INVESTIGATION OF SINKHOLE OCCURRENCES

AT GORETOWN, NEAR LORIS, SOUTH CAROLINA

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INTRODUCTION

Mr. Harvey Graham, III, of Loris, S.C., reported on September 20, 1986, the occurrence of what he thought to be a sinkhole in his cornfield. The site is located along S.C. Highway 9, near the community of Goretown (Fig. 1). A visit by hydrologists of the Water Resources Commission confirmed the existence of a sinkhole, measuring 45 feet across and 8 feet deep, that is continuing to subside, as evidenced by changes in its appearance during successive field visits.

The sinkhole is approximately 1,300 feet from two active mines that have been dewatering the local limestone. One of these is being operated by the Horry County Department of Public Works, and the other by a private firm called Bonzai, Inc., doing business as the No. 9 Mining Company. The area around the mines is largely rural, with many fields and only scattered homes. S.C. Highway 9, recently widened to four lanes, runs adjacent to the mines and is separated from them by a 200-foot-wide buffer zone. The highway right-of-way lies between the mines and the sinkhole in Mr. Graham's field.

There are a number of other active limestone mines in Horry County (Fig. 2), but only one, the G&C mine on U.S. Highway 378, has been active for longer than 6 years. This is also the only other mine associated with sinkholes as a result of dewatering operations. A total of 20 sinkholes have been mapped in that vicinity. The remainder of the mines may be located where conditions are not favorable for sinkhole formation, or they may not have lowered water levels sufficiently to trigger their occurrence.

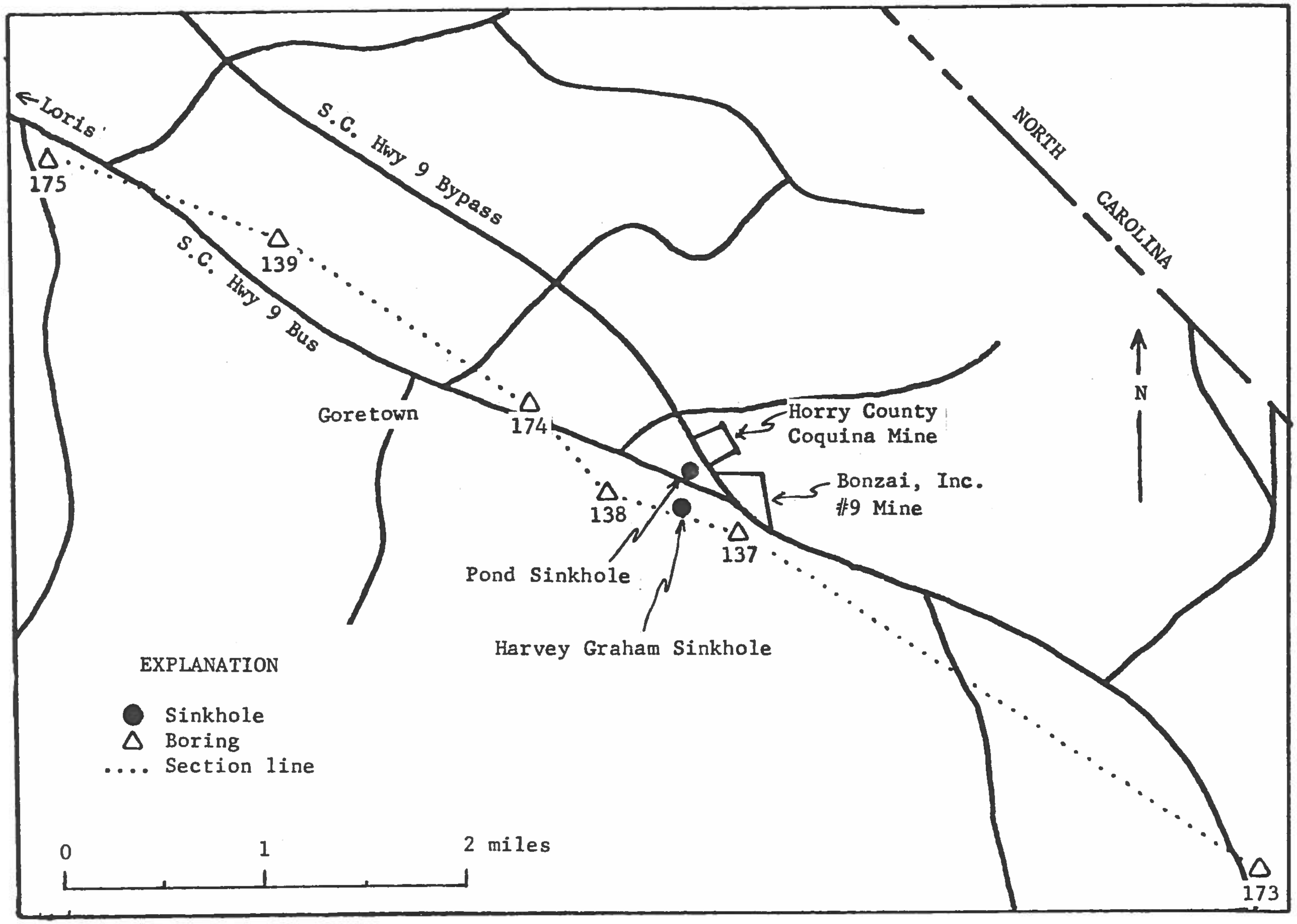


Figure 1.--Location of sinkholes and limestone mines near Goretown, S.C.

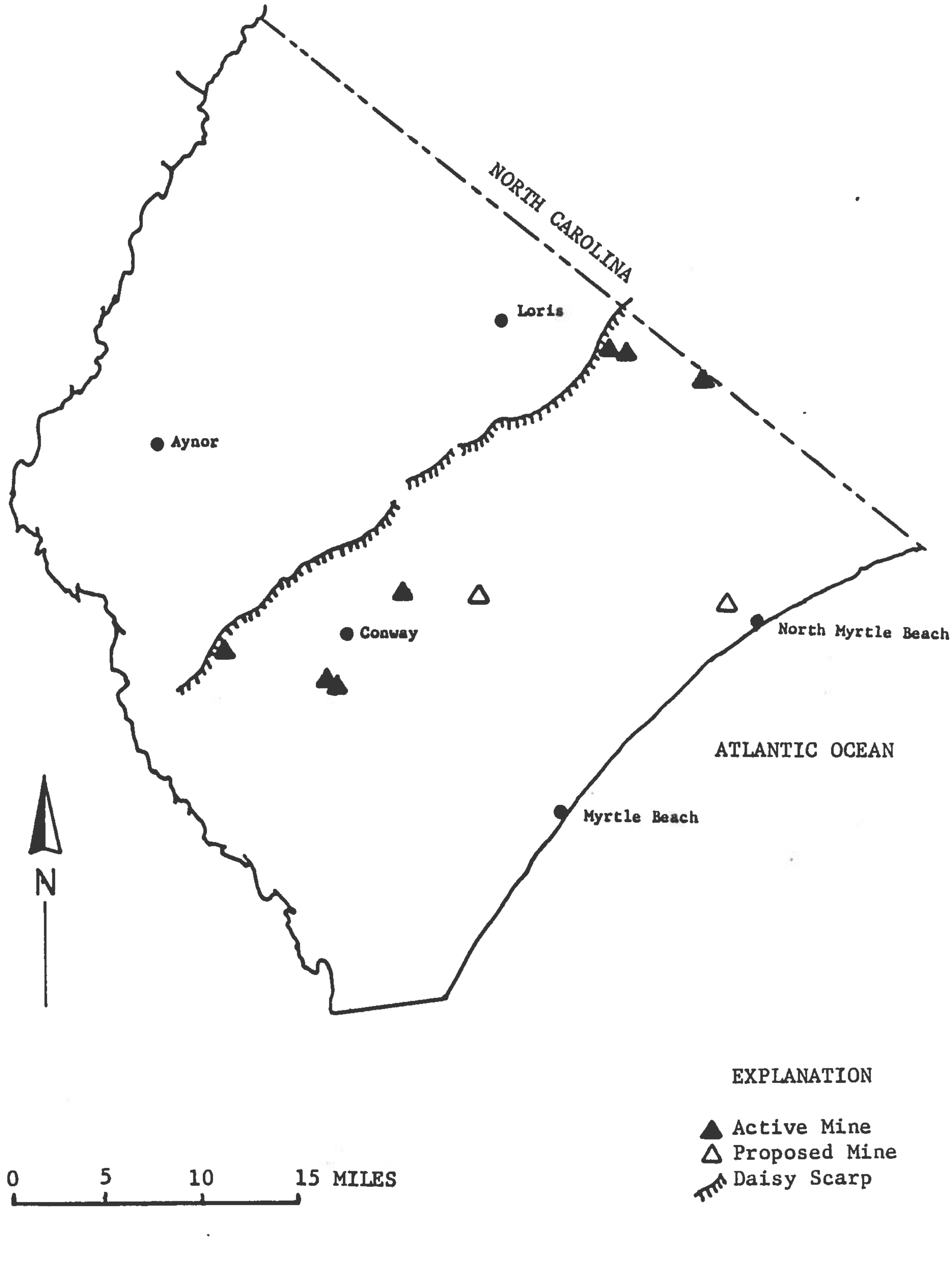


Figure 2.--Location of all active and proposed limestone (coquina) mines in Horry County, South Carolina.

RELATED CASE STUDIES

Two local sites have been investigated concerning sinkhole occurrences resulting from water-level declines attributed to the dewatering activities of local limestone mines. A series of investigations was done at Jamestown in Berkeley County, by SCWRC (South Carolina Water Resources Commission), SCLRCC (South Carolina Land Resources Conservation Commission) and a private consultant, S&ME (Soil and Material Engineers, Inc.). Also, an area located near the Forney community, 7 miles west of Conway in Horry County has been studied. In each of these cases water level data from wells were available to construct maps of the potentiometric surface and to determine the ground-water flow direction.

Water level data are insufficient in the area surrounding the Horry County and No. 9 mines to construct a potentiometric map of the shallow aquifer. Therefore, these other two previous cases are briefly presented so that the relationship between limestone mine dewatering and local water level declines, accommpanied by land surface collapses, may be further understood.

Jamestown

The study area is located about 3 miles southeast of Jamestown in Berkeley County, South Carolina, along S.C. Highway 45, just beyond the boundary of the Waccamaw Capacity Use Area. Land surface elevations range between +15 and +40 feet msl (mean sea level). It is underlain at depth by the Santee Limestone of Eocene age which is the principal source for the aggregate currently being mined. The formation consists of a yellow to light gray, sandy limestone in the upper portion and grades downward into a light to dark gray, massively bedded, fossiliferous, crystalline limestone which is underlain by calcareous sand, silt, and clay. The overall thickness of the Santee Limestone at this site ranges from 63 to 80 feet (S&ME, 1985). The Talbot Formation of Pleistocene age, varying in thickness from between 8 and 20 feet, overlies the Santee Limestone. This formation is comprised of unconsolidated sand and clay (Spigner, 1978).

Mining was first begun in the area by Berkeley Agriculture Sales and Supply (B.A.S.S. Mine) in March or April 1975, with mine dewatering beginning in late summer and continuing periodically until the quarry was closed in December of 1977. Pumping was reported to exceed 10,000 gpm (14.4 mgd) at times (Spigner, 1978). A second operation was opened on December 31, 1976 by Ware Brothers Construction Company (Ware Mine). Dewatering began at this second mine in late January or early February of 1977. On April 7 and 8, 1977 pumping exceeded an estimated 15,000 gpm (21.6 mgd) with a pumping water level elevation of -8.01 feet msl and on September 1 the water level measured -15.2 feet msl (Spigner, 1978). The Southern Aggregates Company purchased the property containing the mines in April of 1981, and currently operates both the Ware and the B.A.S.S. mines.

During late Summer of 1975, many well owners first noticed the loss of water pressure in their wells. Problems with wells became more severe during the summer of 1976 and 1977 when water levels dropped below the pump intake in many wells and, in many others, below the bottom of the wells. Turbidity and sand in the wells also became increasingly more of a problem during this time.

Land surface collapse features first occurred in early April or May of 1976 on the B.A.S.S Mine property. Since then over 60 collapses have been documented. The majority of these occurred during the first few years of mine dewatering with the remaining 20 or so taking place intermittently over the last 5 to 7 years (Pat Walker, oral communication on January 20, 1987). Both the water supply problems and land surface collapse features are generally confined to within a 1.5 mile radius of the mines (S&ME, 1985).

A court injunction was issued in mid-September of 1977 prohibiting the mines from lowering the water level within their operations below +1 feet msl in response to the problems in the area outlined above. In March 1979, an interagency study was initiated involving SCLRCC, SCWRC, USGS (United States Geological Survey), and SCDHEC (South Carolina Department of Health and Environmental Control) to investigate land surface collapse and ground water problems at this site. SCLRCC, in January of 1980, contracted with S&ME to further study this case.

The mining permit conditions were modified to allow lowering of the water level within the pits to -5 feet msl in December of 1981 based on the results from the S&ME report. However, as the mine pits expanded laterally, the free surface of the water within them also expanded, therefore enlarging the cone of depression around the mines. In addition, land surface collapses continued to occur in the area after December of 1981. On February 11, 1987, changes in the mining permit conditions were made to restrict the mine operators from lowering the water level at the mine property boundary below +10 feet msl. This would maintain water levels off-site close to the estimated historical water level conditions prior to mining activity.

Water level measurements from 21 wells on September 7, 1977 provided sufficient data to construct a potentiometric map of the Santee aquifer. This map shows an elliptically-shaped cone of depression that centers on the mines and indicates that ground water is flowing toward the quarries from all directions. Spigner, in his 1978 report, points out that the +20 foot contour line of the potentiometric map delineates the areal extent of the majority of collapse features at this site. He also notes that the incidence of these features increases with proximity to the center of the cone of depression. Other potentiometric maps of the area for dates through February 1985, utilizing additional wells, have confirmed this flow pattern (S&ME, 1985).

Forney

The Forney community is located approximately 7 miles west of Conway in Horry County along U.S. Highway 378. Land surface elevations range from +15 to +60 feet msl. The site is underlain by the Pliocene Duplin Formation which consists of light to medium gray, sandy, fossiliferous limestone. Overlying this are 15 to 30 feet of Pleistocene sediments consisting of moderately sorted quartz sand interbedded with thin layers of clay.

The G&C Mining Company began mining the Duplin Formation in 1975 for a roadbed and fill material, locally referred to as coquina. This coquina was mined under dry conditions made possible by mine dewatering pumps able to remove in excess of 3 mgd of ground water during the wet season. Monthly ground-water use figures have ranged from approximately 24 to 94 million gallons.

Ground-water level declines in wells and land surface collapse features have been reported to have occurred dating back to at least 1980 within a one mile radius of the coquina mine. Twenty sinkholes have been located by SCWRC personel and range in depth from 1.5 to 7 feet and are between 2.5 to 22 feet in diameter (Pelletier and Hockensmith, 1985).

Water level data obtained from 8 unused wells were utilized in constructing an initial potentiometric map which revealed that a local cone of depression was centered about the mine (Pelletier and Hockensmith, 1985). Data from eight additional observation wells further defined this cone of depression (McDowell, 1985). The majority of the collapse features and water supply problems are limited to the area within the +25 foot contour line of the potentiometric surface for August 7-8, 1985.

MINING OPERATIONS IN THE GORETOWN COMMUNITY

Horry County Department of Public Works first began mining at the site in 1983. The limestone is obtained by lowering the water level in the mine to a depth below the working surface. Pans (self-loading, earth-moving machines) are then driven across the floor of the mine to pick up the dry material. Presently the County has two pumps to facilitate dewatering. Their 6-inch diameter pump has a capacity of 350 gpm (gallons per minute) and is reportedly operated a maximum of 4 hours per day on working days. Their 18-inch diameter pump has a rated capacity of 5,100 gpm and is reportedly used only after heavy precipitation. Total ground water usage figures are unavailable.

The material being mined has usually been a soft, shelly, sandy clay. In their most recent mining activities, however, they have encountered a hard, crystalline, dense limestone unit with almost no shells and with few impurities. This hard unit has generated a number of problems for the pans used in the mining activity, including damage to the beds of the pans themselves and cutting of the tires by the sharp edges of the broken rock.

The No. 9 Mining Company began operations in May 1986. At this location, only 250 feet south of the county mine, there is none of the soft, shelly, sandy clay unit. The only rock found is the hard, crystalline underlying unit. According to the owner, the coquina is softer and more easily extracted when saturated. If allowed to dry, it becomes very hard and "cement-like"; therefore, the water level is lowered only to within 12 inches of the pit floor, enough to allow the pans into the pit. A 10-inch diameter pump, capable of withdrawing 5,000 gpm, is located in the pit, but it was reportedly throttled back to between 1,000 and 2,000 gpm and operated from 7 a.m. until 6 p.m. on each working day.

Currently, dewatering operations in both mines have ceased until further notice.

LOCAL HYDROGEOLOGY

Physiographic Setting

The site under investigation is located in the Lower Coastal Plain of South Carolina. It lies at the toe of the Daisy Scarp, which bisects Horry County from northeast to southwest (Fig. 2) and which is marked by a change in elevation from 40 feet on the east to 110 feet on the west (Fig. 3). This scarp describes the boundary between the Conway backbarrier, or lagoonal, deposits and those of the Horry Barrier System (DuBar, 1971).

Geologic Formations

Canepatch Formation

This formation is of Tertiary age and forms several barrier systems in Horry County, including the Conway Barrier system (DuBar, 1971). In this location, on the Conway backbarrier, deposits are light orange-brown and blue-gray, sandy clay. The clay is very stiff and plastic in the mine cuts and is separated by an erosional unconformity from the shelly, clayey sand of the Waccamaw Formation beneath.

Waccamaw Formation

These sediments, also of Tertiary age, form the surface of the Horry Barrier system (DuBar, 1971) and occur in the subsurface of the Conway backbarrier deposits (Fig. 3). To the northwest, they are composed of well-sorted, very fine to medium sand, light yellow-brown or blue-gray in color, grading downward into blue-gray, shelly, sandy clay. Some thin, red clay beds occur near the scarp. Southeast of the Daisy Scarp, these deposits grade into a combination of soft, shelly, clayey, and sandy limestone and directly overlie either the Duplin Formation or, where the Duplin is absent, the Peedee Formation.

Duplin Formation

This Tertiary formation is a very pure, dense, crystalline limestone that has been observed by the mine operators and local well drillers to contain numerous voids and solution channels. Upon the dissolution in hydrochloric acid of a sample of the limestone from the No. 9 mine, the authors found only a few very fine sand grains and almost no clay particles, reflecting the purity of the deposit. Logs of auger borings made by the South Carolina Geological Survey (See Appendix A) indicate that this unit is composed of interbedded hard and soft layers, but this layering was not observed by the authors in either of the mines.

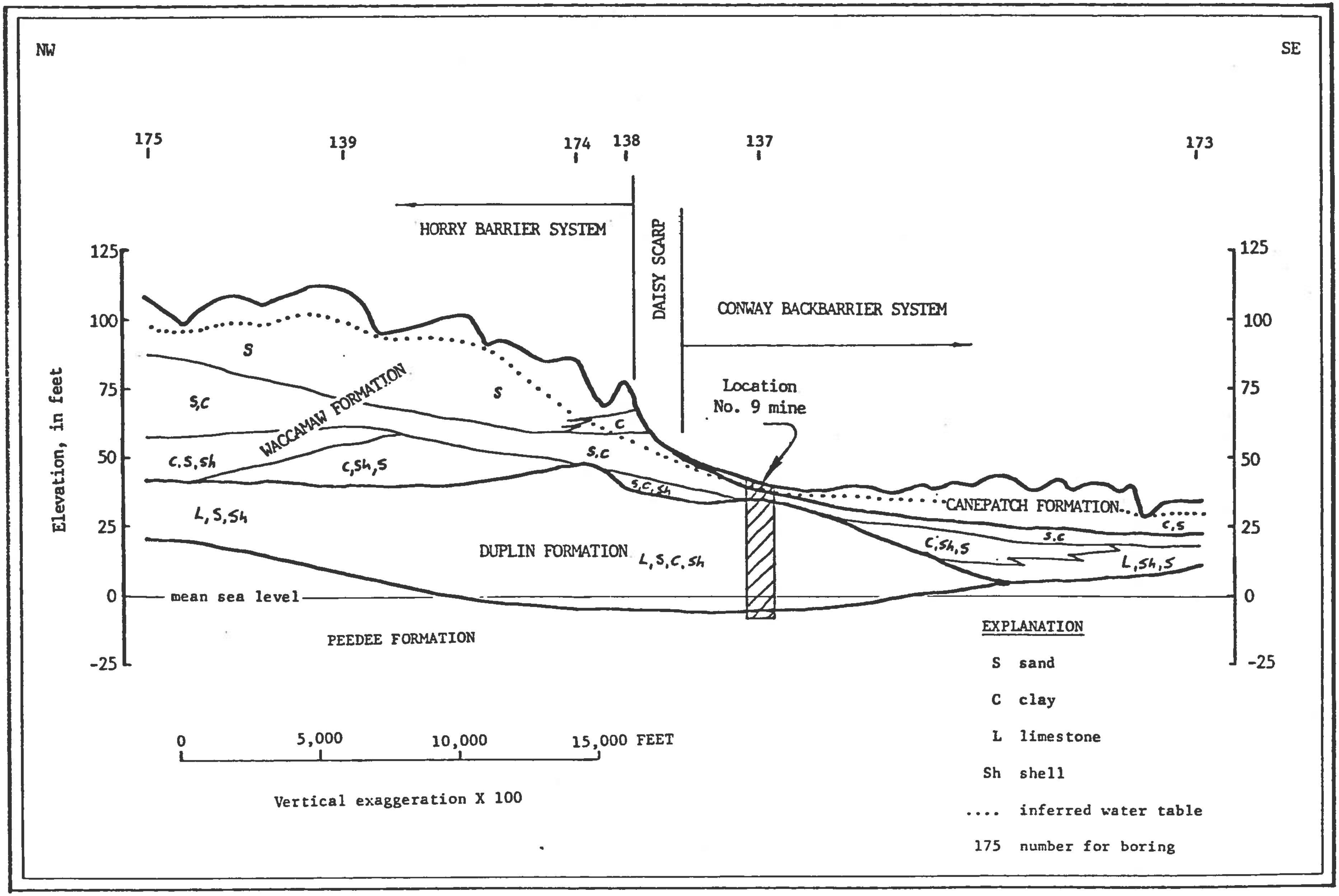


Figure 3.--Geologic section along South Carolina Highway 9 near Goretown, S.C.

Cretaceous Formations

Beneath the Tertiary formations, and extending to approximately 1,000 feet below sea level, is a sequence of calcareous and non-calcareous sand, clay, and sandstone units overlying the crystalline bedrock. The formations that compose this Cretaceous section are the Peedee, Black Creek, and Middendorf. These formations are hydraulically independent of the shallow Tertiary units, because the topmost Peedee Formation is composed of clay and sandstone layers that act as confining beds (Pelletier, 1985).

Hydrology

Surface Water

The principal surface water drainage is provided by Buck Creek, which flows southeast into the Waccamaw River near Longs. The local drainage net is connected to Buck Creek through a series of small tributaries and intermittent streams supplemented by farm and road ditches. The two mine operators currently discharge into a ditch that is between their mines and flows almost due east into Buck Creek.

Ground Water

No accurate information exists concerning water levels prior to the mining activities. Local well drillers reported levels less than 10 feet below ground surface almost everywhere in the shallow aquifers. Jet pumps in 2-inch wells 40 feet deep were common before concerns with the excessive hardness and iron content of the shallow water caused people to drill deeper wells into the Black Creek Formation. Water rose to land surface during excavation of the recharge trench on the site of the # 9 mine. Water levels recorded during installation of the borings noted in Figure 3 indicate that the ground water flows generally to the southeast, perpendicular to the Daisy Scarp, and discharges into Round Swamp and the swamp along Buck Creek.

According to local drillers, the limestone of the Duplin Formation commonly contains solution channels and caves. Wells drilled into this solution system reportedly yield abundant water to domestic wells with almost no drawdown. Investigators in areas of extensive limestone deposits have found that these solution systems tend to follow ground-water flow paths developed along the natural fracture patterns in the limestone (Beck and Sinclair, 1985). This is because the limestone is soluble in water, and as the ground water moves along these fracture planes, it tends to enlarge them by dissolving the rock. As these channels become larger, more water is able to pass through them and more solution takes place, thus accelerating the cave-making process.

In cut walls of the No. 9 mine, the entrances to seven caves were observed. Four of them occurred along a single cut and exhibited a spacing of 70 to 150 feet, with an apparent orientation of approximately north-south. Four of the cave openings had collapsed during the excavation process, but three remained open. The first open cave was 2 to 3 feet in diameter and was found to extend into the wall of the mine, toward Highway 9, a distance of about 15 feet before it turned out of sight. The second was about 2 feet high and 8 feet wide and extended into the wall of the mine approximately 10 feet. The third cave was 7 to 8 feet in diameter but was not accessible for inspection. These solution cavities occurred within the Duplin Formation within a zone located an estimated 20 to 30 feet below land surface.

To this date, there have been only two reported sinkholes in the area. The first occurred in June 1985 and was located on the edge of a farm pond, owned by Mr. Berkeley Gerald, 800 feet south-southwest of the county mine. The pond was reported by Mr. Gerald to have drained into a 16-foot wide, cone-shaped depression that developed overnight. The pond could not be refilled with water until the depression was plugged with clay. The authors were not notified of this collapse until after it had been filled in, but according to Mr. Gerald's description, it appears to have been a sinkhole.

The second sinkhole was discovered in Mr. Harvey Graham, III's corn field on September 20, 1986. It measures 45 feet in diameter and 8 feet in depth. It is located 600 feet due south of the sinkhole by the pond and 1,300 feet south-southwest of the mines. The rate of collapse of this sinkhole is not known because it was not discovered until the corn crop was being harvested.

KARST HYDROLOGY

Karst is defined as a type of topography that forms above soluble formations such as limestone, coquina, gypsum, or dolomite and is characterized by closed depressions, sinkholes, and caves. Karst hydrology refers to the drainage patterns that develop in a karst region, including sinking streams and subsurface drainage through caves (Bates and Jackson, 1980).

Formation of Caves

In the process of cave formation, water becomes weakly acidic by absorbing carbon dioxide as it passes downward through the atmosphere and then through organic soil layers. As it moves through the pore spaces and fractures of the underlying rock, the acidic water dissolves the limestone and enlarges the openings to form a network of interconnecting conduits. Solution of the rock is most rapid where the flow of water is concentrated. This occurs along sets of vertical fractures known as joints, along bedding planes, or within the zone of water table fluctuation.

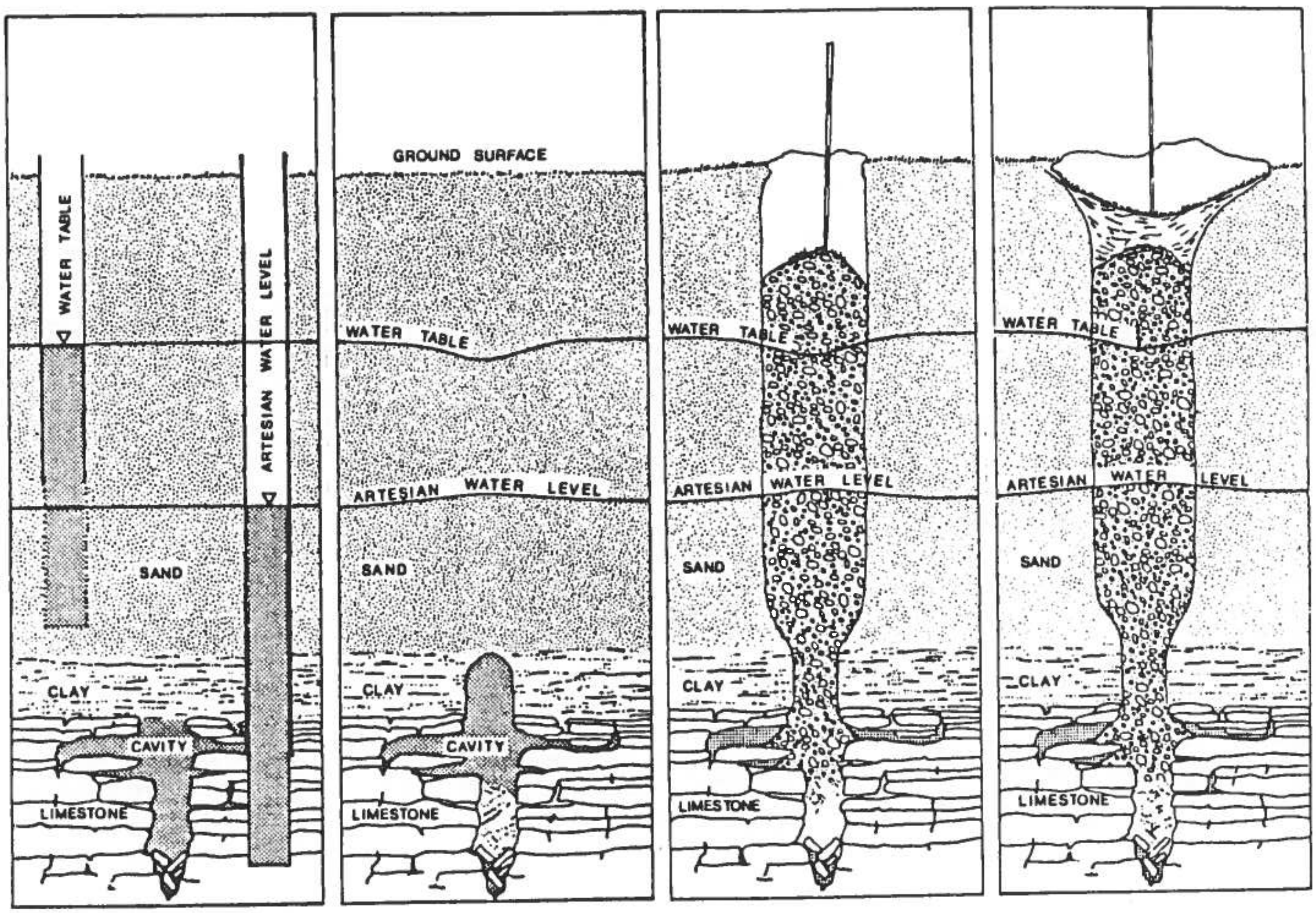
Formation of Sinkholes

Sinkholes are round or elliptically shaped, closed depressions in the land surface, caused by the filling of subsurface cavities with overlying surficial material. Sinkholes can occur through either gradual subsidence or sudden collapse. Two types of sinkholes, cover collapse and limestone collapse, may have occured in portions of Horry County.

Cover-collapse sinkholes are the most common; they develop in areas where a relatively loose cover material, such as sand, is separated from the underlying limestone by a dense, relatively impermeable clay layer as shown in Figure 4. Movement of acidic ground water from overlying formations, over a time frame of centuries, causes the development of cavities in the uppermost portions of the limestone (Fig. 4a). The cohesiveness of the clay will support the roof of the cave for some time, but eventually the clay will collapse when the stresses acting on it exceed its bearing strength for the span over the cave opening (Fig. 4b). Once this occurs, the less cohesive material flows downward, in a process called piping, carried by the flow of surface water moving downward to recharge the dewatered parts of the underlying aquifer (John Newton, 1986, oral communication), and allowing the cavity to migrate upward to the surface (Fig. 4c).

Limestone-collapse sinkholes occur by failure of the rock roof of a cavity and are far less common than cover-collapse sinkholes. In this case, the cavity originally forms along a bedding plane or fracture or near the water table (Figure 5a). Dissolution, minor spalling, and erosion continually enlarge the cavity (Figure 5b) until the roof can no longer support itself and the overburden, resulting in an abrupt collapse (Fig. 5c).

Although sinkholes are a natural phenomena, they may be triggered, or their development enhanced, by a number of different mechanisms. These mechanisms include fluctuations of the water table, changes in the hydraulic gradient, localized overloading, and vibration. Natural events, such as droughts,



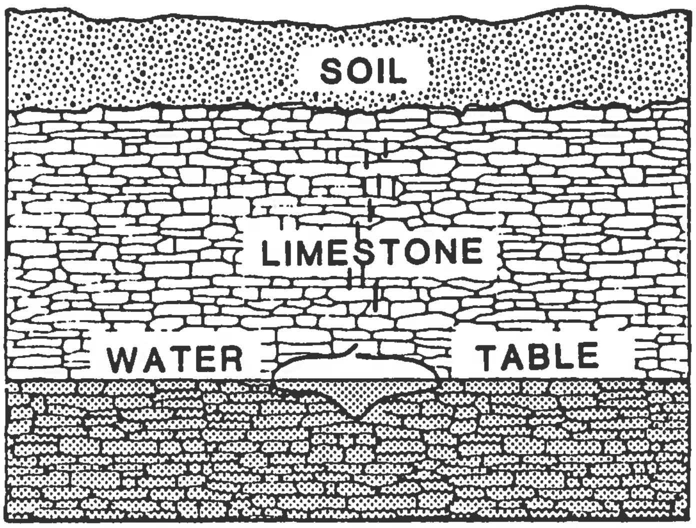
(a) Cavity dissolved in limestone by percolating water. Time: Centuries.

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

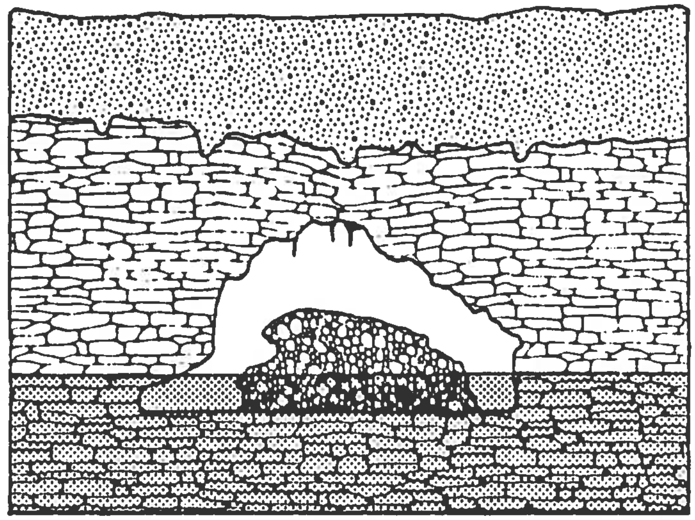
(c) Spalling of cohesionless sand into cavity. Time: Hours-days.

(d) Modification of sinkhole by surface erosion. Time: 10 years between C and D.

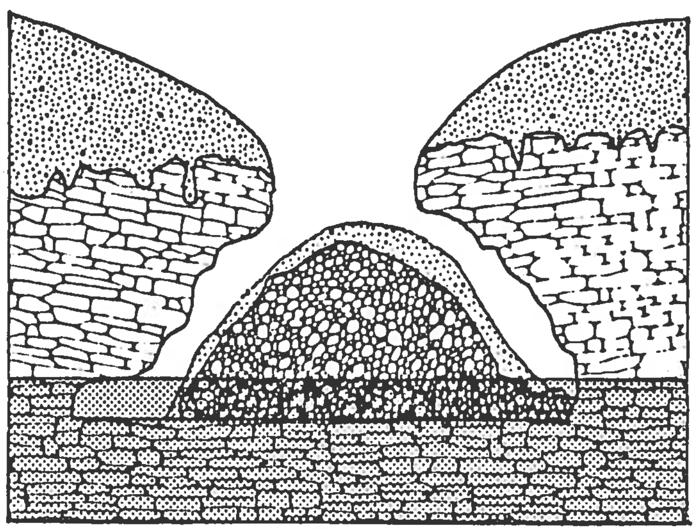
Figure 4.--Development of a cover-collapse sinkhole. (From Beck and Sinclair, 1985)



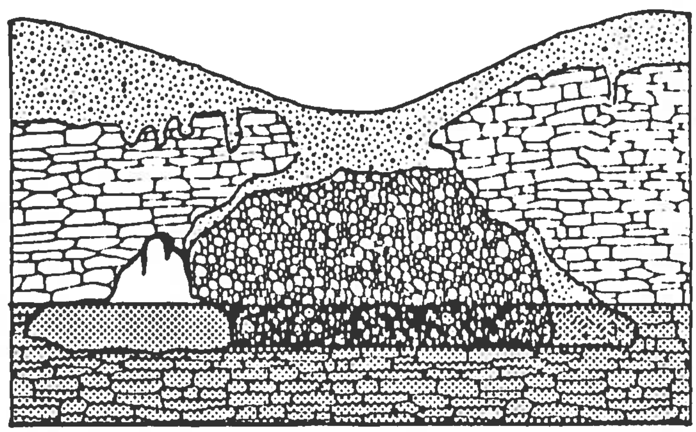
(a) Solution cavity develops along a joint, or other plane of weakness, at the water table.



(b) The roof collapses, most likely at a joint intersection. Undercutting of cave walls, by subsurface erosion, continues.



(c) The roof collapse reaches land surface. Undercutting continues.



(d) Soil washes into the depression and obscures its origin. Breakdown and cave roof cemented by recrystallized limestone. Ground water flow established in a new conduit.

Figure 5.--Development of a limestone-collapse sinkhole. (From Beck and Sinclair, 1985)

floods, earthquakes, or heavy rains, can also act as triggers for these sudden collapses.

In sinkhole-prone areas, a difference may exist between the hydrostatic heads in the water table aquifer and underlying confined limestone aquifer (Fig. 4). Fluctuations of these heads can stress and weaken the clay or limestone roof of the cave. For example, periods of drought or local overpumping can decrease the hydraulic, or buoyant, support of a cave roof, and heavy precipitation can increase the load that it must bear.

An increase in the hydraulic gradient near a pumping well or a dewatering mine also causes an increase in the ground-water flow velocity and can result in accelerated subsurface erosion. This erosion within the cavities and conduits of the limestone may remove physical support from the roof of the cave and initiate a collapse. Any additional load that is applied to the area above such a cavity will increase the likelihood of a collapse. The load may be rain-saturated soils, ponding of reservoirs, construction of buildings, or movement of heavy equipment over the site.

The physical properties of the limestone and its overburden are major controlling factors in the development of sinkholes. These include the effective stress, lithologic composition, degree of fracturing, and thickness of the limestone and overlying materials.

Effective stress, or intergranular pressure, is the average normal force per unit area that is transmitted directly from particle to particle in a material, and it is influenced by pore pressure and overburden thickness (Bates and Jackson, 1980). Generally, effective stress increases with increasing overburden thickness and other additional loading. The pore pressure in water-saturated materials is positive and reduces the effective stress, but in unsaturated materials it is negative, owing to attraction by capillary forces, and increases the effective stress. If, for example, the water table were to drop from a level within the overburden to some other level below the roof of a cavity, the effective stress in the overlying material could increase. If the effective stress exceeds the material strength, then a failure will occur. Vibration may also trigger a collapse by increasing the pore pressure in cohesionless material, thereby reducing the effective stress, and making it more likely to flow. Blasting activities, earthquakes, heavy equipment, trains, and other traffic may generate sufficient vibration to initiate a collapse event of this type.

The composition of the limestone and overburden material will influence sinkhole development. Clay has good cohesive properties so that, generally speaking, the greater the clay content in overburden materials the more likely it is that a sudden collapse would occur. Formations that are well indurated, or cemented, would also tend to form sudden collapse sinkholes. In relatively cohesionless materials, such as sand and gravel, a gradual subsidence would be more typical.

It has already been mentioned that caves tend to follow fractures in the limestone because they are natural flow paths in the rock. Sinkholes tend to form at the intersections of these joints and fractures where the ground water flow is more concentrated. This further accelerates the dissolution process and causes cavities to form more rapidly.

Sinkhole Abatement Techniques

As can be seen from the preceding discussion, the stabilization of ground-water levels and the control of surface water recharge must be the primary goals for any sinkhole abatement program. Ground-water levels can be stabilized by the modification of the pumping scheme, or by the establishment of a subsurface hydraulic barrier to prevent or reduce ground-water inflow to the mines. Surface water recharge to the underlying aquifer can be controlled by transporting the runoff out of the cone of depression created by the dewatering activity (Newton, 1986, oral communication).

The modification of the pumping scheme can range from a reduction in the pumping rate to the cessation of pumping altogether. This modification may require the operators to:

1) Maintain water levels in the mine or at the mine property boundary at some acceptable elevation,
2) Mine the coquina under wet conditions, or
3) Abandon the mining operation.

In order to stop or reduce ground-water flow into the mines, a subsurface hydraulic barrier around their perimeters, to the depth of an impervious stratum beneath the limestone, may be effective. This barrier may take the form of a clay seal, a grout curtain, or other physical barrier; or it may take the form of a hydrologic barrier such as a recharge trench. The clay seal would entail excavating a trench around the mine and backfilling it with clay. Placement of a grout curtain would involve drilling a line of closely spaced borings and forcing a cement mixture into them at pressures high enough to cause the cement to migrate into the formations between the holes where it will set up and form the impermeable barrier.

Construction of a circumferential recharge trench that is hydraulically connected to the limestone may be appropriate. Water removed during mine dewatering would be circulated around the trench to raise the ground water level outside the mine to near normal levels. This option would also increase the amount of water the operator would need to pump from the mine, because of recirculation of water from the trench back into the mine. Use of a recharge trench in conjunction with a grout curtain or clay seal may be a very effective method of water-level stabilization that would reduce recirculation of the pumped water.

In order to protect certain structures within a cone of depression around a mine site, it would be advisable to route all runoff water away from those structures with lined ditches, waterproof culverts, or other such devices. This would reduce the amount of water recharging the aquifer in the vicinity of the structure, thereby reducing the potential for piping in the overburden materials (Newton, 1986, oral communication).

Reduction or removal of vibratory loads might decrease the rate of sinkhole occurrence. This could be accomplished by limiting or prohibiting blasting activities or by requiring a buffer zone between the mining operations and traffic zones such as highways and railroads. Farm equipment can also create a vibratory load, which could be avoided in fields adjacent to mines through the purchase or leasing of these fields by mine operators.

Sinkholes may occur within an area of up to at least a 1.5 mile radius of mining activity as evidenced at the Jamestown and Forney sites. To contain the entire area effected by mining activity within mine property boundaries would obviously be impractical in most cases. Therefore, in addition to requiring mining operators to obtain as large a buffer zone as possible, it will be neccessary for these operators to also take other measures, such as maintaining water levels at specified elevations at the mine property boundaries, in order to prevent land surface collapses and water level declines from occurring off-site.

CONCLUSIONS

1. The Horry County Department of Public Works and the No. 9 Mining Company are mining different formations. Horry County is mining the soft, sandy, shelly, clay deposits of the basal Waccamaw Formation, while the No. 9 mine is extracting more consolidated deposits from the Duplin Formation. In the 500-foot cut of the County pit, there is evidence that the Waccamaw Formation pinches out to the south. It occurs as only isolated remnants on top of the Duplin Formation in the No. 9 pit 250 feet to the south.

2. The limestone of the Duplin Formation is dense, hard, pure, and crystalline, with few fossils. Upon dissolution of a sample from the No. 9 mine, there was little sand or clay evident. The Duplin is apparently pure and hard enough to allow caves of considerable size to develop.

3. The cave system in the Duplin Formation apparently is well developed and extensive. The caves found in the No. 9 mine exhibited a north-south orientation with a spacing of 70 to 150 feet. No caves are evident in the Waccamaw Formation at either mine.

4. The size of the caves in the Duplin is a cause for concern. The largest cave observed was approximately 7 or 8 feet across and could have presented a major threat to property if it had occurred off-site.

5. The most probable cause for both collapses were declining water levels resulting from mine dewatering operations. Mr. Gerald's pond was drained by a sinkhole that occurred when only the County mine was in operation, indicating that the local hydrologic system was perhaps already stressed sufficiently to trigger these events. The hole in Mr. Grahams's field occurred after the record summer drought of 1986, which would have contributed to the decreased local water levels. In addition, both mine operators were dewatering their respective pits at that time and thus further lowering water levels.

6. The case studies conducted at the Jamestown and Forney sites bear strong correlations to the Goretown site with respect to the type of geologic formation being mined, the overburden material, general quarry operations, and the proximity of sinkhole occurrances to the mines. This substantiates the conclusion that the collapses were most probably the result of mine dewatering activities.

7. If uncontrolled pumping continues, additional collapse events will likely occur. As water levels further decline and subsurface erosion within the caverns proceeds, the cave systems will become increasingly stressed.

8. The threat to S.C. Highway 9 is real. It may be that the heavy equipment vibrations, roadbed grading and compaction, and other recent construction activities would have precipitated the collapse of any incipient sinkhole sites at that time. However, extended periods of low water level, with the resulting increased subsurface erosion, could open some caverns that are currently filled with sediment, and the potential for piping in the sediments underlying the ditches on either side of the road could create new sinkhole threats.

9. The geology of the area, coupled with the two sinkholes found to date, indicates that future sinkholes will probably occur as sudden collapse-type events, rather than the slower subsidence-type event common in some other places.

RECOMMENDATIONS

Require both the No. 9 Mine and the Horry County Department of Public Works coquina mine to cease all pumping activity until reliable investigations have shown that pumping activities can continue without hazardous land surface collapses occurring off site. To accomplish this, each operator must retain a qualified consultant to investigate the site to determine the most efficient means to maintain the off-site water level above the top of the Duplin Formation. This investigation will be utilized in further evaluations of the present ground-water use permit applications submitted by each mine. The following are minimum requirements to be included in the study and are not to be construed to be the limit of what is deemed necessary in order to obtain reliable data.

1. Drill a minimum of 10 (5 for each mine) core holes to be converted into observation wells into the Duplin Formation at locations selected by the consultant, obtaining a driller's log, geologic samples, and detailed well construction records for each. Sufficient data is to be obtained from these wells to construct potentiometric and structure maps of the Duplin Formation. The wells must satisfy all current well construction standards;

2. Establish the elevation, to fourth-order accuracy, with respect to mean sea level for the measuring point of each monitoring well;

3. Establish staff gages in each pit. These shall be set to record the water level relative to mean sea level. The operator shall report daily water levels on a quarterly basis;

In the event that a reliable investigation by the consultant confirms the findings contained herein and establishes that sinkhole abatement techniques implimented by the quarry operators will be effective in the prevention of further collapses, the following are a minimum of what will be deemed necessary to ensure compliance with a temporary ground-water use permit:

1. Maintain water levels in all monitoring wells at the mine property boundary to at least a minimum elevation such as the top of the Duplin Formation, as determined during drilling, or such elevation as determined based on the investigation;

2. Record pumpage volumes daily, and report water use quarterly;

3. Set up a rain gage and report daily amounts on a quarterly basis.

SCWRC and SCLRCC will continue cooperative review of various investigations and findings within the Waccamaw Capacity Use Area with regard to mining operations and coordinate to assure compliance with the permit conditions established by each agency.

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APPENDIX

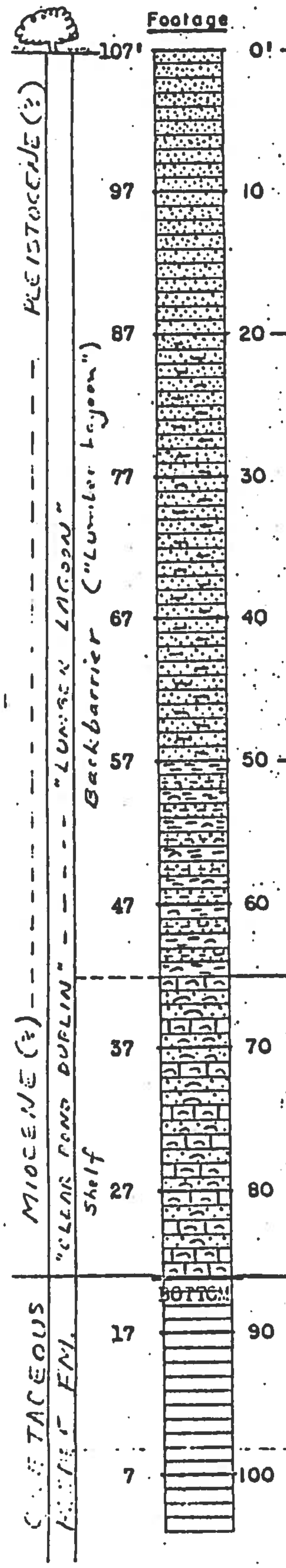
Logs of auger borings used in constructing Figure 3.
(from South Carolina Geological Survey)

Drill hole: HORRY #175 (power auger hole) **Date:** 17 June 1966 (Rev. 21 Sept. ...) **Total depth:** 86'

Location: SW/4 Goretown 7½' quad.; on County Road 66 at point about 500 ft. S of junction with S. C. 9; about 2 mi. NW of Goretown.

Collar elevation: 107' (est. from B.M.) **Logged by:** Henry S. Johnson, Jr. and Bruce G. Thom

Drilled by: Division of Geology
S. C. State Development Board



Description

0-20(?)': Sand, F, light brown in upper portion becoming dark brown to black downward; organic stained (humate); well sorted but with a few M-C grains; water saturated below about 10'.

20(?)-50(?)': Sand, F, clayey, sticky, light brown in upper portion becoming blue gray at about 25'; has soupy consistency.

50(?)-65': Clay with some sand (probably interbedded), sparsely shelly, plastic, blue gray; clay non-calcareous to very slightly calcareous; sparse shell fragments.

65-86': Limestone, coquinoid, and highly calcareous shelly sand, light bluish gray; contains interbedded layers of hard coquina which becomes more abundant towards base of unit.

86': Hard layer; no recovery; drill sticks badly; drills like basal unit (90-91') of HORRY #174.

Bottom at 86' in hard marl or limestone.

Remarks:
Water table at about 10'.
Samples 50(?)-65' (off rods) and 65-86' (off rods) to Du Bar.
Du Bar reports as follows: ________________

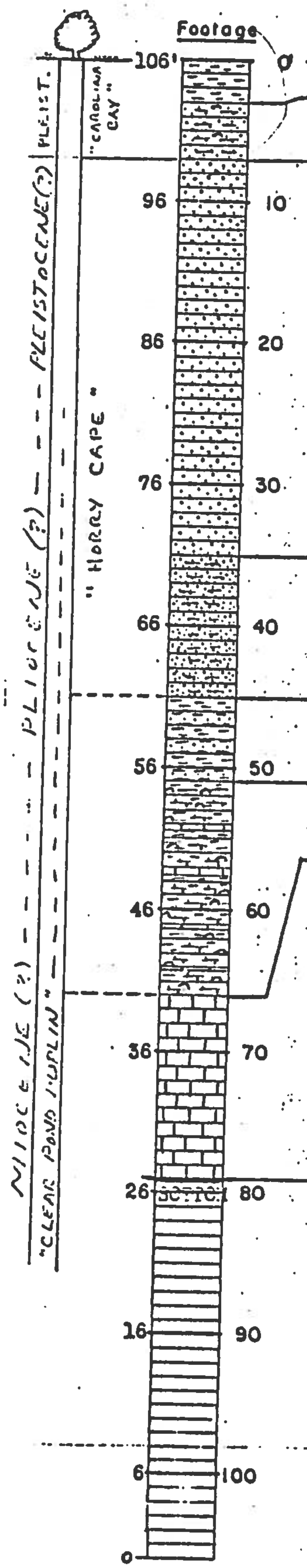
-Over-

Drill hole: HORRY #139 (power auger hole) **Date:** 27 August 1965 **Total depth:** 79'

Location: SW/4 Goretown, S.C.-N.C., 7½' quad.; 1 mi. N 45° W of Goretown; on dirt road in center of a Carolina bay, 0.2 mi. NE of S. C. 9; 3.5 mi. ESE of center of Loris.

Collar elevation: 106' (est. from contours) **Logged by:** H. S. Johnson, Jr. and B. G. Thom

Drilled by: Division of Geology, S. C. State Development Board



Description

0-3': Peat, black.

3-7': Sand, F, very clayey, firm to moderately plastic, dark gray becoming lighter with depth; sparse freshwater shells.

7-35': Sand, M-F, well sorted, wet, light gray; contains sparse heavy minerals.

35-45': Sand, VF, very clayey, soupy, blue gray; contains some M grains.

45-51': Clay, slightly sandy, very plastic, bluish green; contains very slightly calcareous tiny white fragments.

51-66': Clay or marl, sandy, soupy, shelly, blue gray; contains abundant shell fragments; contains thin hard layers of blue gray to white coquinoid limestone.

66-79': Limestone, coquinoid, hard, very calcareous; contains interbedded hard and soft layers and small solution cavities; poor recovery.

Bottom at 79' in limestone.

Remarks:
Sands and clays above 51' appear to grade downward into coquinoid limestone.
Sample 51-66' to Du Bar. Sample 66-79' to Du Bar.
Du Bar reports as follows:

FAUNAL CHECK LIST - H139(66-79')
(J. R. Du Bar; 31 October 1965)

Pelecypoda
Chlamys sp. R

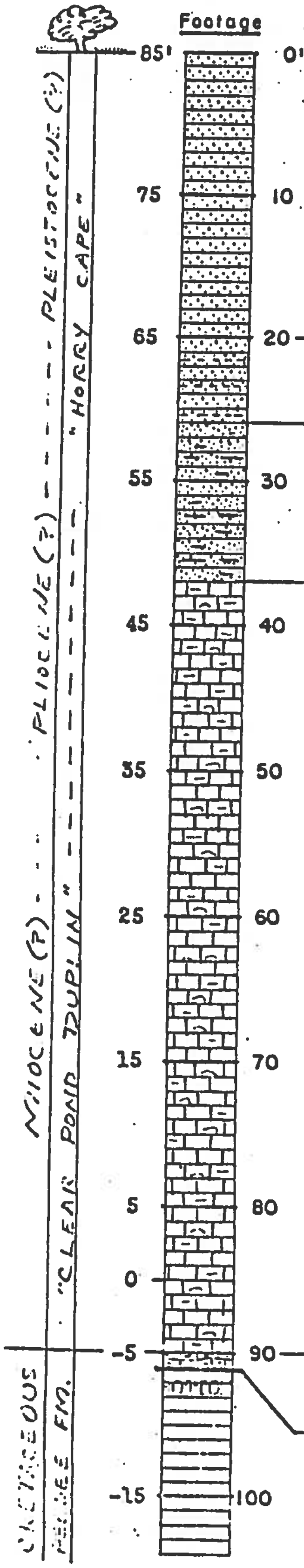
Drill hole: HORRY #174, (power auger hole) **Date:** 16 June 1966 **Total depth:** 91'

Location: SE/4 Goretown 7½' quad.; on S. C. 9 highway at point 0.6 mi. SE of Goretown and 0.34 mi. WNW of Sweet Home School.

Collar elevation: 85' (est. from contours) (road level about 5 ft. below land level)

Logged by: Bruce G. Thom, Henry S. Johnson, Jr.

Drilled by: Division of Geology, South Carolina State Development Board



Description

0-20': Sand, F, well sorted, light yellow brown to gray brown; moist and slightly sticky below 15'.

20-26': Sand, F, reddish brown; contains thin (thickness unknown) interbedded layers of red clay.

26-37': Silt to sand, F, slightly clayey, soupy, blue gray; may contain thin seams of calcareous cemented material.

37-90': Limestone, calcarenite, soft, clayey, bluish gray to white; contains thin seams of hard calcareous cemented "coquina" which becomes abundant with depth; drills with interbedded hard and soft feel.

90-91': Limestone or marl, stiff, gray; drill sticks badly; hard to recover rods; 6 inch sample of gray marl recovered from bit had strong petroliferous(?) or phosphorous(?) odor.

Bottom at 91' in stiff gray marl.

Remarks:

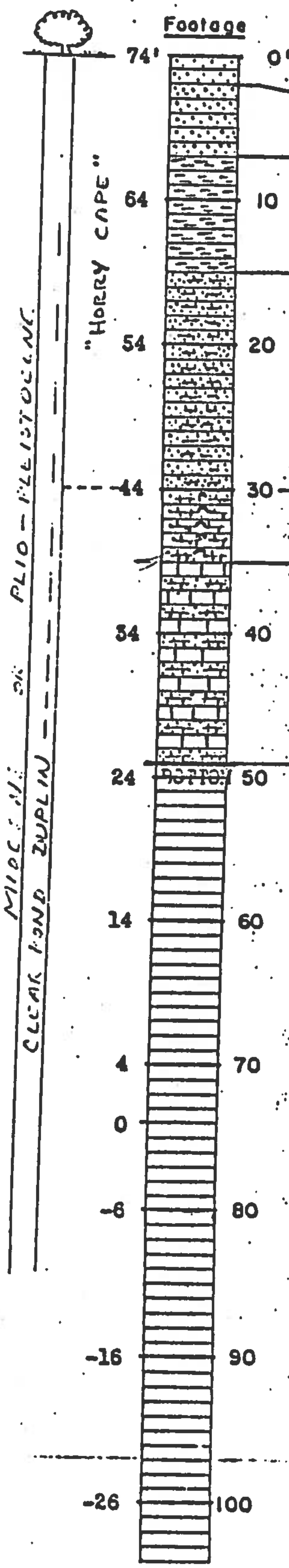
Water table at 20'.

Drill hole: HORRY #138 (power auger hole) **Date:** 27 August 1965 **Total depth:** 49'

Location: SE/4 Goretown, S.C.-N.C., 7½' quad.; on dirt road, 1.0 mi. S 65° E of Goretown; 0.1 mi. due S of Sweet Home School.

Collar elevation: 74' (est. from contours) **Logged by:** H. S. Johnson, Jr. and B. G. Thom

Drilled by: Division of Geology, S. C. State Development Board



Description

0-2': Sand, M-F, well sorted, organic stained, dark brown.

2-7': Sand, F with some M grains, creamy white to light yellow; quartz grains are clear and subangular.

7-15': Clay, tough, very plastic, creamy gray with very thin red mottled streaks.

15-30': Sand, VF, very clayey, soupy, non-calcareous, blue gray; contains sparse C angular clear quartz grains.

30-35': Sand, M-C, very clayey, soupy, shelly, calcareous, blue gray; coarsens downward; shell fragments become abundant with depth.

35-49': Limestone and interbedded calcareous clayey sand or marl; limestone layers are 1 to 3 inches thick and are bluish white fragmental coarse coquinoid calcirudite; interbedded soft layers are 1 to 3 inches thick and are thought to be similar to unit 30-35'.

Bottom at 49' in interbedded soft and hard limestone and marl.

Remarks:
Water table at about 15'.
Sample 7-15' to Heron.
" 35-49' to Du Bar.
Du Bar reports as follows:

FAUNAL CHECK LIST - H138(35-49')
(J. R. Du Bar; October 1965)

Pelecypoda
- Donax variabilis — R
- Gemma magna? or gemma — R
- Mulinia lateralis — R

Bryozoa
- Discoporella c.f. denticulata — R

Arthropoda
- Balanus sp.

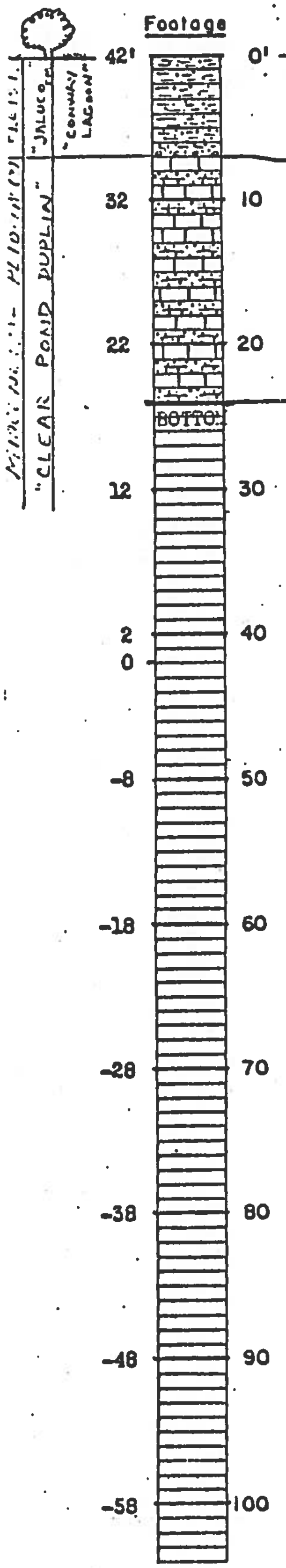
Remarks.— Probably a surf deposit but fauna too sparse for ecologic or age determination. It looks younger than Duplin. Doesn't look like typical calcarenite fauna of area. Could it have come from the overlying unit?

Drill hole: HORRY #137 (power auger hole) **Date:** 27 August 1965 **Total depth:** 24'

Location: SE/4 Goretown, S.C.-N.C., 7½' quad.; on S. C. 9, 1.86 mi. ESE of Goretown; 0.87 mi. S 65° E of Sweet Home School.

Collar elevation: 42' (est. from contours and B.M.) **Logged by:** H. S. Johnson, Jr. and B. G. Thom

Drilled by: Division of Geology, S. C. State Development Board



Description

0-7': Clay, very sandy, poorly sorted, plastic, dull brown grading to blue gray at 4'; contains sparse C angular quartz grains in upper part; more sandy below 5'; contains angular to subrounded quartz and feldspar pebbles to ¼ inch at base of unit.

7-24': Limestone, sandy, coquinoid, whitish gray; 1 to 6 inch thick well-cemented beds of coarse bioclastic limestone interbedded with clayey calcareous sand or marl.

Bottom at 24' in interbedded hard and soft limestone.

Remarks:
Water table at 3'.
Sample 15' to Du Bar.
Du Bar reports as follows:

FAUNAL CHECK LIST - H137(15')
(J. R. Du Bar; October 1965)

Arthropoda
Balanus sp. C

Echinoidea
Regularia spines C

Remarks.-- Recrystallized limestone; sandy; light gray; close to a calcarenite. Molds of small forms common but unidentifiable. -- Probably young Duplin-- i.e., Clear Pond phase.

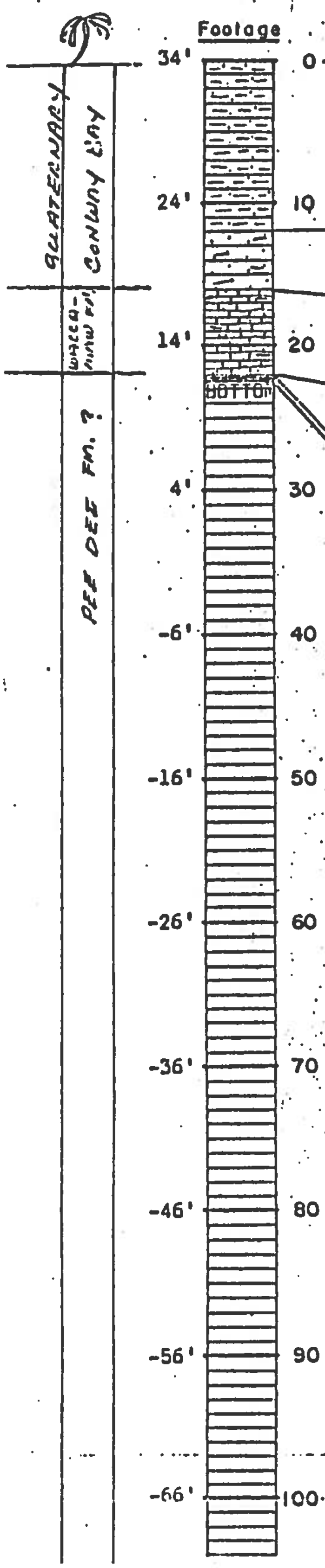
- - -

Drill hole: HORRY #173 **Date:** 16 June 1966 **Total depth:** 22'

Location: NW/4 Longs 7 1/2' quad.; on S. C. 9, 3.7 mi. NNW of Longs

Collar elevation: 34' (spot elev.) **Logged by:** H. S. Johnson, Jr.
B. C. T.
C. R. Strickland

Drilled by: Division of Geology,
S. C. State Development Board



Description

0-12': Clay, sandy, F, light brown to blue-gray; stiff, plastic.

12-16': Sand, C, with clay, very sticky, blue-gray; grains angular.

16-22': Limestone, soft, very abundant shell fragments, light bluish gray, stiff and clayey, somewhat sandy with small 1/4" granules of quartz.

22(?)': Limestone or marl, soft, dark gray, very slight recovery on tip of bit, drills very stiff and hard (like Pee Dee).

Bottom at 22'.

Remarks: Water table at 5'; sample 16-22' off rods (DuBar).