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SINKHOLE TYPE, DEVELOPMENT, AND DISTRIBUTION IN FLORIDA

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INTRODUCTION

Sinkholes are a natural and common geologic feature in areas underlain by limestone and other rock types that are soluble in natural water. The term sinkhole is used for closed depressions in the land surface that are formed by surficial solution or by subsidence or collapse of surficial materials owing to the solution of near-surface limestone or other soluble rocks. Discussion here refers to sinkhole occurrence in limestone and dolomite, the most common rock types in Florida.

Sinkholes occur in a variety of shapes from steep-walled "natural wells" to funnel-shaped or bowl-shaped depressions. Sinkholes are a product of solution-erosion processes and are analogous to valleys carved by rivers in areas underlain by insoluble clastic rocks. Just as rivers constantly erode the land surface by carrying away particles of rocks a grain at a time, limestone is carried slowly away in chemical solution an ion at a time. The ions are carried by water that percolates through cavities and conduits that were developed by solution of the limestone along fracture systems, bedding planes, and other permeable zones in the rock. Surface erosion by rivers is well understood and subject to some control by man, but the detection of cavities at depth and prediction of potential sinkhole collapse is inherently difficult.

Sinkholes are of interest in Florida because they are one of the predominant landform features of the State; because their development may be sudden, resulting in possible loss of life and property; because they may cause flooding during storms when the drainage capacity of natural subsurface conduits is exceeded; and because they may provide an avenue for pollutants on the land surface to move rapidly into the underlying limestone and dolomite—the source of more than 80 percent of the drinking water in the State. The purpose of this report is to describe the geologic and hydrologic features controlling the development of sinkholes so that sinkholes and their related problems may be better understood.

FACTORS THAT AFFECT SOLUTION OF LIMESTONE

The ultimate cause of collapse or subsidence that forms virtually all sinkholes in Florida is solution of soluble rock by acidic water. As rain falls through the atmosphere, it dissolves carbon dioxide and other gases and becomes slightly acidic. Rainwater percolating through the soil zone continues to dissolve carbon dioxide that is released by bacterial action and decomposition of organic material. The amount of carbon dioxide available in soils is 10 to 100 times greater than that available in the atmosphere (Hem, 1960, p. 35).

Water percolating through the soil zone becomes a weak carbonic acid that reacts readily with limestone and dolomite as it moves downward. The reactions are:

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

$$\underset{\text{(carbonic acid)}}{H_2CO_3} + \underset{\text{(limestone)}}{CaCO_3} \rightleftharpoons \underset{\text{(calcium ions)}}{Ca^{++}} + \underset{\text{(bicarbonate ions)}}{2(HCO_3)^-}$$

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

As the reaction proceeds, water gradually assimilates calcium and bicarbonate ions until it is saturated and further solution of limestone is not possible. The reaction is reversible depending on such variables as temperature and carbon dioxide pressure. Thus, the same reaction that dissolves limestone may deposit a scale of calcium carbonate (limestone) in a teapot when water is boiled. Under natural conditions, the reaction can reverse, resulting in deposition, such as the formation of stalactites and the sealing of voids and fractures by precipitation of carbonate minerals.

The chemistry of rocks is important in controlling the development of solution cavities. Pure limestone ($CaCO_3$) is commonly more easily dissolved by natural water than is dolomite [$CaMg(CO_3)_2$], the second most prevalent rock in Florida. The presence of impurities, such as sand and clay, within the rock will reduce the rate of carbonate solution. The insoluble clay particles commonly form an impermeable residuum that mantles the limestone and retards infiltration of water, thus reducing further solution.

The reaction between water and rocks is controlled by the rate of circulation of water and this, in turn, is controlled by the rate of recharge and by the rate of ground-water flow. Solution is most intense where the corrosive water first contacts the limestone surface and along joints or vertical fracture zones within the limestone. Solution of limestone is also enhanced where ground-water flow is concentrated at depths below the limestone surface. For example, in areas where the water table is below the limestone surface, ground water is chemically most active in the zone of fluctuation of the water table. Consequently, solution of limestone is usually accelerated in this zone, causing still more vigorous ground-water circulation. Solution may also be accelerated along unconformities, bedding planes, and other changes in rock structure and texture where flow is concentrated if the water is chemically active.

The relation of sea level to land surface has been the dominant factor in the geologic history of Florida. Periods of submergence of the land and deposition of limestone have alternated with periods of exposure of the land and dissolution of the carbonate rocks. Table 1 summarizes the major geologic units deposited over the last 60 million years.

Fluctuations in sea level have had an important effect on hydrologic conditions and on development of sinkholes throughout the State. The central ridges that parallel Florida's east coast are capped by deposits of relict beaches that formed from about middle to late Miocene time. These beaches have stood above the sea for 5 to 10 million years. 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 the underlying limestone bedrock.

More recent (Pleistocene) fluctuations of sea level, associated with the advance and retreat of glaciers, have ranged from 400 feet below to about 100 feet above the present sea level. In response, ground-water levels have also fluctuated, and factors that affect solution of the limestone and development of sinkholes have varied.

During the warm interglacial period prior to the last major glaciation, the sea rose to about 100 feet above its present level. Wave action and coastal currents swept surficial sand and clay into land-surface depressions and produced a relatively subdued topography that consisted of beaches, dunes, and terraces that mantled an irregular bedrock surface. Many sinkholes, lakes, and springs were effectively buried, but major topographic features, such as bedrock ridges and river valleys, are discernible through the surficial mantle.

As the last glacial expansion kept progressively more of the world's water frozen on the land, the sea declined 300 to 400 feet below its present level. Florida's land area increased by more than a factor of two as the coasts moved seaward and gulfward to the edges of the continental shelf. This change in 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 direction of ground-water flow in some areas. As the glaciers waned, the sea gradually rose to its present level, and Florida's hydrologic system developed into its present state. However, the system is controlled to some extent by topography and solution conduits that were formed under varied conditions over geologic time.

Although Florida is underlain by thousands of feet of limestone and dolomite that are susceptible to solution by ground water, most of the State is covered by a mantle of insoluble clastic rock material, such as sand and clay, that control, to a great extent, the ultimate route of water that falls as rain. In areas where limestone is exposed at land surface, or is thinly covered, rainfall infiltrates directly through a network of conduits that have been opened and enlarged by solution of the rock. Where the limestone is covered by permeable sand, however thick, the rainwater is largely held where it falls and infiltrates downward through the sand into the limestone below.

Surface runoff is uncommon where rainfall moves directly into the aquifers. Streams and rivers are widely separated, and valleys that were developed by occasional flood runoff are poorly defined. Conversely, in areas where limestone is covered by thick 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 a closely spaced network of tributaries.

TYPES OF SINKHOLES

Three major types of sinkholes common to Florida are solution sinkholes, cover-collapse sinkholes, and cover-subsidence sinkholes. These sinkhole types are distinguished by their mode of formation; the type of sinkhole that may develop in a given area is controlled largely by the geology and hydrology.

Solution Sinkholes

Solution sinkholes occur in areas where limestone is exposed at land surface or is covered by thin layers of soil and permeable sand. Solution is most active at the limestone surface and along joints, fractures, or other openings in the rock that permit water to move easily into the subsurface. Dissolved limestone and some insoluble residue are carried downward by the percolating water along enlarged openings as solution of the limestone progresses. Large voids commonly do not form because subsidence of the soil layer occurs as the limestone surface dissolves. The result is a gradual downward movement of the land surface and development of a depression that collects increasing amounts of surface runoff as its perimeter expands. This type of sinkhole usually forms as a bowl-shaped depression with the slope of its sides determined by the rate of subsidence relative to the rate of erosion of the walls of the depression from surface runoff. Surface runoff may also carry sand and clay particles into the depression, which may form a relatively impermeable seal in the bottom. A marsh or lake forms when water is ponded because infiltration is restricted by the clayey seal. The gently rolling hills and shallow depressions typical of solution-subsidence topography are common over large parts of Florida.

Cover-Collapse Sinkholes

Cover-collapse sinkholes occur where a solution cavity develops in the limestone to a size such that the overlying cover material can no longer support its own weight. Collapse is generally abrupt when this occurs and is sometimes catastrophic. Collapse sinkholes provide dramatic local changes in topography. They may occur in any area of soluble rock; however, they are less likely to occur in areas of deeply buried rocks. Collapse sinkholes generally occur in areas where the limestone is near land surface and the limestone aquifer is under water-table conditions. Ground-water circulation is most vigorous at and just below the water table where solution of the limestone is accelerated. Accelerated solution also may occur at certain depths where bedding planes in the limestone or changes in rock composition concentrate the flow of ground water.

Limestone is commonly exposed in the vertical or overhanging walls of collapse sinkholes shortly after they form. The sinkholes generally are circular in shape and the walls may be round and smooth, but mostly they are irregular in shape because of the influence of joints and fractures in the rock. Surface drainage, erosion, and deposition of sediment into collapse sinkholes will eventually smooth the sides and reduce their slopes until they may become indistinguishable from other types of sinkholes.

Cover-Subsidence Sinkholes

Limestone, like most bedrock, generally lies beneath a cover of soil and other unconsolidated material, such as sand and clay. Coastal sediments and beach deposits left during periods of high sea level occur throughout Florida at various altitudes. The variable thickness and composition of this cover is important in sinkhole development.

Cover-subsidence sinkholes occur where the cover material is relatively incohesive and permeable, and individual grains of sand move downward in sequence to replace grains that have themselves moved downward to occupy space formerly held by the dissolved limestone. In areas where the sand cover is 50 to 100 feet thick, subsidence sinkholes generally are only a few feet in diameter and depth.

Where the limestone is buried beneath a sufficient thickness of unconsolidated material, few sinkholes generally occur. Spalling of sand into solution cavities that have developed along joints in the limestone may cause subsidence due to upward migration of the cavities (a process known as piping) to form cylindrical holes at the land surface. If the overburden is incohesive sand, the upward-migrating cavity is dissipated by a general lessening of density over a large area, and the result will be a relatively broad and extensive subsidence of the land surface that occurs over a period of time. Generally, subsidence of this type may go unnoticed for several years. If the overburden is a dense plastic clay, its low permeability may impede downward movement of ground water and retard the development of solution cavities in the underlying limestone. For this reason, areas underlain by relatively impermeable clay generally are not affected by sinkholes.

TYPES OF LIMESTONE COVER

Four areas of sinkhole occurrence in Florida, based on the type and thickness of cover material overlying the limestone, are described in this section and are delineated on the map.

Area I.—*Bare or thinly covered limestone. Sinkholes are few. Generally shallow and broad, and develop gradually. Solution sinkholes dominate.*

Throughout large areas of the State, the cover material ranges in thickness from less than a foot to about 25 feet (Area I on map). Generally, the cover material is very permeable, and the effect, in terms of solution development of the limestone, is that of bare limestone exposed to weathering. Solution at the limestone surface and in joints near the surface decreases with depth, but the solution of limestone is the dominant process in landscape development throughout Area I. Area I reportedly has very few collapse sinkholes, and those that occur generally are very shallow and broad and develop slowly.

Area II.—*Cover is 30 to 200 feet thick and consists mainly of incohesive and permeable sand. Sinkholes are few, shallow, of small diameter, and develop gradually. Cover-subsidence sinkholes dominate.*

In areas where limestone is covered by materials that are relatively incohesive and permeable, sinkholes develop by gradual subsidence (Area II). In some areas, particularly where the sand cover is relatively thick, consolidation and compaction of the sand grains lend a certain cohesiveness. Generally, cover-subsidence sinkholes are only a few feet in diameter and depth. Their small size and innocuous mode of occurrence evolve because cavities in the limestone surface cannot develop to an appreciable size before they are filled with sand. The cover sand in Area II is relatively permeable; water infiltrates directly to the water table, which may be in the sand or limestone, depending on the topography. Few sinkholes develop in Area II. Most sinkholes are less than 10 feet deep and average 5 to 15 feet in diameter.

Area III.—*Cover is 30 to 200 feet thick and consists mainly of cohesive clayey sediments of low permeability. Sinkholes are most numerous, of varying size, and develop abruptly. Cover-collapse sinkholes predominate.*

Throughout much of Florida, the sand cover becomes increasingly clayey with depth, and a layer of low-permeability clay generally 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. Failure of the bridge results in a cover-collapse sinkhole, typical of Area III, whose dimensions are related to the size of the cavity and the bearing strength of the clay. The mechanism of solution erosion of limestone that precedes a cover-collapse sinkhole is similar to that of a cover-subsidence sinkhole. The distinction between the two categories of sinkholes is one of degree of cohesion or bearing strength of the cover material. Cohesion or strength controls whether the cover material subsides slowly or collapses abruptly.

A factor equally as important as the cohesion or bearing strength of the clay is its low permeability. In areas where the cover contains a clay layer of sufficiently low permeability to greatly retard downward infiltration of water, a difference in head develops across the confining clay between water perched in the surficial material and the water level in the underlying carbonate aquifer. Fluctuations in head differences between the surficial aquifer and the carbonate aquifer tend to weaken the overlying clay bridge. An increase in head difference, either because of flooding at land surface or a decline in head in the lower aquifer, tends to load the clay bridge with an increased hydrostatic force that, in conjunction with the forces of gravity already at work on the cover material, may stress the clay beyond its bearing strength. Pumping of water from the lower aquifer, with consequent drawdown of the water level, is possibly the most common mechanism by which sinkholes are induced by man.

Throughout Area III, the thickness and composition of unconsolidated material that covers the limestone has an important effect on the shape and size of land-surface collapse. A thick layer of dense clay may have sufficient strength to bridge a large-diameter cavity whose roof crumbles and spalls into a solution-enlarged joint in the limestone. When the clay layer finally fails, the resulting 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 of the subsequent cover-collapse sinkhole. 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 is proportional to the thickness and bearing strength of the cover material and the volume of the underlying cavity. Area III reportedly has the greatest number of sinkhole occurrences in the State. Most of the sinkholes are of the cover collapse type, such as the sinkhole that occurred in Winter Park, May 8-13, 1981.

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

Area IV is defined, principally, on the occurrence of a thick section of clastic sediments that generally overlie the carbonate rock. The sediments limit ground-water circulation in the underlying carbonate rocks and the development of solution cavities. Carbonate layers, however, are common within the section of clastic sediments in some areas, and silty, sandy, phosphatic limestone and dolomite may be the principal rock types. In areas where the shallow carbonate rocks are permeable enough to permit ground-water circulation, they too are subject to solution and subsequent collapse of overburden. These carbonate rocks are discontinuous within the sand-clay cover of Area IV, and their occurrence and extent are not well known. Area IV reportedly has very few sinkhole occurrences, although several large diameter, deep sinkholes are present in the area.

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Table 1.—*Geologic framework*
[Modified from Wilson and Gerhart, 1980, table 1]

System	Series	Stratigraphic unit	General lithology	Major lithologic 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	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
Tertiary	Pliocene	Undifferentiated deposits[2]	Clayey and pebbly sand; clay, marl, shell, phosphatic	Clastic		5
	Miocene	Hawthorn Formation	Dolomite, sand, clay, and limestone, silty, phosphatic	Carbonate and clastic		
		Tampa Limestone	Limestone, sandy, phosphatic, fossiliferous; sand and clay in lower part in some areas		Exposure and weathering	24
	Oligocene	Suwannee Limestone	Limestone, sandy limestone, fossiliferous		Carbonate deposition Exposure and weathering	38
	Eocene	Ocala Limestone	Limestone, chalky, foraminiferal, dolomitic near bottom	Carbonate	Carbonate deposition Exposure and weathering	55
		Avon Park Formation	Limestone and hard brown dolomite; intergranular evaporite in lower part in some areas		Carbonate deposition Exposure and weathering	63
		Oldsmar Formation	Dolomite and limestone, containing intergranular gypsum in most areas	Carbonate containing evaporites	Carbonate deposition	
	Paleocene	Cedar Keys Limestone	Dolomite and limestone containing beds of anhydrite			

[1] Geologic Names Committee, 1983, Major geochronologic and chronostratigraphic units: U.S. Geological Survey.
[2] Includes all or parts of Caloosahatchee Marl, Bone Valley Formation, Alachua Formation, and Tamiami Formation.

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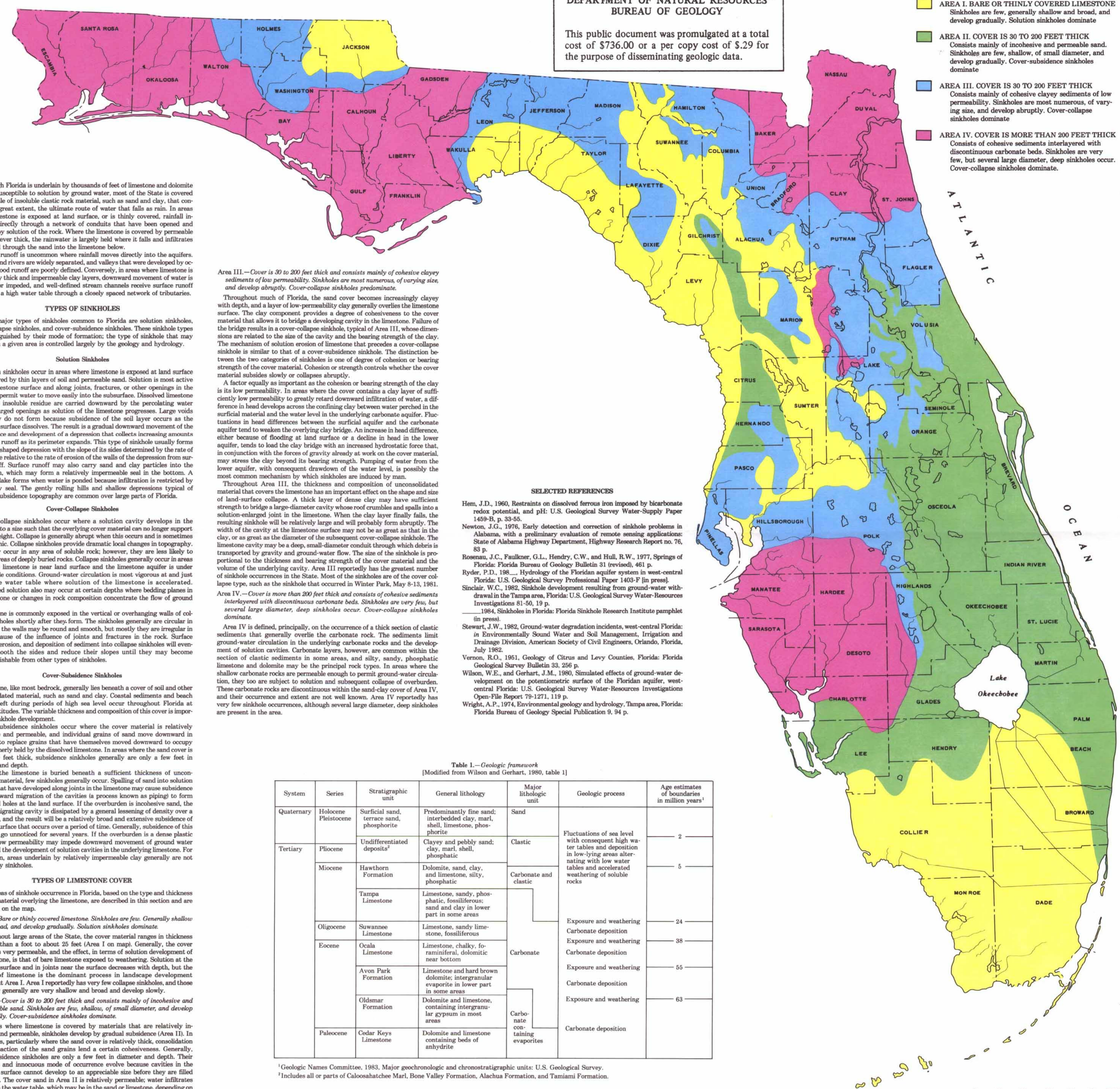

EXPLANATION

AREA I. BARE OR THINLY COVERED LIMESTONE
Sinkholes are few, generally shallow and broad, and develop gradually. Solution sinkholes dominate

AREA II. COVER IS 30 TO 200 FEET THICK
Consists mainly of incohesive and permeable sand. Sinkholes are few, shallow, of small diameter, and develop gradually. Cover-subsidence sinkholes dominate

AREA III. COVER IS 30 TO 200 FEET THICK
Consists mainly of cohesive clayey sediments of low permeability. Sinkholes are most numerous, of varying size, and develop abruptly. Cover-collapse sinkholes dominate

AREA IV. COVER IS MORE THAN 200 FEET THICK
Consists of cohesive sediments interlayered with discontinuous carbonate beds. Sinkholes are very few, but several large diameter, deep sinkholes occur. Cover-collapse sinkholes dominate.