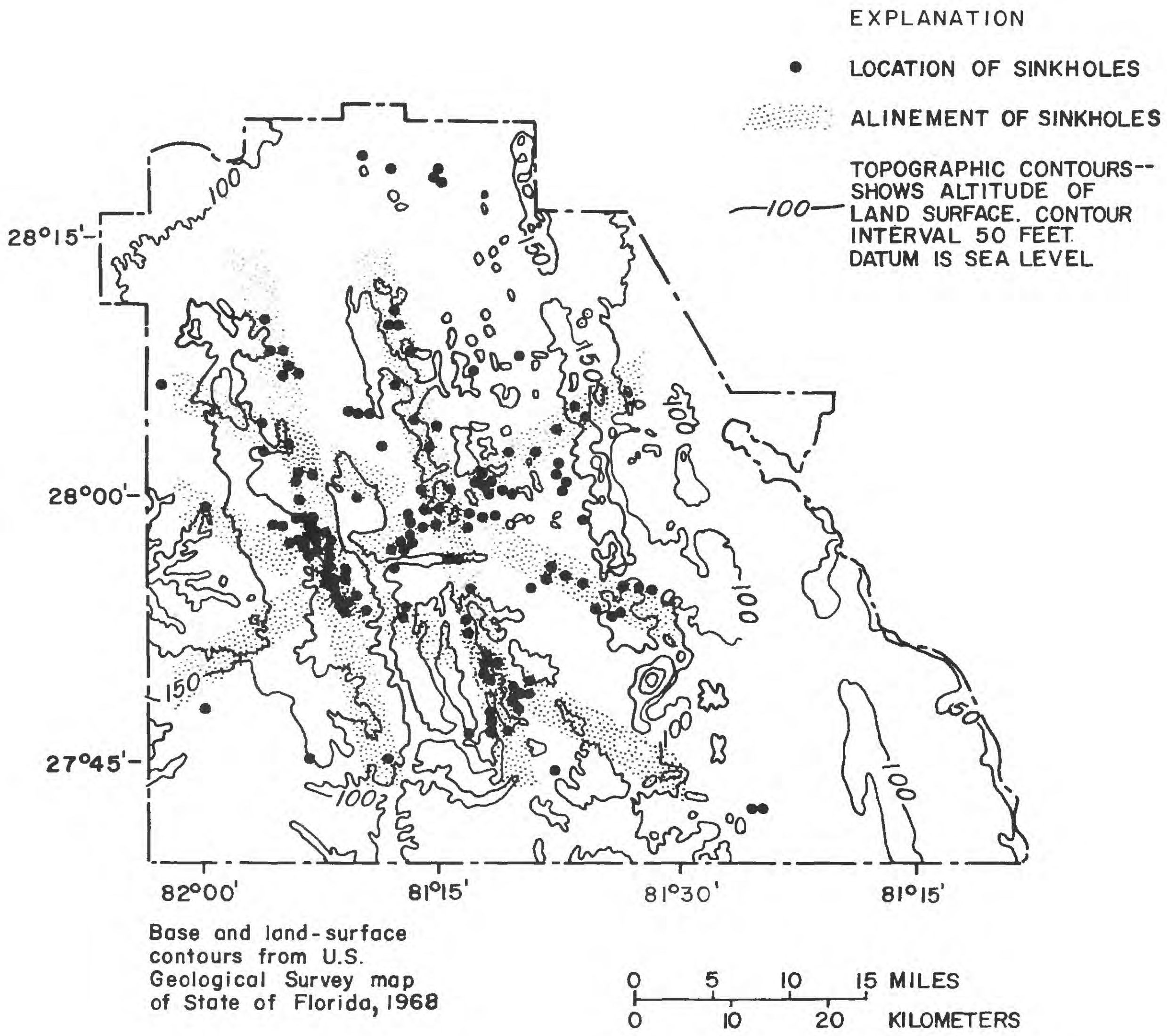
The photograph on page 64, which shows the bed of former Lake Grady, should have appeared on page 56 with the caption, "Bed of former Lake Grady near Tampa drained by a cover-collapse sinkhole, May 1974. (Photograph by J. W.



Base and land-surface contours from U.S. Geological Survey map of State of Florida, 1968

Figure 34.--Topography and locations of sinkholes, Polk County.

Figures 7, 8, 21, and 22 illustrate the increasing thickness of confining beds that overlie the Upper Floridan aquifer from north to south. In areas where the confining beds are about 100 to 150 feet thick, the bearing strength and leakance of the beds preclude infiltration of corrosive water and development of sinkholes. In zone 7 (fig. 29), the thick confining bed provides sufficient bearing strength to bridge all but the largest cavities that may develop in the underlying limestone. The low leakance of the confining bed minimizes recharge and corrosion of limestone.



Base and land-surface contours from U.S. Geological Survey map of State of Florida, 1968

Figure 35.--Major lineations along which sinkholes have occurred in Polk County.

## Reported Sinkholes in West-Central Florida

A listing of 181 sinkholes reported for 1958 and 1968-81, their location, date of occurrence, and description is given in table 3. The table was compiled from newspaper accounts, records of the Florida Department of Transportation, files of the U.S. Geological Survey, files of the Polk County Department of Public Safety, and files of the Southwest Florida Water Management District. Figure 37 shows the locations of the sinkholes. The reported information for

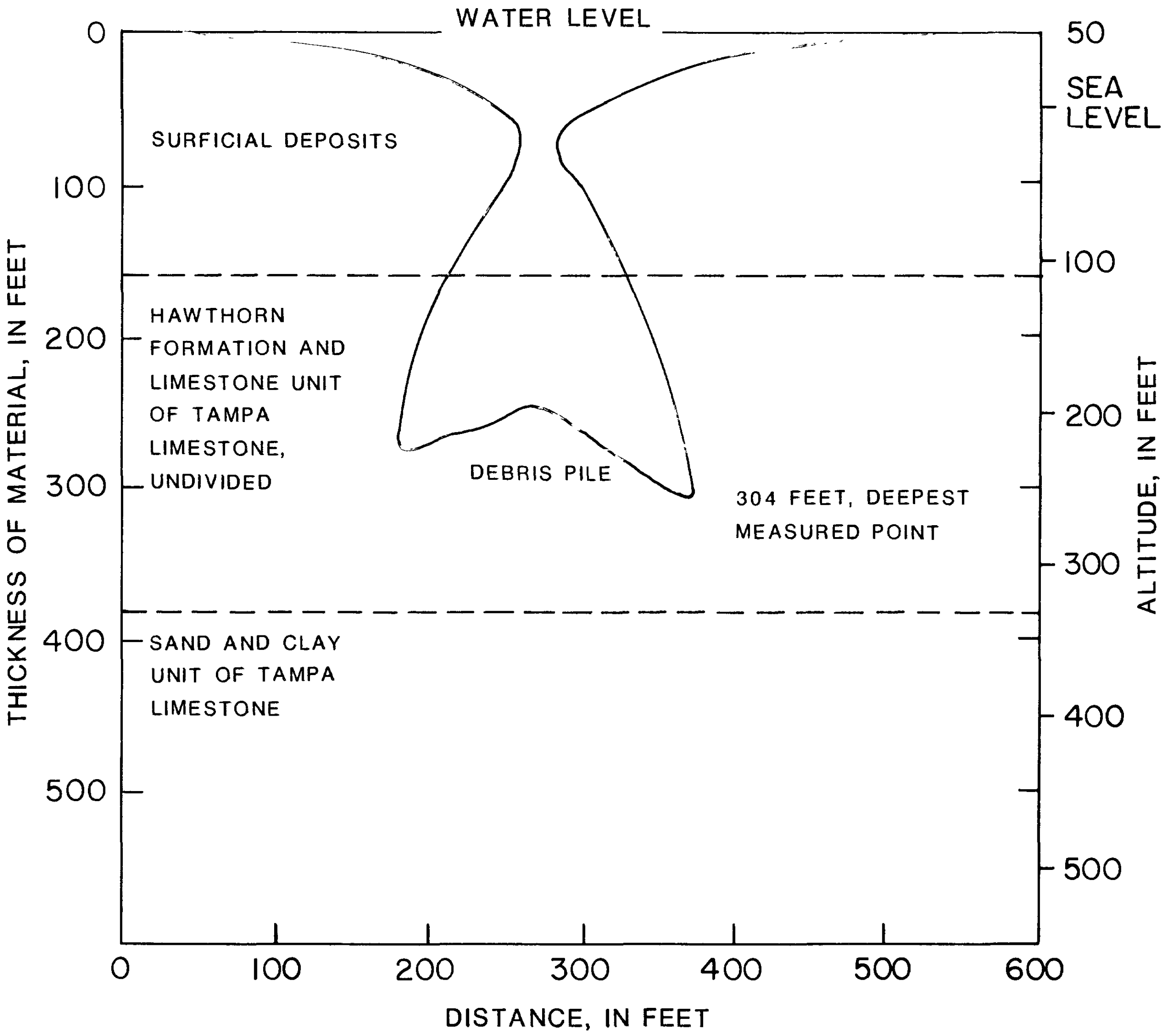


Figure 36.--Cross section of a cover-collapse sinkhole beneath Deep Lake near Arcadia. (Modified from Wilson, 1977; Sinclair, in press.)

sinkholes is somewhat skewed because of the method of data collection and land-use factors. For example, very few sinkholes are reported from rural areas such as farms, limestone quarries, phosphate mines, and forests, whereas many sinkholes are reported in developed areas. Many of the reported sinkholes are in Polk County because the county's Department of Public Safety monitors sinkhole occurrences. Thus, more sinkholes are reported in Polk County than in other counties that do not have sinkhole monitoring programs. The list does not include the many sinkholes caused by ground-water withdrawals for frost-freeze protection or well-field development because of inadequate documentation on many of those occurrences.

Table 3.--Inventory of reported sinkholes

[Location: T, township; R, range; S, section. Date of occurrence: M, month; D, day; Y, year. Description: L, length; W, width; D, depth; B, bearing; Sh, shape; Sl, slope. Length, width, and depth are in feet; bearing is in degrees from north]

| Location | | | Date of occurrence | | | Description | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T | R | S | M | D | Y | L | W | D | B | Sh | Sl | |
| 12S | 18E | 34 | 09 | 01 | 74 | 006 | 006 | 003 | 0 | | Flat | Very wet. |
| 12S | 18E | 34 | 09 | 01 | 74 | 008 | 008 | 006 | 0 | | Flat | Very wet. |
| 13S | 19E | 23 | 04 | 24 | 74 | 006 | 006 | 006 | 0 | | High | Depth to rock 3 feet. |
| 13S | 21E | 18 | 10 | 15 | 74 | 006 | 006 | 006 | 0 | | Slope | Very wet. |
| 14S | 21E | 04 | 03 | 21 | 74 | 001 | 001 | 004 | 0 | Pipe | High | Very dry. |
| 14S | 21E | 22 | 04 | 02 | 74 | 008 | 008 | 004 | 0 | Pipe | Low | Very dry, blasting. |
| 14S | 21E | 22 | 04 | 02 | 74 | 006 | 006 | 006 | 0 | Pipe | Low | Very dry, blasting. |
| 14S | 21E | 22 | 05 | 23 | 76 | 012 | 012 | 010 | 0 | | Slope | Very wet, rain. |
| 14S | 21E | 22 | 04 | 02 | 74 | 003 | 003 | 003 | 0 | Pipe | | Very dry, blasting. |
| 14S | 21E | 31 | 02 | 06 | 78 | 005 | 004 | 006 | | | | |
| 16S | 16E | 24 | 01 | 02 | 73 | 006 | 006 | 006 | 0 | Pipe | Low | Depth to water 12 feet; depth to rock 16 feet. |
| 16S | 16E | 35 | 06 | 14 | 73 | 002 | 002 | 005 | 0 | Pipe | Low | |
| 16S | 16E | 35 | 10 | | 69 | 002 | 002 | 003 | 0 | | | |
| 16S | 17E | 13 | 10 | | 69 | 015 | 015 | 005 | 0 | | | |
| 16S | 21E | 18 | 11 | | 72 | 004 | 004 | 006 | 0 | Pipe | | |
| 17S | 16E | 09 | 10 | | 69 | 002 | 002 | 003 | 0 | | | |
| 17S | 20E | 17 | 11 | | 73 | 002 | 002 | 004 | 0 | Pipe | | |
| 17S | 21E | 12 | 01 | 29 | 75 | 010 | 010 | 006 | 0 | | | |
| 17S | 22E | 30 | 02 | 07 | 80 | 004 | 004 | 008 | 0 | Sink | Low | Very dry, traffic. |
| 18S | 17E | 08 | 07 | 09 | 73 | 002 | 002 | 003 | 0 | Pipe | Flat | |
| 18S | 17E | 17 | | | | 003 | 003 | 003 | 0 | Pipe | Flat | Very dry. |
| 18S | 17E | 22 | 06 | 02 | 81 | | 008 | 006 | | | | |
| 18S | 17E | 22 | 07 | 02 | 76 | 004 | 003 | 004 | | | | 2-inch well in center of sink. |
| 18S | 17E | 27 | 01 | 22 | 80 | 006 | 006 | 006 | 0 | Sink | Flat | Very dry. |
| 18S | 17E | 28 | 03 | 07 | 79 | 003 | 003 | 003 | 0 | | | A second sinkhole is 10 feet east. |

Table 3.--Inventory of reported sinkholes--Continued

| Location | | | Date of occurrence | | | Description | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T | R | S | M | D | Y | L | W | D | B | Sh | Sl | |
| 18S | 22E | 04 | 12 | 21 | 72 | 003 | 003 | 003 | 0 | Pipe | | |
| 18S | 22E | 05 | 08 | 08 | 76 | 003 | 003 | 012 | 0 | Pipe | | Depth to rock 10 feet. |
| 19S | 17E | 21 | 12 | 14 | 77 | 005 | 005 | 006 | 0 | | | |
| 19S | 17E | 26 | 07 | 15 | 76 | 003 | 003 | 003 | | | | Bulldozer fell in sinkhole. |
| 19S | 17E | 28 | 02 | 16 | 73 | 009 | 009 | 007 | 0 | Pipe | Flat | |
| 19S | 20E | 16 | 04 | 21 | 76 | 012 | 011 | 003 | | | | |
| 19S | 20E | 24 | 04 | 04 | 78 | 008 | 006 | 005 | | | | |
| 19S | 20E | 32 | 06 | 03 | 77 | 020 | 015 | 001 | | | | |
| 19S | 20E | 34 | 06 | 20 | 77 | 025 | 025 | | 0 | | | |
| 19S | 21E | 23 | 03 | 27 | 80 | 004 | 008 | 008 | | | | |
| 19S | 23E | 08 | 07 | 19 | 74 | 004 | 004 | 004 | 0 | | Flat | |
| 21S | 22E | 36 | 07 | 28 | 78 | 008 | 008 | 004 | | | | Depth to water 5 feet. |
| 22S | 17E | 01 | 09 | 19 | 74 | 150 | 130 | 070 | 350 | Sink | Flat | Boatwright and Allman (1975). |
| 22S | 20E | 32 | 02 | 03 | 76 | 035 | 035 | 015 | 0 | | | |
| 23S | 17E | 10 | 06 | 01 | 81 | 015 | 015 | 018 | 0 | | Flat | Drilling machine fell in sink. |
| 23S | 17E | 27 | 02 | 14 | 78 | 005 | 004 | | | | | |
| 23S | 17E | 33 | | | | 001 | 010 | 002 | | | | Many small depressions in area. |
| 23S | 18E | 36 | 02 | 02 | 78 | 010 | 007 | 005 | | | | |
| 23S | 18E | 36 | 09 | 08 | 70 | 010 | 010 | 003 | 0 | Pipe | | Water retention, depth to rock 16 feet. |
| 23S | 19E | 15 | 09 | 01 | 76 | 002 | 001 | 005 | | | Slope | |
| 23S | 19E | 31 | 09 | 19 | 79 | 015 | 010 | 006 | | | | |
| 23S | 20E | 03 | 01 | 01 | 68 | 015 | 015 | 008 | 0 | | | |
| 23S | 20E | 21 | 02 | 24 | 81 | 005 | 005 | 004 | 045 | | Slope | |
| 23S | 20E | 24 | 07 | 05 | 76 | 100 | 100 | 4 | 0 | | Slope | Very wet. |
| 23S | 20E | 35 | | | | 100 | 100 | 030 | 0 | | Rolling | |
| 24S | 16E | 01 | 02 | 16 | 74 | 050 | 050 | 010 | 0 | | | Very dry. |
| 24S | 16E | 23 | 08 | 07 | 74 | 001 | 001 | 004 | 0 | | | Very wet. |
| 24S | 16E | 27 | 09 | 21 | 77 | 004 | 003 | 008 | | | | |
| 24S | 16E | 27 | 11 | 28 | 79 | 009 | 009 | 005 | 0 | Pipe | Flat | Well in center of sink, poorly cemented. |
| 24S | 16E | 34 | 01 | 08 | 80 | 013 | 012 | 010 | | | | |

Table 3.--Inventory of reported sinkholes--Continued

| Location | | | Date of occurrence | | | Description | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T | R | S | M | D | Y | L | W | D | B | Sh | Sl | |
| 24S | 17E | 06 | 01 | 03 | 73 | 004 | 004 | 004 | 0 | Pipe | Flat | |
| 24S | 17E | 25 | 03 | 06 | 78 | 050 | 025 | 020 | | | | |
| 24S | 18E | 01 | 02 | 18 | 77 | 004 | 004 | 005 | 0 | | Flat | |
| 24S | 18E | 17 | 12 | 22 | 73 | 070 | 070 | | 0 | | Slope | Depth to water 15 feet, drilling at site. |
| 24S | 18E | 22 | 10 | 23 | 74 | 012 | 012 | 005 | 0 | | Low | Very dry, depth to water 4 feet. |
| 24S | 18E | 22 | 10 | 23 | 74 | 008 | 008 | 004 | 0 | | Low | Very dry, depth to water 4 feet. |
| 24S | 18E | 22 | 11 | 06 | 72 | 008 | 008 | 002 | 0 | Pipe | | Rain. |
| 24S | 21E | 21 | 02 | 09 | 78 | 012 | 008 | 026 | | | | Sink began draining small lake. |
| 24S | 21E | 28 | 09 | 09 | 74 | 002 | 002 | 005 | 0 | | High | Very wet, X-drain, depth to rock 5 feet. |
| 24S | 21E | 34 | 05 | 06 | 78 | 003 | 002 | 004 | | | Hilly | |
| 25S | 16E | 01 | 10 | 29 | 79 | 005 | 004 | 003 | | | | Very dry. |
| 25S | 16E | 02 | 08 | 15 | 79 | 006 | 003 | 006 | | | Old | Drain sink, sink is in older sink. |
| 25S | 16E | 03 | 10 | 25 | 79 | 012 | 006 | 010 | | | | |
| 25S | 16E | 10 | | | | | | | | | | |
| 25S | 16E | 15 | 08 | 21 | 78 | 002 | 002 | 004 | 0 | Sink | Flat | Very wet, rain. |
| 25S | 16E | 15 | 06 | 07 | 77 | 005 | 004 | 005 | | | | Drilling in area. |
| 25S | 16E | 21 | 07 | 18 | 77 | 019 | 018 | 010 | | | | |
| 25S | 16E | 36 | 10 | 01 | 77 | 003 | 003 | 002 | 0 | | | |
| 25S | 17E | 31 | 05 | 17 | 77 | 012 | 011 | 009 | | | | |
| 25S | 18E | 04 | 02 | 22 | 78 | 005 | 005 | 006 | 0 | | | A second sink 20 feet south. |
| 25S | 18E | 29 | 03 | 28 | 81 | 008 | 006 | 003 | 045 | | Flat | |
| 25S | 19E | 09 | 05 | 27 | 81 | 012 | 006 | 010 | | | Flat | |
| 25S | 19E | 20 | 04 | 25 | 78 | 008 | 008 | 007 | | | | |
| 25S | 19E | 34 | 10 | 13 | 72 | 003 | 003 | 004 | 0 | Pipe | Low | |
| 25S | 20E | 09 | | | | 006 | 004 | 005 | 145 | | Lakeshore | In shore of Lake Drief, drilling nearby. |
| 25S | 24E | 20 | | | | 029 | 021 | 015 | | | | |
| 26S | 15E | 23 | 02 | 12 | 79 | 009 | 008 | 005 | | | | Rain. |
| 26S | 15E | 31 | 12 | 01 | 72 | 008 | 008 | 005 | 0 | Pipe | Flat | Very dry. |
| 26S | 16E | 28 | 07 | 21 | 77 | 005 | 004 | 004 | | | | Earlier sink improperly filled. |
| 26S | 16E | 29 | 05 | 22 | 79 | 023 | 021 | 010 | | | | |

Table 3.--Inventory of reported sinkholes--Continued

| Location | | | Date of occurrence | | | Description | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T | R | S | M | D | Y | L | W | D | B | Sh | Sl | |
| 26S | 16E | 30 | 02 | 09 | 79 | 021 | 021 | 008 | 0 | | | Rain. |
| 26S | 16E | 31 | 03 | 26 | 79 | 017 | 014 | 009 | | | | Rain. |
| 26S | 17E | 24 | 07 | 13 | 70 | 003 | 003 | 004 | 0 | Pipe | | |
| 26S | 18E | 23 | 08 | 28 | 73 | 012 | 008 | 008 | | | Flat | |
| 26S | 18E | 32 | 04 | 18 | 78 | 005 | 003 | 003 | | | | |
| 26S | 19E | 01 | 08 | 30 | 79 | 011 | 009 | 008 | | | | Rain. |
| 26S | 19E | 13 | 03 | 19 | 80 | 005 | 005 | 003 | 0 | Sink | Low | |
| 26S | 19E | 19 | 02 | 17 | 81 | 002 | 002 | 003 | 0 | | Flat | |
| 26S | 21E | 16 | 08 | 29 | 73 | 003 | 003 | 003 | 0 | Pipe | Flat | |
| 27S | 15E | 27 | 03 | 18 | 81 | 018 | 018 | 006 | 0 | Sink | Flat | Irrigated new lawn, pumped 220,000 gallons in month. |
| 27S | 17E | 09 | 04 | 19 | 72 | 062 | 062 | 002 | 0 | | | |
| 27S | 17E | 10 | 08 | 13 | 73 | 035 | 035 | 030 | 0 | | | Near South Pasco well field. |
| 27S | 17E | 11 | 08 | 09 | 73 | 016 | 016 | 010 | 0 | | Lakeshore | |
| 27S | 18E | 15 | 06 | 24 | 74 | 010 | 010 | 001 | 0 | | Flat | Low water table. |
| 27S | 18E | 35 | | | 81 | | | | | | | Subsidence apparently due to pumping. |
| 27S | 18E | 35 | 07 | 08 | 75 | 007 | 004 | 002 | 360 | | | |
| 27S | 18E | 35 | 05 | 03 | 75 | 017 | 005 | 004 | 360 | | | Many small sinks in area recently. |
| 27S | 19E | 07 | 03 | 14 | 80 | 006 | 006 | 0.1 | | | | Subsidence. |
| 27S | 19E | 23 | 05 | 01 | 77 | 012 | 012 | 004 | 0 | Sink | Flat | Very dry, Suwannee Limestone. |
| 27S | 24E | 16 | 03 | 25 | 74 | 010 | 010 | 005 | 0 | Pipe | High | Very wet, rain, depth to water 15 feet. |
| 27S | 24E | 20 | 05 | 19 | 81 | 029 | 021 | 015 | | | | |
| 27S | 25E | 02 | 05 | 16 | 74 | 020 | 020 | 002 | 0 | | Flat | Very wet, drilling. |
| 27S | 25E | 34 | 05 | 18 | 81 | 175 | 175 | 003 | 0 | | Lakeshore | |
| 28S | 15E | 34 | | | 77 | 015 | 009 | 004 | | | | Subsidence during a 2-year period. |
| 28S | 17E | 35 | 05 | | 78 | 003 | 003 | 031 | 0 | Pipe | Flat | |
| 28S | 18E | 01 | 03 | 23 | 64 | 016 | 016 | 005 | 0 | | Flat | Depth to rock 25 feet. |
| 28S | 18E | 03 | 09 | 14 | 71 | 006 | 006 | 003 | 0 | Pipe | | |
| 28S | 18E | 10 | 06 | 20 | 75 | 025 | 025 | 010 | 0 | | Flat | |
| 28S | 18E | 16 | 03 | 28 | 79 | 010 | 010 | 005 | 0 | | Flat | Several small sinks in recent years. |
| 28S | 18E | 16 | 05 | 05 | 80 | | | | | | | Subsidence. |

Table 3.--Inventory of reported sinkholes--Continued

| Location | | | Date of occurrence | | | Description | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T | R | S | M | D | Y | L | W | D | B | Sh | Sl | |
| 28S | 18E | 23 | 02 | 23 | 67 | | | | | | | Depth to water 7 feet, depth to rock 23 feet, construction area. |
| 28S | 18E | 27 | 05 | 06 | 80 | 006 | 006 | 004 | 0 | | | |
| 28S | 19E | 05 | 05 | 18 | 76 | 005 | 003 | 005 | | | | Several small depressions in area. |
| 28S | 19E | 05 | 10 | | 69 | 010 | 010 | 004 | 0 | Pipe | | |
| 28S | 19E | 06 | 05 | 17 | 79 | 002 | 002 | 010 | 0 | Pipe | Undulating | |
| 28S | 19E | 07 | 11 | | 78 | 002 | 002 | 002 | 0 | | Flat | Construction in area. |
| 28S | 19E | 11 | 05 | 08 | 79 | 020 | 007 | 001 | 360 | | Flat | Subsidence, homes built on large filled depression. |
| 28S | 19E | 14 | 05 | | 77 | 003 | 003 | 027 | 0 | Pipe | Undulating | |
| 28S | 19E | 17 | 08 | 12 | 75 | 030 | 030 | 025 | 0 | | Flat | Pumping 2.5 Mgal/d within 0.5 mile. |
| 28S | 19E | 24 | 08 | 18 | 74 | 003 | 002 | 004 | 073 | | | |
| 28S | 19E | 24 | 08 | 18 | 74 | 003 | 002 | 003 | | | | |
| 28S | 19E | 28 | 12 | 30 | 78 | 014 | 014 | 007 | 0 | Pipe | Flat | |
| 28S | 19E | 31 | 06 | 03 | 75 | 025 | 025 | 025 | 0 | | Slope | |
| 28S | 20E | 05 | 03 | 01 | 80 | 004 | 004 | 024 | 0 | Pipe | Ridge | Tried to pull well casing 6 feet west. |
| 28S | 20E | 09 | 05 | 30 | 81 | 002 | 002 | | 0 | | Undulating | Sink developed in treated effluent pond. |
| 28S | 20E | 35 | | | | 008 | 004 | 006 | | | Rolling | |
| 28S | 22E | 20 | 05 | 11 | 74 | 024 | 024 | 015 | 0 | | Low | Very dry, depth to water 12 feet. |
| 28S | 24E | 18 | 05 | 11 | 76 | 040 | 040 | 035 | 0 | | | Depth to water 25 feet, X-drain. |
| 28S | 24E | 29 | | | 66 | 100 | 100 | 070 | 0 | | | |
| 29S | 17E | 02 | 03 | 25 | 81 | 003 | 003 | 003 | 0 | | Flat | |
| 29S | 20E | 04 | 08 | 22 | 74 | 015 | 015 | 015 | 0 | | High | Construction. |
| 29S | 20E | 12 | | | 81 | 040 | 020 | 005 | 360 | Mult | Swale | Three sinks developed during drilling. |
| 29S | 23E | 17 | 07 | 09 | 74 | 025 | 025 | 070 | 0 | | | Rain. |
| 29S | 24E | 14 | | | 71 | 060 | 060 | 050 | 0 | | | |
| 29S | 24E | 15 | | | 67 | 150 | 150 | 070 | 0 | | | |
| 29S | 24E | 23 | | | 67 | 200 | 200 | 040 | 0 | | | |
| 29S | 24E | 36 | | | 66 | 125 | 125 | 080 | 0 | | | |
| 29S | 25E | 01 | 08 | 11 | 71 | 006 | 006 | 006 | 0 | Pipe | | |
| 29S | 25E | 13 | 05 | 01 | 81 | 130 | 130 | 035 | 0 | | Undulating | |
| 29S | 25E | 22 | 09 | 31 | 79 | 012 | 012 | 008 | 0 | Sink | High | Very wet, depth to water 8 feet. |

Table 3.--Inventory of reported sinkholes--Continued

| Location | | | Date of occurrence | | | Description | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T | R | S | M | D | Y | L | W | D | B | Sh | Sl | |
| 29S | 25E | 28 | 06 | 04 | 74 | 050 | 050 | 0.5 | 0 | | High | Very dry, traffic. |
| 29S | 25E | 28 | 07 | 05 | 74 | 003 | 003 | 004 | 0 | | Low | Rain. |
| 29S | 25E | 28 | 07 | 04 | 74 | 003 | 003 | 0.5 | 0 | | Low | Rain. |
| 29S | 25E | 28 | 06 | 20 | 74 | 016 | 016 | 003 | 0 | | High | Rain. |
| 29S | 25E | 28 | 06 | 28 | 74 | 020 | 020 | 0.5 | 0 | | High | Rain. |
| 29S | 25E | 28 | 07 | 07 | 74 | 020 | 020 | 010 | 0 | | Low | Rain. |
| 29S | 25E | 28 | 07 | 09 | 74 | 010 | 010 | 003 | 0 | | Low | Very wet, traffic. |
| 29S | 25E | 28 | 07 | 29 | 74 | 010 | 010 | 008 | 0 | | Low | Very wet, traffic. |
| 29S | 26E | 02 | 04 | 27 | 81 | 130 | 130 | 030 | 0 | | Hilly | Subsidence noted over $0.25\text{-mi}^2$ area. |
| 29S | 26E | 16 | 07 | 22 | 81 | 030 | 030 | 035 | 0 | | Rolling | |
| 29S | 27E | 03 | 07 | 26 | 74 | 020 | 020 | 012 | 0 | | Low | Very wet, drilling. |
| 30S | 20E | 22 | 04 | 10 | 74 | 025 | 025 | 012 | 0 | | | |
| 30S | 20E | 36 | 04 | 16 | 75 | 020 | 020 | 025 | 0 | | Hilltop | Near Lake Grady. |
| 30S | 20E | 36 | 05 | 24 | 74 | 045 | 040 | 018 | 045 | | Swale | Lake Grady. |
| 30S | 21E | 04 | 08 | 31 | 70 | 005 | 005 | 003 | 0 | | | |
| 30S | 21E | 31 | 08 | 08 | 81 | 008 | 008 | 006 | 0 | Pipe | Rolling | |
| 30S | 23E | 03 | 05 | 01 | 74 | 050 | 027 | 001 | 090 | | | |
| 30S | 25E | 06 | | | 65 | 175 | 175 | 035 | 0 | | | |
| 30S | 25E | 06 | 12 | 27 | 79 | 003 | 003 | 010 | 0 | Sink | Low | Very wet. |
| 30S | 25E | 06 | | | 58 | 200 | 200 | 060 | 0 | | | |
| 30S | 25E | 06 | | | 67 | 025 | 025 | 020 | 0 | | | |
| 30S | 25E | 06 | | | 68 | 040 | 040 | 015 | | | | |
| 30S | 25E | 06 | | | 68 | 030 | 030 | 015 | 0 | | | |
| 30S | 25E | 06 | | | 68 | 120 | 120 | 015 | 0 | | | |
| 30S | 25E | 06 | | | 67 | 060 | 060 | 060 | 0 | | | |
| 30S | 25E | 06 | | | 67 | 050 | 050 | 040 | 0 | | | |
| 30S | 25E | 06 | | | 66 | 060 | 060 | 060 | 0 | | | |
| 30S | 25E | 07 | 03 | 25 | 74 | 010 | 010 | 025 | 0 | | | Very wet, rain, depth to water 25 feet, depth to rock 9 feet. |
| 30S | 25E | 14 | | | 67 | 200 | 200 | 150 | 0 | | | Depth to rock 100 feet. |
| 31S | 21E | 26 | 04 | 07 | 74 | 130 | 100 | 050 | | | | Very dry, depth to water 46 feet. |

Table 3.--Inventory of reported sinkholes--Continued

| Location | | | Date of occurrence | | | Description | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T | R | S | M | D | Y | L | W | D | B | Sh | Sl | |
| 31S | 25E | 32 | | | 68 | 200 | 200 | 045 | 0 | | | |
| 31S | 26E | 11 | | | 68 | 060 | 060 | 050 | 0 | | | |
| 31S | 27E | 06 | | | 67 | 225 | 225 | 050 | 0 | | | |
| 32S | 20E | 13 | 06 | 15 | 76 | 025 | 015 | 009 | 090 | | Slope | |
| 38S | 19E | 32 | 07 | 21 | 81 | 008 | 008 | 005 | 0 | | Flat | Depth to water 5 feet. |
| 39S | 19E | 29 | 07 | 22 | 81 | 002 | 001 | 005 | | | Flat | |

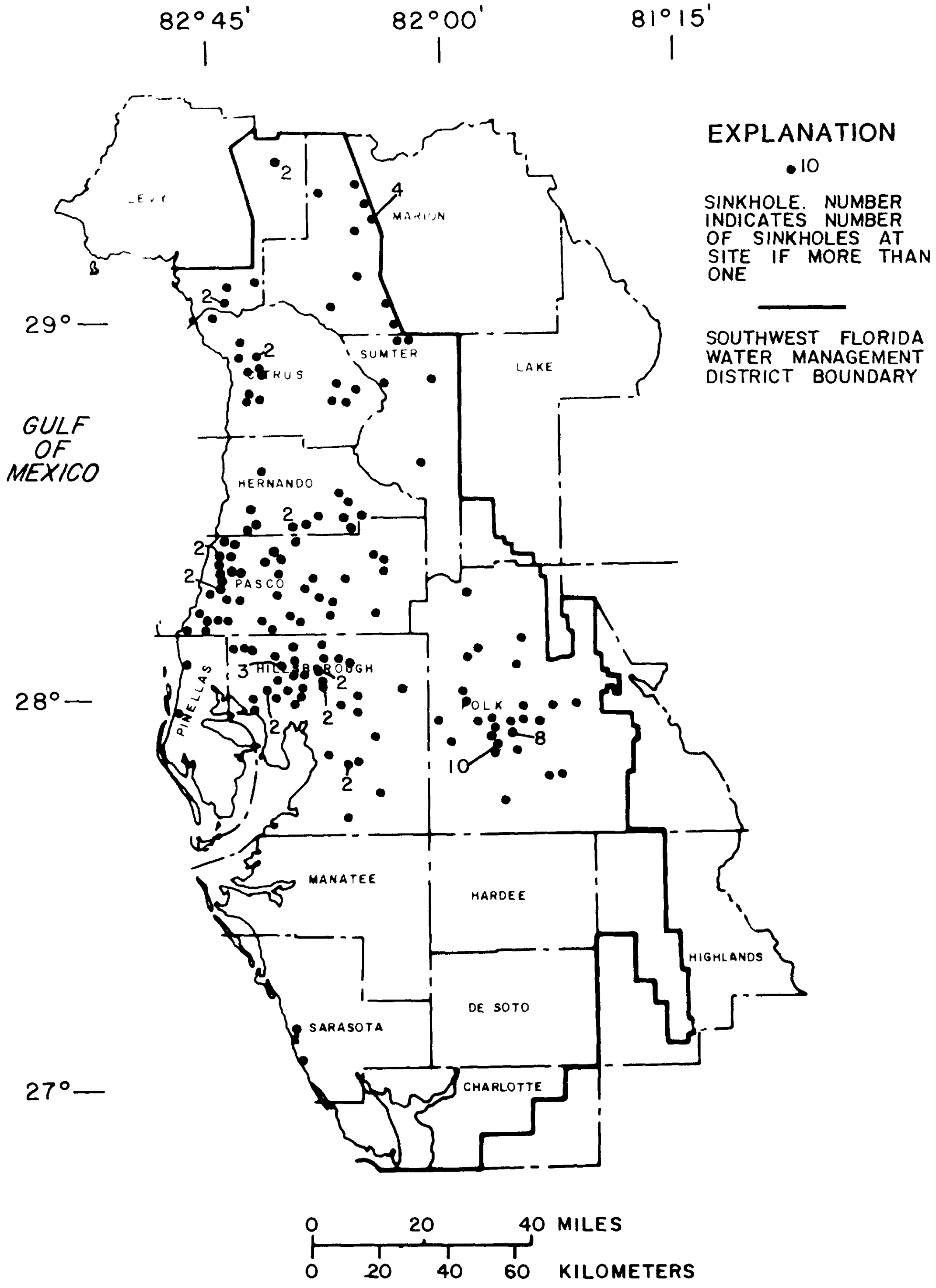


Figure 37.--Locations of reported sinkholes.
(Descriptions are given in table 3.)

Sinkhole data from the Department of Transportation are the least skewed for any particular area. They report 34 sinkholes in Polk County and 33 in Suwannee County, a smaller, less developed county in northern Florida. Because Polk County contains many more miles of right-of-way than Suwannee County, it seems likely that the data may be skewed.

Given the slow progression of geologic events that lead to sinkhole formation under natural conditions, it is believed that most recently (since 1960) developed sinkholes were induced by some triggering factor related to man's activities. Of the sinkholes listed in table 3, 98 have maximum width-depth dimensions of 10 feet or less. Twenty-seven have widths or lengths of 100 feet or more. The largest sinkholes have occurred in areas where the overburden is thick (more than 150 feet). In the Bartow area (Polk County), for example, where most of the reported sinkholes have occurred, two had widths or lengths in excess of 150 feet. Of the sinkholes described, about 20 percent had depths greater than their largest horizontal dimension.

Conclusions cannot be drawn from data on induced sinkholes or recent sinkholes as to where sinkholes might occur under natural conditions or where they might occur in undeveloped areas. The sinkhole data in table 3 are listed to provide a basis for further study and documentation.

Data in table 3 show that sinkholes have occurred during each month of the year. May had the most reported occurrences (23) and November the least (5). In general, sinkhole occurrences are higher during the February to May low rainfall period when irrigation is high and again in July and August, when surface loading is increased by heavy rains.

## SINKHOLES AS SOURCES OF WATER SUPPLY OR GROUND-WATER POLLUTION

Sinkholes are potential sources of water supply. They are also potential sources of contamination to existing supplies because of surface inflow into the sinkholes. As a source of water, Stewart (1977) documented a pumping test on the Morris Bridge Road sinkhole northeast of Tampa. The test was run for 25 days at an average pumping rate of 4,000 gal/min. Analysis of the data indicated that the sinkhole would be capable of yielding 10,000 gal/min (15 Mgal/d) on a sustained basis with a maximum drawdown not likely to exceed about 23 feet. This capacity is equivalent to the production capabilities of some large well fields in west-central Florida. However, long-term pumping from the sinkhole probably would cause reduction in flow of a nearby stream.

Tests of Curiosity Sink north of Tampa also indicate suitability of a sinkhole for water supply (Stewart, 1982). Based on a pumping rate of 5,000 gal/min and a drawdown of 2 feet, the specific capacity of the sinkhole is about 2,500 gal/min per foot of drawdown.

The potential for pollution of the Upper Floridan aquifer through sinkholes or internally drained areas caused by sinkholes in west-central Florida have also been documented. Analyses of a water sample collected from a sinkhole northeast of Tampa suggest that water-quality degradation has occurred. The concentrations of calcium (37 mg/L), bicarbonate (128 mg/L), alkalinity (105 mg/L as $CaCO_3$), and dissolved solids (144 mg/L) indicate a mixture of water from surface runoff and from the Upper Floridan aquifer (Stewart, 1977). A nitrate concentration of 0.77 mg/L as nitrogen also indicates degradation due to surface-water inflow or introduction of refuse into the sinkhole.

Analyses of water-quality data for Sulphur Springs at Tampa (fig. 4) suggest water-quality degradation from several sinkholes 1 to 2 miles upgradient of Sulphur Springs (Stewart and Mills, 1984). High ground-water velocities in the area permit most bacteria in the water from the upgradient sinks to survive the traveltime needed to reach Sulphur Springs.

Most internally drained areas are devoid of perennial streams, and surface drainage is internal through sinkholes that are directly or indirectly connected to the Upper Floridan aquifer. In many areas, overland runoff to internally drained areas is of poor quality, and because of the direct connection to the Upper Floridan aquifer without benefit of natural purification, absorption, and filtration through soils and sands, the aquifer can undergo water-quality degradation.

Aside from the hazards that sinkholes may cause, many are potential sources of water supply. However, sinkholes provide direct routes through which surface water can move into underlying aquifers and cause degradation of ground water.

## SUMMARY AND CONCLUSIONS

Sinkholes are a natural and common geologic feature in areas underlain by limestone and other soluble rocks. Abrupt sinkhole collapse occurs infrequently under natural conditions. Stresses on the hydrologic system, such as ground-water withdrawals and construction, have caused an increase in the occurrence of sinkholes in west-central Florida, a trend that is likely to continue.

The dominant factor that determines the ability of recharge water to dissolve limestone is acidity of the water. Rainwater is naturally acidic, but becomes more acidic as it reacts with organic matter in the soil zone. Based on equations for dissolution of limestone material and a recharge rate of 5 in/yr, it is estimated that $3.66x10^{-4}$ in$^{3}$ of the material would dissolve under each square inch of land in the Bartow area each year. At this rate, it would take 33,000 years to dissolve an average 1-foot deep cavity. Because recharge is generally focused in fractures and joints, however, much less time would be required to create a 1-foot cavity where flow is concentrated.

Four major types of sinkholes are common to west-central Florida. They include limestone solution, limestone collapse, cover subsidence, and cover collapse. The first two occur in areas where limestone is bare or is thinly covered. The second two occur where there is a thick cover (30 to 200 feet) of material over limestone.

Limestone-solution sinkholes, the most common type of sinkhole in areas of thin cover, result from subsidence that occurs at roughly the same rate as dissolution of the limestone. The sinkholes reflect a gradual downward movement of the land surface and development of funnel-shaped depressions. Limestone-collapse sinkholes occur when a solution cavity grows in size until its roof can no longer support its weight, causing generally abrupt collapse that can be catastrophic. The occurrence of limestone-collapse sinkholes is relatively uncommon in the study area.

Cover-subsidence sinkholes develop as individual grains of sand in the cover material move downward into space created by dissolution of limestone. Resultant sinkholes are generally only a few feet in diameter. Cover-collapse sinkholes occur where clay layers that overlie limestone have sufficient cohesiveness to bridge developing cavities in the limestone. Eventual failure of the bridge results in a cover-collapse sinkhole. The thickness and composition of materials that cover limestone affect the shape and size of land-surface collapse. A thick layer of clay (more than 150 feet), for example, upon failure will develop a relatively large sinkhole that forms abruptly.

Large withdrawals of water for water supply, irrigation, or frost protection may provide a triggering mechanism for sinkhole occurrence. Removal of water's buoyant support of unconsolidated deposits that overlie cavities can cause the materials that bridge the cavity to fail and sinkholes to appear. Such occurrences are common at well fields and irrigation areas in west-central Florida. Conversely, loading of the land surface by impoundments causes failure of materials bridging cavities below the impoundment and sinkholes may form. The impoundments may also provide continuous sources of recharge water that hastens development of cavities in limestone.

West-central Florida was divided into seven zones based on geology, landscape, and geomorphology and how they relate to types of sinkholes that occur in each zone. The zones are: (1) areas of bare or thin sand cover that have slowly developing limestone-collapse sinkholes; (2) areas of thin cover, little recharge, high overland runoff, and few sinkhole occurrences; (3) areas of incohesive sand cover of 50 to 150 feet thick that have high recharge and generally experience cover-subsidence sinkholes; (4) areas that have 25 to 100 feet of cover, many sinkhole lakes and cypress heads, and have predominantly cover-collapse sinkholes; (5) areas of 25 to 150 feet of sand cover overlying thick clay with both cover-collapse and cover-subsidence sinkholes; (6) areas with more than 200 feet of cover, numerous lakes and sinkholes, and high land-surface altitudes with numerous cover-subsidence sinkholes and occasional large-scale cover-collapse sinkholes; and (7) areas with cover greater than 200 feet with 100 or more feet of clay and where sinkhole occurrences are rare. In areas where the confining beds are 100 to 150 feet thick, the bearing strength and leakance of the beds preclude infiltration of corrosive water and development of sinkholes.

Based on an inventory of 181 reported sinkholes, 98 had maximum widths or lengths of 10 feet or less and 27 had widths or lengths of 100 feet or more. Most sinkholes occur during the February to May dry period and during the July and August wet period. No particular period dominates, however, and no month is without reported sinkhole occurrences.

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