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REVIEW OF SINKHOLE-COLLAPSE PROBLEMS
IN A CARBONATE TERRANE

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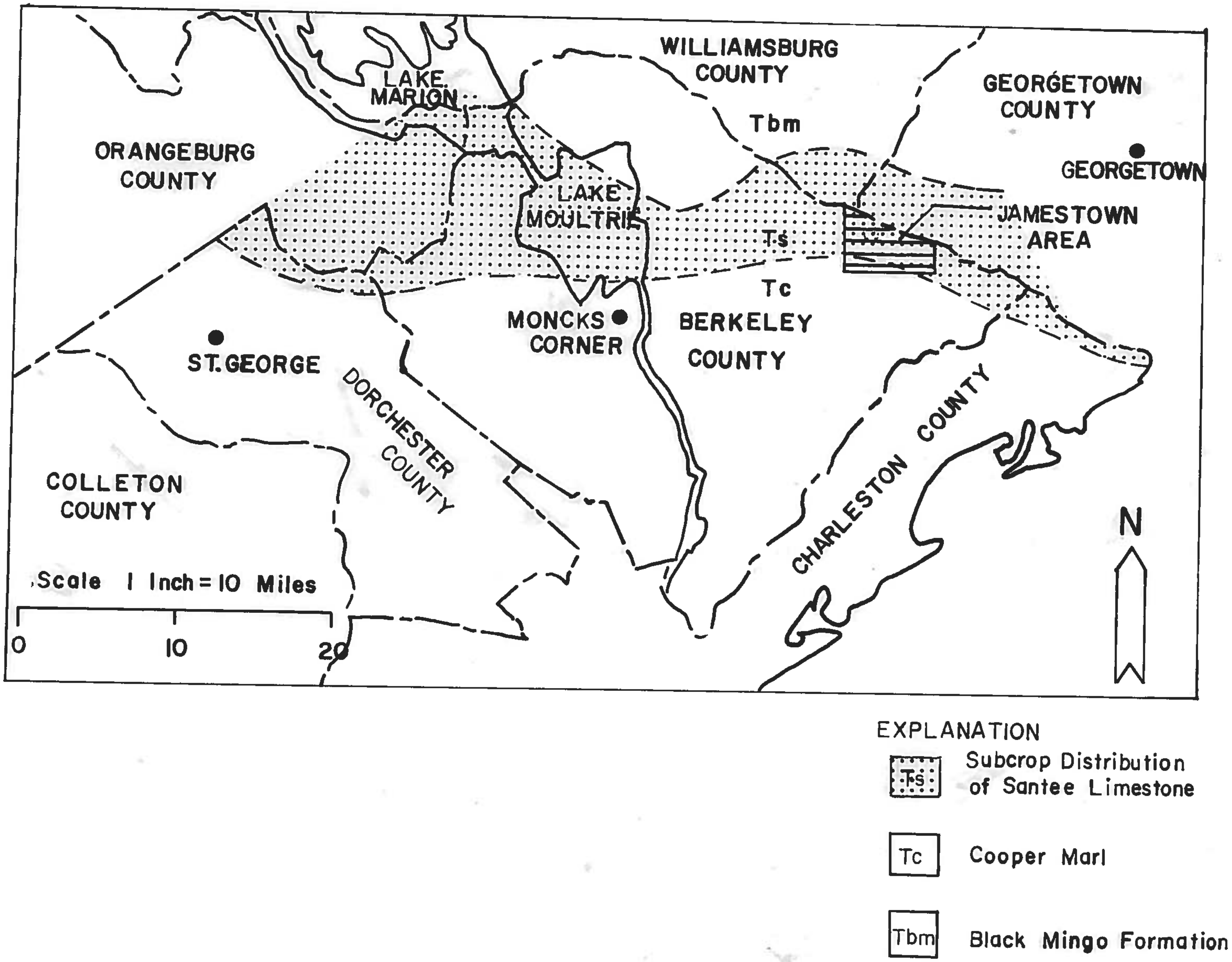
Introduction

The Eocene Santee Limestone occurs near land surface in a large part of the lower Coastal Plain of South Carolina, but natural exposures of this formation are rare because it is covered by Pleistocene sediments. Heron (1962) constructed an updip areal extent map of the Santee using outcrop data supplemented with drillers' logs of shallow exploratory boreholes. Part of Heron's areal extent map is shown in figure 1. In the Jamestown area of Berkeley County (fig. 1) and other localities, the Santee Limestone is quarried for construction aggregate, agricultural lime, or raw material for Portland cement. The Santee Limestone is also an important aquifer and supplies ground water to many wells in the South Carolina Coastal Plain.

In some areas underlain by the Santee, karst features are well developed, and the topography is characterized by dolines, sinking streams, small caves, and karst springs. However, large areas could be characterized as a mantled karst terrane, where karst features are not particularly well developed. Induced sinkhole collapse has been an infrequent occurrence in South Carolina, generally limited to a few sinkhole collapses on farmland or near construction operations. However, in the Jamestown area of Berkeley County, over 50 sinkhole collapses and subsidence depressions have occurred since the fall or winter of 1975.

In 1976 the South Carolina Water Resources Commission (SCWRC) began an investigation to determine the cause of land-surface collapse in the Jamestown area. This investigation was part of a continuing project being conducted by the SCWRC on "Hydrology of Limestone Terranes in the South Carolina Coastal Plain."

FIGURE I. MAP OF A PART OF THE SOUTH CAROLINA COSTAL PLAIN SHOWING LOCATION OF THE JAMESTOWN AREA, AND SUBCROP DISTRIBUTION OF THE SANTEE LIMESTONE.



Hydrogeology

The Jamestown area lies on the southwest flank of the Cape Fear arch, and Upper Cretaceous and Tertiary sedimentary rocks dip toward the south southwest at approximately 5 to 20 ft/mi. The stratigraphic relationships and water-bearing properties of the rocks in the Jamestown area are summarized in table 1. In this report these rocks are subdivided into 4 major aquifer systems or hydrogeologic units on the basis of their hydrogeologic properties. The Black Creek and Black Mingo aquifer systems supply ground water to several municipal or industrial wells in the area. However, the Santee aquifer supplies most of the water for domestic and stock supplies (approximately 10,000 gpd); small-diameter open-hole wells from 15 ft to 110 ft deep tap this aquifer.

The Santee aquifer is approximately 65 ft thick in the Jamestown area, and is composed of light-yellow to dark-gray, thin- to massively-bedded fossiliferous limestone. According to Heron (1962) the Santee Limestone is composed largely of yellowish-gray calcarenites and calcirudites that are sparsely glauconitic with glauconite and quartz increasing near the base of the formation. The Santee has a high percentage of calcium carbonate (over 85 percent) in the Jamestown area, and is mined as a source of agricultural lime and construction aggregate at the Santee Ag Lime (Ware) quarry; the limestone was formerly mined at the adjoining B.A.S.S. (Berkeley Agricultural Sales and Supply) quarry.

Ground water in the Santee aquifer occurs under confined conditions in solutionally-enlarged openings, primarily along bedding planes and lithologic contacts. Jointing is practically absent in the Santee Limestone, but the upper surface of the formation is characterized by pinnacled weathering and vertical or near-vertical solution cavities

Table 1. Summary of geologic formations and water-bearing properties of the rocks in the Jamestown area.

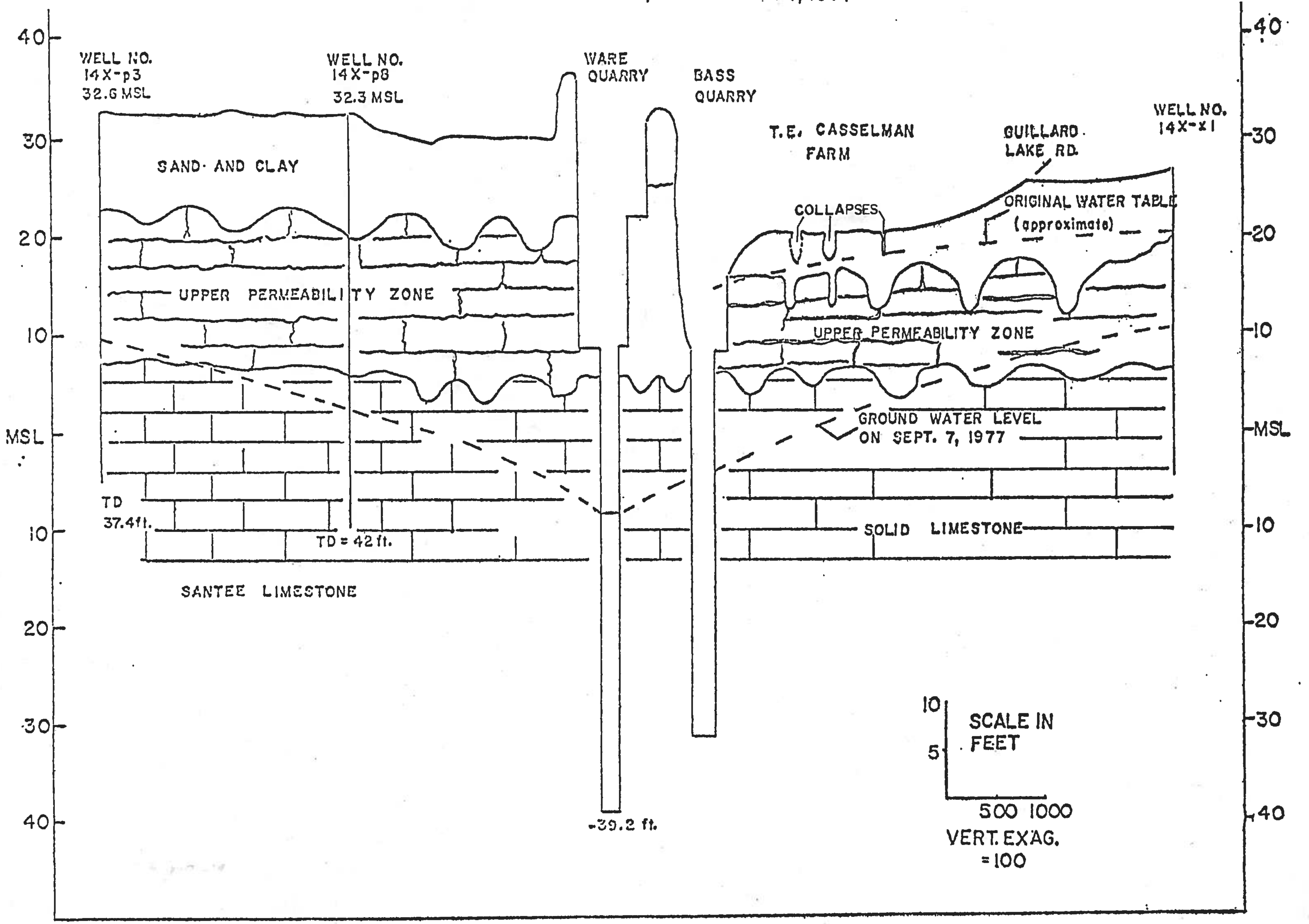
SYSTEM	SERIES	GEOLOGIC FORMATION	HYDROGEOLOGIC UNIT	DESCRIPTION AND WATER-BEARING PROPERTIES
HOLOCENE	PLEISTOCENE	Talbot Formation		Unconsolidated sands and clays, 0-20 ft thick. Hydraulically connected and supplies recharge to underlying Santee aquifer.
TERTIARY	MIDDLE EOCENE	Santee Limestone	Santee Aquifer System	Light-yellow to dark-gray, thin-to-medium bedded limestone and sandy limestone or calcareous sand near bottom. Major aquifer for domestic use in study area: supplies sufficient quantities of water for domestic, stock, and light industrial use.
	LOWER EOCENE PALEOCENE	Black Mingo Formation	Black Mingo Aquifer System	Upper unit: interbedded clastics and carbonates; Middle unit: limestone; Lower unit: mainly fine-grained clastics interbedded with well-cemented, thin-bedded sandstones. Hydrologic properties poorly known but upper and middle units should supply sufficient water for domestic, stock, and possibly light industrial use. Water may contain high concentrations of iron.
CRETACEOUS	UPPER CRETACEOUS	Peedee Formation	Peedee Aquifer System	Approximately 400 ft of alternating beds of clay, fine-grained sand, and hard sandstone or sandy limestone. No wells in study area completed in this aquifer system and hydrologic properties poorly known.
		Black Creek Formation	Black Creek Aquifer System	Alternating beds of gray-to-white sand, dark-gray clay, and sandy limestone or calcareous sandstone. Sands are good aquifers and individual wells yield several hundred gallons of water per minute.
		Tuscaloosa Formation	Tuscaloosa Aquifer System	Not tapped by wells in study area and hydrologic properties unknown. Good aquifer in St. Stephens area of Berkeley County and in adjacent counties (Williamsburg and Orangeburg).

Note: Boundaries of hydrogeologic units may not necessarily correspond to formal geologic formation boundaries.

(cutters) which provide a high degree of vertical permeability development. Permeability is apparently greater in the upper, highly-weathered part of the aquifer and this upper permeability zone contains extensively-interconnected water-bearing solution openings that can be observed in the walls of the two quarries. This upper permeability zone supplies ground water to many shallow, small-diameter, open-hole wells in the area. Unfortunately it is this same zone which is being dewatered in order to mine the underlying limestone (fig. 2).

The largest pumpage from the Santee aquifer is at the Santee Ag Lime quarry. Intermittent pumpage from the quarry has been occasionally in excess of 15,000 gpm (21.6 mgd) since dewatering operations began in late January--early February, 1977. Pumpage at the abandoned B.A.S.S. quarry, in operation from approximately April, 1975 to December, 1977, was periodically in excess of 10,000 gpm (14.4 mgd). Therefore, combined pumpage from the two quarries is estimated to have been in excess of 36 mgd in early 1977. Effects of concentrated ground-water pumpage extend outward in a large radius around the Santee Ag Lime quarry (fig. 3). Water levels have been lowered below the bottom of some wells, below the pump intakes of some wells, and below the practical pumping lifts of shallow-well jet pumps in other wells (Spigner, 1978).

FIGURE 2. HYDROGEOLOGIC CROSS SECTION, DUTART CREEK AREA SHOWING CONE OF DEPRESSION, SEPTEMBER 7, 1977



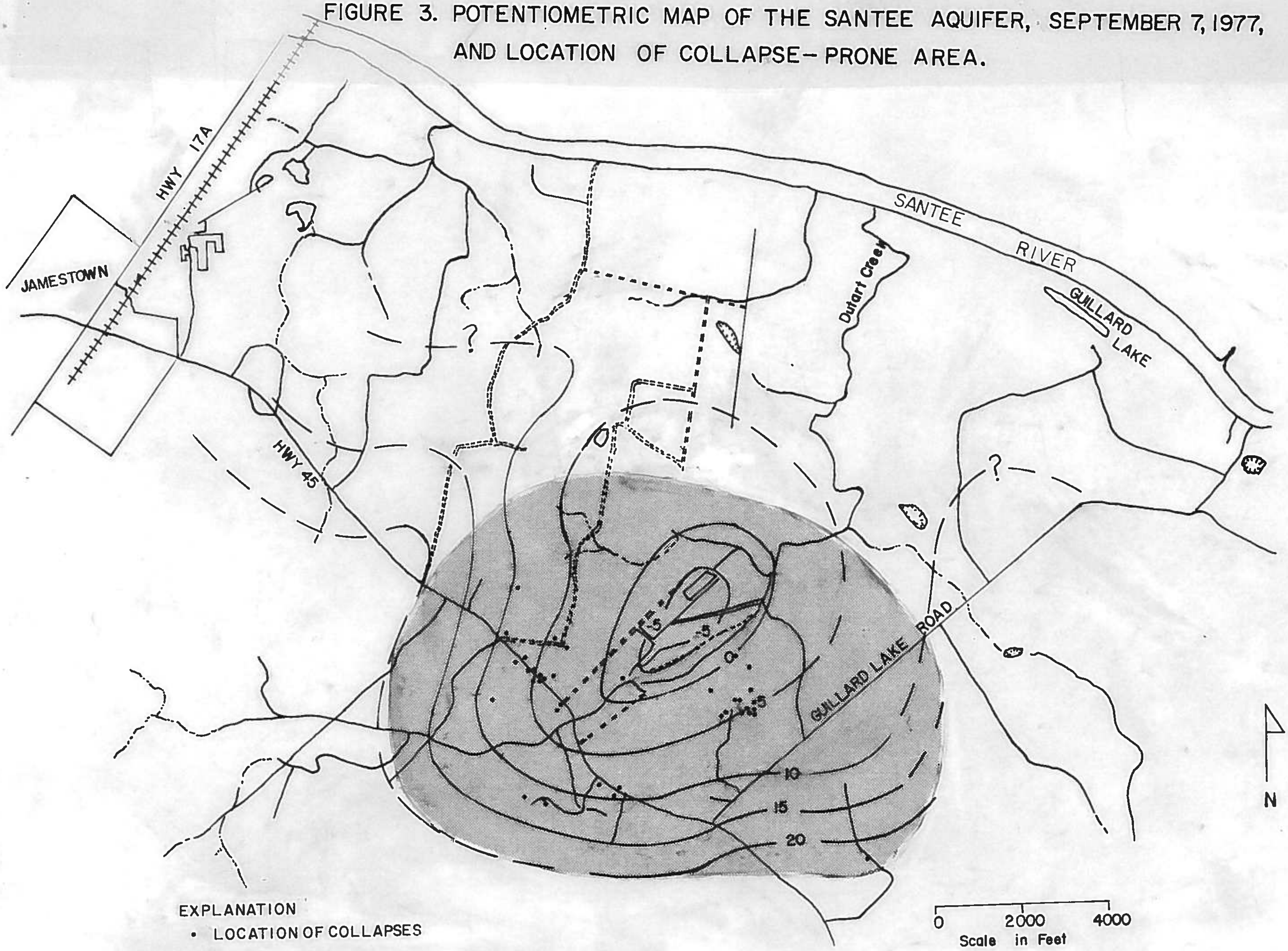
Land-Surface Collapse

Occurrence and History

Over 50 sinkhole collapses and subsidence depressions have been mapped in the Jamestown area, and a collapse-prone area has been delineated (fig. 3). Other collapses and subsidence depressions probably exist, but have not yet been discovered or have not been reported. Sinkhole collapses are closed, steep-sided depressions that often occur suddenly and without warning. Subsidence depressions are closed, generally shallow depressions lacking the steep sides common to collapses and occur by the gradual lowering of the land surface. All sinkhole collapses and subsidence depressions have occured in the Talbot sediments; no solid limestone (Santee) has been observed in the depressions. The diameters of collapses range from less than 1 ft to 25 ft, and depths average approximately 4 ft. Depths greater than 10 ft have been measured in some collapses, and several have been reported by local residents to be over 20 ft deep.

Some collapses probably occurred in late 1975, but the earliest date verified accurately was in February, 1976. In the spring and summer, 1976, collapses became more numerous, and in August or September, 1976, several collapses damaged the apron of Highway 45, the foundation of a church recreation building, and additional collapses on farmland were reported. During the winter, 1976, a local resident was reportedly injured by a fall into a collapse on her property. Collapses continued to form in 1977, and in September, 1977, mining officials had to prohibit excessive pumpage by quarries. Collapses continue to occur in the collapse-prone area delineated in figure 3, and at least five local residents have reported that they have narrowly escaped injury when collapses occurred beneath their cars or farm vehicles.

FIGURE 3. POTENTIOMETRIC MAP OF THE SANTEE AQUIFER, SEPTEMBER 7, 1977, AND LOCATION OF COLLAPSE-PRONE AREA.



EXPLANATION

• LOCATION OF COLLAPSES

▨ COLLAPSE-PRONE AREA

—— 5 —— WATER-LEVEL CONTOURS DATUM MEAN SEA LEVEL

Mechanics of Formation

The general mechanics of sinkhole collapse are fairly well known and have been described from many areas. Particularly instructive reports that describe the mechanics of sinkhole collapse and relate collapse to specific causative mechanisms have been published by Foose (1953), Donaldson (1963), Brink and Partridge (1965), Newton and Hyde (1971), and Bezuidenhout and Enslin (1969).

Sinkhole collapses have occurred in carbonate terranes as a result of naturally-occurring processes. However, the occurrence of numerous, previously-unrecorded sinkhole collapses in a small area is usually caused by dramatic declines of the ground-water table of a karst aquifer. These declines are most often artificially created by man: Examples of artificial influences are dewatering operations, concentrated pumpage from a well or wells, and construction operations.

In the Jamestown area, the following conditions have combined to cause the development of sinkhole collapses and subsidence depressions: (1) the presence of the Santee aquifer, a cavernous, uncapped limestone aquifer at shallow depths below land surface; (2) a variable thickness of unconsolidated sands and clays (Talbot Formation) overlying and hydraulically connected with the Santee aquifer; (3) hydraulic connection of the land surface to the aquifer through solution openings such as cutters (vertical solution slots), sinkholes, and features constructed by man (e.g., drainage ditches); (4) pumpage of large quantities of ground water from the Santee aquifer by quarry dewatering operations which has resulted in dramatic water-level fluctuations and water-table decline in the Santee aquifer; and (5) the movement of ground water from recharge to discharge areas.

The contact between the Santee aquifer and overlying sands and clays of the Talbot Formation is characterized by cutters and pinnacles (fig. 2). Some cutters are filled with residual or transported clays that normally support overlying sands and clays and loads imposed on these sediments. Prior to dewatering operations, the water table of the Santee aquifer was above the limestone-soil (Santee-Talbot) contact, and the water table provided hydrostatic support to the Talbot sediments. However, when the ground-water table was lowered below the contact, hydrostatic support was withdrawn and collapses and subsidence depressions formed in the Talbot Formation. The decline of the water table in the Santee aquifer has been estimated to have been at least 35 ft at the Santee Ag Lime quarry and as much as 25 ft at the B.A.S.S. quarry since the beginning of dewatering operations (Spigner, 1978). Prior to dewatering, the annual fluctuation of the potentiometric surface of the Santee aquifer in the vicinity of the quarries was probably on the order of 10 ft.

Collapses of the land surface are caused by the collapse of subsoil cavities in clays or sandy clays of the Talbot Formation. The formation of subsoil cavities in Talbot sediments can be explained by the following mechanisms. Subsoil cavities are formed when the water table declines or continually fluctuates across the Talbot-Santee contact. In some cases, subsoil cavities are probably formed by the "arching" of cohesive clays over underlying cavities in the limestone--a process described by Donaldson (1963) and Brink and Partridge (1965). Eventually, the shear strength of the clays is exceeded; the clays can no longer support the arched roof of the subsoil cavity, and the arch and overlying soils collapse. The arching of cohesive soils would explain the frequently-observed convex-outward or "bell-shape" of collapses in cross section. Subsoil arches can be overloaded by the weight of a person, a passing vehicle, or the accumulation of moisture in the arch. The overloading of a subsoil arch explains why collapses often occur suddenly without warning, and during or immediately following periods of heavy rainfall. The arching concept was used to explain one type of sinkhole collapse in South Africa by Bezuidenhout and Enslin (1969, p. 490) caused by the collapse of subsoil arches formed above the water table. In the Jamestown area, subsoil arches apparently can be formed either above or below the water table, but become enlarged above the water table.

Although the arching concept is believed by the writer to best explain the occurrence of collapses in the Jamestown area, other mechanisms probably contribute to the formation of sinkhole collapses. Cutters may become "bridged" by the accumulation of soils in a constricted vertical or near-vertical passage. This bridge can be removed as the water table continually fluctuates across this constricted passage. The removal of this bridge by the downward movement of soils then allows overlying soils to be carried downward into the cutter, and eventually a collapse occurs on the land surface. Arching of soils is not necessarily required in this process. Bridging over constricted passages that formed below the water table was described by Bezuidenhout and Enslin (1969, p. 492-493) who described resulting collapses as "sinkholes triggered by dewatering."

In some cases, the movement of water from land surface into underlying bedrock cavities (e.g., cutters) or into subsoil cavities probably contributes to the process of subsurface erosion. Piping, a well-known concept in soils engineering, can contribute to the subsurface erosion of cohesive and non-cohesive soils, and eventually can lead to collapse in overlying soils. Piping could be caused by the downward movement of surface or ground water, and could occur concurrently with arching or the removal of soils in constricted passages (bridging).

Once an area has been made prone to the development of collapses, various "triggering" mechanisms can cause final collapse of subsoil cavities or arches, or aggravate the subsoil erosion process. Examples are surface loading, setting off explosive charges, and formation of soil fractures by drying and shrinkage of clays.

Detection and Prevention

There is no direct method of accurately predicting the probable locations of collapses and subsidence depressions prior to their occurrence. Various methods have been used to delineate underlying bedrock cavities and soil-filled bedrock depressions which are most likely to become locations of collapses. Such methods include geologic and soils mapping, closely-spaced drilling, surface geophysics (such as seismic, gravity, and electrical resistivity), remote sensing, and standard hydrogeologic methods (e.g., water-level monitoring). Some success has been reported from the use of these methods, usually when used collectively, but their application has usually been after the onset of land-collapse problems.

In order to effectively prevent further collapses, the underlying cause of the problem must be addressed. In the Jamestown area, this cause is the concentrated pumpage of ground water from the upper permeability zone of the Santee aquifer. Collapses will probably continue as long as the water table remains below this upper permeability zone. A collapse-prone area, delineated by mapping the distribution of collapses and subsidence depressions and determining the limits of water-level declines in domestic wells, correlates with a potentiometric map constructed in September, 1977 (fig. 3). If pumpage continues, collapses should be expected to continue, and if withdrawals increase, the collapse-prone area will likely be enlarged.

The problems experienced in the Jamestown area point out the critical need of detailed hydrogeologic investigations prior to the beginning of mining operations and construction projects in carbonate terranes. These problems would likely have been less serious or perhaps could have been avoided altogether if the proper investigations had been conducted. Where the Santee aquifer occurs near land surface and is not overlain by an effective confining bed, the potential for collapse exists from large dewatering operations.

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Road Log and Description of Stops

Road log begins in Jamestown at the intersection of Highway 17A and Highway 45.

Mileage Between Points	Cumulative Mileage	
	0.0	City of Jamestown. Northwest corner of study area. Municipal water system supplied by 1 well located under water tank. Well contains 63 ft of 5 5/8 - in diameter screen from interval 700-891 ft below land surface in sands of Black Creek aquifer system. Reported specific capacity 0.63 gpm/ft. Drive southeast on Highway 45.
0.4	0.4	Entrance on left to Santee Wool Combing plant. Plant supplied by 1 well, 900 ft deep; contains 50 ft of 6-in diameter screen in interval 700-880 ft below land surface in sands of Black Creek aquifer system. When drilled in 1954, pumped at 275 gpm with specific capacity of 2.5 gpm/ft of drawdown.
0.8	1.2	Enter area of water-supply problems (see fig. 3). Domestic and stock wells on left have been affected by pumpage at Santee Ag Lime quarry - located approximately 1.5 mi to the southeast.
0.6	1.8	Road to James Pipkin farm on left. Location of "earthquake holes" formed several days after Charleston earthquake of August 31, 1886. Unique examples of naturally-occurring sinkhole collapses. Interesting account of similar holes in Dutton (1889) who called holes formed during earthquake as "craterlets". This is the northwestern limit of the collapse-prone area (fig. 3).
0.7	2.5	Mt. Zion A.M.E. Church (STOP 1) Structural damage to the foundation and walls of the recreation building can be seen. A collapse, approximately 6 ft in diameter and 8 ft deep (?) occurred under building during the Fall-Winter, 1976, and has been subsiding since that time, despite efforts to fill in the collapse.

(Cont'd Stop 1)

At this location, several large collapses can be observed (have been filled in by the S. C. Dept. Highways and Transportation). Note asphalt filling in Highway 45 in front of the recreation building. Several of these collapses have been 6 to 8 ft in diam. and over 10 ft deep; one was reported to be over 20 ft deep.

0.1	2.6	Continue southeast on Highway 45 and turn left into the Santee Ag Lime quarry.
0.3	2.9	Santee Ag Lime quarry (STOP 2) Parts of the Pleistocene Talbot Formation and the Santee Limestone of Eocene age are exposed by mining operations. Approximately 65 ft of the Santee Limestone has been exposed in the northeast end of the quarry where the pumps are located. Note pinnacled weathering of the upper surface of the Santee Limestone.
0.3	3.2	Return to Highway 45 and turn left. Cross Dutart Creek. Prior to dewatering operations was a spring-fed stream. Now is dry.
0.1	3.3	Entrance to abandoned B.A.S.S. quarry.
0.7	4.0	Turn left on Guillard Lake road.
0.2	4.2	Turn left into T. E. Casselman farm.
0.3	4.5	T. E. Casselman farm (STOP 3) Several collapses can be observed that occurred in June, 1976. Most recent occurred on May 26, 1978 during disking. Several collapses have occurred under Mr. Casselman's tractor or combine.
4.0	8.5	Return to Highway 45 and return to Jamestown. End of field trip.