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Topographic and hydrogeologic controls on sinkhole formation associated with quarry dewatering

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ABSTRACT

In August and September 1994, a series of sinkholes developed at a residential property located adjacent to a limestone quarry. Field observations and water levels from the quarry were evaluated to assess the problem. A creek flows between the residential property and the quarry, and this stream occupies a small, but well defined valley, with a steep escarpment of 1.5 to 2.2 m relief between the valley floor and surrounding uplands. The valley bottom is a permanent wetland approximately 25 m across adjacent to the residence. At the time of the field evaluation, the wetland appeared dewatered. The quarry extracts aggregate from the Eocene Castle Hayne Formation, a moldic bioclastic limestone.

During the field visit it was noted that sinkhole development near the quarry occurs along the upland area adjacent to the escarpment that bounds the stream valley. The sinkholes are up to 5 m in diameter and 3 m deep. Concentric cracks tangential to some sinkhole boundaries indicate additional sinkhole growth will probably occur.

A series of 8 transient electromagnetic soundings were performed to develop an apparent resistivity profile of the subsurface. The results show high apparent resistivities, ranging up to 700 ohm-meters, with a steep vertical gradient to the resistivity maxima. The relatively high values for apparent resistivities may reflect voids and enhanced porosity zones that are associated with sinkhole development.

The association of sinkholes and subsidence areas with the upland edge of the stream valley escarpment suggests a topographic control of secondary porosity development in the limestone. Infiltration at the edge of the upland has a relatively short flow path to discharge to the stream valley. The short flow path would have a higher flow velocity because of the hydraulic gradient at the edge of the escarpment, and the ground water would not reach chemical equilibrium with the carbonate matrix of the limestone. Both of these factors would increase secondary porosity development along the valley scarp.

Large changes in head have been observed in the monitoring wells at the quarry as the active pit has been moved across the quarry site. The collapse of the sinkholes concurrent with large changes in water levels at the quarry suggests that head changes in the limestone aquifer may have been a triggering mechanism for sinkhole collapse.

REGIONAL SETTING

Geology and Geomorphology

The study area is located in the outcrop belt of two Tertiary formations that comprise the Castle Hayne Aquifer system in the North Carolina coastal plain, the Eocene Castle Hayne Limestone and the Oligocene River Bend Formation (Figure 1). These units are exposed in the eastern portion of the coastal plain, from New Bern to Wilmington, North Carolina. The coastal plain has been eroded into a series of terraces by eustatic sea level changes during the Cenozoic. The limestone outcrop belt occurs mostly between the Surry and Suffolk Scarps, at elevations between 25 and 3 meters above sea level. A thin veneer of terrestrial, nearshore marine and shelf sediments was deposited across most of the terrace surfaces, and has been partially removed by subsequent erosion. To the north of the outcrop belt, the carbonates are overlain by the Pliocene Yorktown Formation. The southern end of the outcrop belt occurs where the updip limit of the limestones intersects the modern coastline, near the Cape Fear River. The terrace surfaces have been dissected by erosion associated with modern drainage systems. Areas between major streams are often nearly flat, with poorly drained pocosins or upland swamps, while major drainages may be incised up to 12 m below the regional grade. Minor drainages have less pronounced relief, with valleys often less than 5 m below surrounding uplands.

The Castle Hayne Limestone is a sandy fossiliferous limestone that was deposited in shallow marine shelf and bank environments (Jones, 1983). The stratigraphic and paleontologic relationships of the Castle Hayne have been disputed, but the upper part of the Castle Hayne, the Spring Garden Member, is widely recognized as a middle Eocene sandy molluskan limestone with moldic porosity. The overlying River Bend Formation, of Oligocene age, is also a sandy molluskan limestone. This unit may comprise the upper 2 to

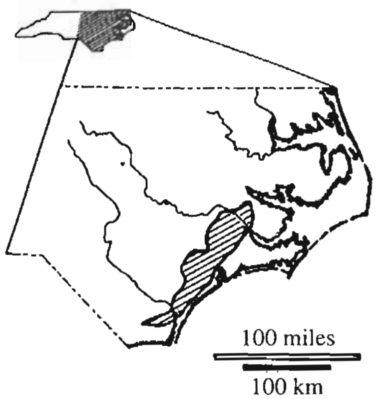

Figure 1. Location of the Eocene Castle Hayne Limestone Outcrop Belt

4 m of the Castle Hayne Aquifer system in the study area. Abundant mollusk tests in the original carbonate sediment have been preferentially dissolved during meteoric diagenesis, resulting in secondary porosity that ranges up to 42 per cent (Thayer and Textortis, 1977). These sediments have been subaerally exposed for significant amounts of time since their deposition in the middle Eocene and Oligocene; meteoric diagenesis has infilled primary interparticle porosity and developed moldic porosity from dissolution of fossil shells . The macrofaunal assemblage of these rocks is dominated by pelecypods, gastropods and bryozoans. The original mineralogy of these fossils was mostly aragonite with some magnesian calcite. Concurrent with the dissolution of the aragonite and high magnesium calcite, low magnesium calcite was precipitated as a fine to medium grained spar cement in the primary pore spaces (Thayer and Textortis, 1977). In the uppermost portion of the limestone section, dissolution features have been observed that are not fabric selective, such as vugs and channels, a result of the dissolution of low magnesium calcite.

Hydrogeology

In the shallow subsurface, ground water generally flows from upland recharge areas to the nearest streams. Interstream areas are usually relatively flat uplands, and hummocky surfaces and mottled soils associated with limestone dissolution are sometimes present. Major and minor stream valleys often have associated wetlands, reflecting discharge along the streams and the interconnection of the surface waters with unconfined aquifers in the recent alluvium. In the middle and lower members of the Castle Hayne Limestone and in the underlying confined aquifers, regional flow is primarily to the east and east-southeast, parallel to regional dip. Some aquifers discharge to the Atlantic Ocean where these units are truncated on the continental shelf. The Castle Hayne and underlying aquifers are water supplies of regional importance where chloride concentrations are below drinking water standards. Because of high aquifer transmissivities, the radii of influence for pumping centers for the Castle Hayne are localized in this area, while regional drawdown is occurring in the underlying confined aquifers beneath and west of the limestone outcrop belt. An extensive cone of depression is present in the Castle Hayne Aquifer System to the northeast of the outcrop belt, where the limestone aquifer is pumped for depressurization at a phosphate mine.

SINKHOLE OCCURRENCE AND FIELD INVESTIGATION RESULTS

In August and September, 1996, seven sinkholes up to 1.75 m in diameter catastrophically collapsed at a residential property located 1 km north of an active limestone quarry in Craven County, North Carolina (Figure 2). In March 1997, the Division of Land Resources (DLR) of the North Carolina Department of Environment and Natural Resources asked the Division of Water Resources (DWR) to evaluate the area impacted by sinkholes and provide recommendations to DLR on possible causes of sinkhole formation and potential mitigation strategies. DWR performed field reconnaissance, transient electromagnetic soundings and reviewed existing hydrogeologic information, including quarry monitoring information, to evaluate the sinkholes.

During the site visits, DWR personnel observed seven sinkholes at the residential property. The largest sinkholes were 5 m in diameter and approximately 3 m deep. The smallest sinkholes were approximately 0.3 m in diameter and up to 0.2 m deep. Two of the larger sinkholes were partially surrounded by concentric cracks in the ground surface, the margin of the sinkhole was underlain by void space, and further lateral growth of these sinkholes appeared to be a strong possibility. Caswell Branch is a permanent stream (mean flow approximately 1 m/sec) that flows between the residential property and the quarry. The stream valley is 1.5 to 2.2 m below the adjacent areas of the residential property and the quarry, with a broad, level valley floor approximately 25 m across. Upland areas near the stream are wooded or open land, with well-drained soils. The small stream valley is densely wooded with mature Black Gum (*Nyssa Sylvatica*) and Bald Cypress (*Taxodium distichum*). Cypress knees were abundant on the valley floor, indicating that the trees had grown in soil that was constantly or frequently saturated (Radford, et al, 1968). No sinkholes were observed in the valley floor. The stream valley is a wetland, as evidenced by phreatophyte dominated flora and a mat of organic debris that had accumulated under subaqueous conditions. At the time of the field evaluation, the wetland appeared dewatered, which was of particular interest, as the field observations were made in early spring, and climatic conditions were not significantly drier than normal. The stream has an anastomosing to braided architecture. The creek flows in relatively well defined channels, and the valley floor was dry, as noted above.

A similar distribution of subsidence features were observed on the quarry side of the stream valley, with a different style of development. Subsidence in this area occurs in a less dramatic fashion, with hummocky depressions up to 5 m across and 0.7 m deep present near the valley boundary. Sinkholes with steep sides and collapse structure were not observed south of the creek. The different style of subsidence probably reflects the control of tree roots on land subsidence. The area is wooded, with mixed white pines and hardwoods up to 40 m tall. This relatively mature forest community has extensive roots in the soil which would prevent development of the pronounced collapse structures present in the open areas on the other side of the creek. Also, it was noted during the field visit that in some of these gentle depressions, a wooden stick 1 cm in diameter could be pushed by hand into the soil approximately 0.8 m, indicating the presence of significant void space in the subsurface.

A series of 8 transient em soundings were performed at the site to develop an apparent resistivity profile of the subsurface along an east-west transect, roughly parallel to the edge of the escarpment of the stream valley. The profile results show high apparent resistivities, ranging up to 700 ohm-meters, with a steep vertical gradient to the resistivity maxima at a depth of 15 to 20 m below land surface. There were two pronounced anomalies detected along the profile, one approximately 21 m east of the west end of the profile and one at 130 m east in the profile. The eastern anomaly extends from just below land surface to an apparent depth of 67 m, with the highest apparent resistivity at 700 ohm-meters (Figure 3). The western anomaly extends from just below land surface to a depth of approximately 30 m, with the highest resistivity at 400 ohm-meters. Both resistivity maxima appear associated with sinkhole development, as they are parallel to the position of two groups of sinkholes north of the transect line, located along the escarpment. The relatively high values for apparent resistivities may reflect voids and enhanced porosity zones that are associated with sinkhole development.

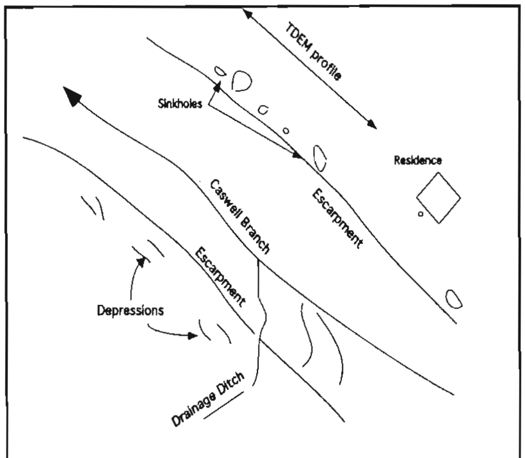

Figure 2. Schematic Map of Affected Residential Property with Sinkhole Locations

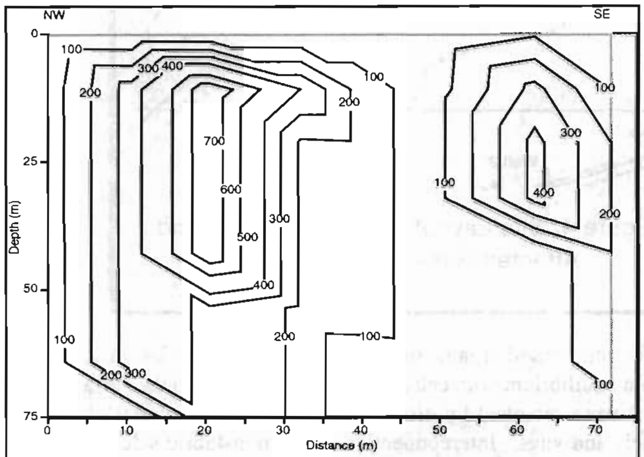

Figure 3. Apparent Resistivity Profile at the Sinkhole Area

QUARRY OPERATION

A construction materials company operates a quarry 600 m southeast of the location where the sinkholes developed (Figure 4). The quarry is an open pit operation. The pit is dewatered by a drainage trench system which runs from the pit face to a pumping station. The drainage system is constructed with a sump approximately 15 m below land surface. Extracted water is routed to settling ponds and then discharged to Caswell Branch. In order to dewater the pit, the drainage system is pumped at a rate of 38 million liters per day. Water levels in monitoring wells on the perimeter of the quarry site have declined by as much as 5 m below pre-pumping conditions. Data from the state of North Carolina's regional monitoring well network indicates that transmissivity of the upper Castle Hayne Limestone in the region is approximately 1.1×10^{-2} m^2/sec.

Water level monitoring performed by the quarry operator shows rapid changes in water levels at the quarry site (Figure 5). Monitoring well 5 at the quarry is approximately 75 m east of the easternmost sinkhole on the residential property. Water level measurements show that the head at well 5 dropped by nearly 3 m in July 1992. After that time the water level at this well varied by no more than 0.1 m until August, 1994, when the water level increased by nearly 3 m. The sinkholes formed on the property north of the quarry in August and September, 1994. The quarry operator's consultant has speculated that there were errors in the water level measurements at the quarry site. However, the consistency of the measurements within the 2 year period between the large changes would not be expected if there were random error introduced by inaccurate measurements. The variance in water levels can be explained by moving the pumping center (the pit face) to the northeastern portion of the quarry property during the time period in question. Concurrent with the recovery of water levels at well 5, water levels decrease at wells 3, 7 and 1, which would be consistent with a southward advance of the quarry pit. Monitoring well 6, located west of well 5, was dry during the 1992-1994 period, reflecting the decrease in water levels at the north side of the site.

INTERPRETATION: CONTROLS ON SINKHOLE FORMATION

The association of sinkholes and subsidence areas with the upland edge of the stream valley suggests a topographic control of secondary porosity development in the Castle Hayne Limestone. This is supported by two aspects of the areal distribution of sinkholes: 1) the absence of subsidence features in the stream valley, and 2) occurrence of only one sinkhole 10 m from the escarpment, with all other subsidence features within 3 m of the escarpment.

Precipitation infiltrating into the ground at the edge of the upland would have a relatively short flow path to discharge to the stream. The steeper hydraulic gradient at the edge of the stream valley causes higher flow velocity for groundwater at the edge of the escarpment. Water infiltrating from soil with significant organic matter often has elevated carbon dioxide content, with pCO_2 for soil water up to 10^{-2} atm (Drever, 1982). The short flow path from the soil zone to the discharge point, combined with the CO_2

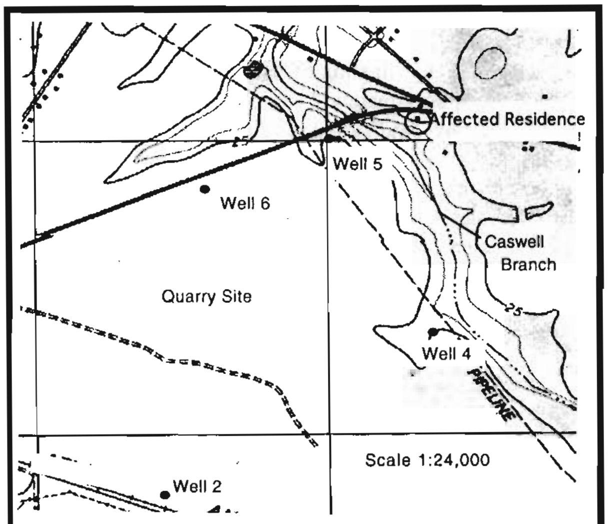

Figure 4. Site Layout for Quarry, Wells and Affected Residential Property

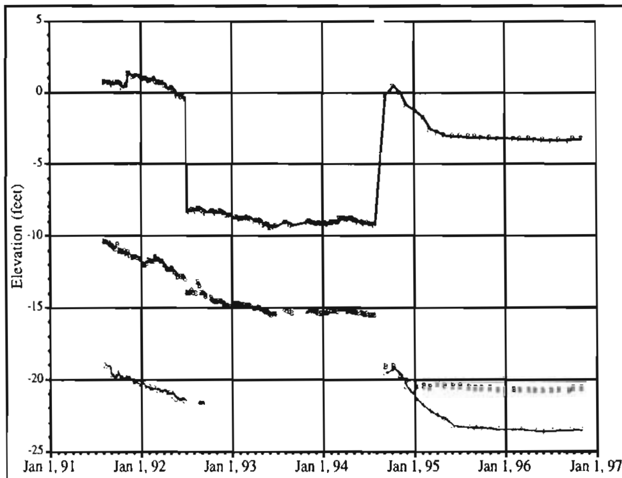

Figure 5. Water Levels from Quarry Monitoring Wells

contribution for soil organic matter, enhances the dissolution of carbonate minerals, as the ground water would not have sufficient time to attain equilibrium with calcite before discharging to the surface drainage. After the less stable carbonates (aragonite and magnesium calcite) were removed by dissolution of the shell material, dissolution of low magnesium calcite in the rock matrix has produced channels and vugs. Interconnection of the non-fabric selective secondary porosity has created larger scale void spaces, which have collapsed to form the sinkholes.

The topography and stream valley flora both suggest that under hydraulic equilibrium, the valley escarpments would be discharge points for groundwater, contributing to base flow of the stream. Wetlands are commonly present at other drainages of similar size and elevation in nearby areas. The wetland was dewatered when the water levels at well 5 were 1 m below sea level. Larger water level declines must have occurred at the stream and sinkhole area when water levels had dropped 3 m at well 5. The relative relationships of the water table, the wetland and land surface during the different pumping conditions are shown in Figure 6. Recovery of the water table in the stream area would have resulted in upward stresses as the water table rebounded to near pre-pumping conditions, and may have triggered the collapse of overlying materials into the pre-existing void spaces that had formed along the edge of the stream valley. DLR is working with the quarry operator to assure that the quarry dewatering does not cause rapid fluctuations in water levels in the aquifer surrounding the site, in order to minimize the potential for further sinkhole development.

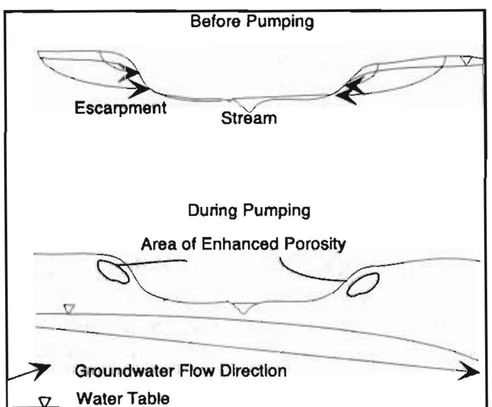

Figure 6. Ground Water Flow Scenarios for Caswell Branch

REFERENCES

Drever, J.I., 1982, *The Geochemistry of Natural Waters* (Prentice-Hall: Englewood Cliffs, N.J.) 388 p.

Radford, A.E., H.E. Ahles, and C.R. Bell, 1968, *Manual of Vascular Flora of the Carolinas* (Chapel Hill, N.C.: The University of North Carolina Press). 1183 p.

Thayer, P.A. And D.A. Textortis, 1977, *Faunal and Diagenetic Controls of Porosity and Permeability in Tertiary Aquifer Carbonates, North Carolina*, Special Publication 7, North Carolina Department of Natural and Economic Resources, Geology and Mineral Resources Section. 35 p.