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Stratigraphy and hydrogeology of a submarine collapse sinkhole on the continental shelf, northeastern Florida

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ABSTRACT

Red Snapper Sink is located on the continental shelf, about 42 km (26 ml) east of Crescent Beach, Florida. In 1991, advanced technical-diving techniques enabled divers to explore the bottom of the sinkhole for the first time. The opening of the sinkhole at a depth of 27.5 m (90 ft) is approximately 122 m (400 ft) in diameter. The maximum recorded depth in the sinkhole is 147 m (482 ft). The sloping sides of the sinkhole are developed on loose Holocene sand and shell from 27 to 34.5 m (88 to 113 ft). Pleistocene sand and clayey sand crop out from 34.5 to 41 m (113 to 134 ft). From 41 m (134 ft) to about 116 m (380 ft), Red Snapper Sink is a vertical shaft measuring about 45.5 m (150 ft) in width to *52* m (170 ft) in length. The walls of the shaft from 41 to 50 m (134 to 164 ft) transect slightly indurated Pliocene shelly sand. The walls are composed of moderately indurated Pliocene silty sands and sandy silts from 50 to 63 m (164 to 206 ft). From 63 to 102 m (206 to 335 ft), the walls are developed in clayey sands and sandy clays of the Upper Hawthorn Group (Miocene). The Lower Hawthorn consists of a dolomitic limestone containing phosphate pebbles and carbonate interclasts with phosphatic rims from 102 to 116 m (335 to 380 ft). The top of the Ocala Limestone occurs at 116 m (380 ft), and below this depth, the walls of the shaft are undercut. Water samples collected at the bottom show normal seawater specific conductance and chloride and sulfate concentrations. During a dive to 147 m (482 ft), sea water was observed flowing into small caves at the base of the wall, indicating that during the dive period, the sinkhole conveyed saltwater into the Floridan aquifer system. Seismic profiles show that Red Snapper Sink is the surficial expression of a dissolution collapse feature that possibly originated in Upper Cretaceous or Paleocene rocks. Similar buried features in northeastern Florida could provide a hydraulic connection between freshwater zones and deeper, more saline zones of the Floridan aquifer system. The presence of these collapse features could help explain the anomalous distribution of elevated chloride concentrations in parts of eastern Duval County.

INTRODUCTION

High-resolution seismic reflection profiles off the coast of northeastern Florida show dissolution and collapse features that are widely scattered across the continental shelf (Popenoe and others, 1984). Off the coast of St. Johns County, limestone beds are nearer to the seafloor surface and solution features are more commonly seen in seismic profiles. Large submarine collapse sinkholes in this area have breached the sea floor at Crescent Beach Spring, 4 km (2.5 mi) off the coast of Crescent Beach, Florida and at Red Snapper Sink, about 42 km (26 mi) offshore from Crescent Beach (figure 1).

Hydrogeologic information about the offshore area has been obtained in recent years through various drilling efforts, particularly in the area off the coast of southeastern Georgia and Fernandina Beach, northeastern Florida. However, little hydrogeologic information is available about the continental shelf off the coast of St. Johns County, Florida (figure 1). Red Snapper Sink, the deepest known collapse shaft on the Florida platform, provides an excellent opportunity to directly study and obtain additional information about the stratigraphy and hydrogeology of the continental shelf.

The occurrence and distribution of collapse features are important because they could play a substantial role in the distribution of saline water in the freshwater zones of the Floridan aquifer system on the Florida Peninsula. Similar, but buried collapse features in northeastern Florida, especially in parts of eastern Duval County, could have high vertical hydraulic conductivities that could provide a hydraulic connection between freshwater zones and deeper, more saline zones.

BACKGROUND

Red Snapper Sink was first discovered in 1962 by a commercial fisherman, who lost the site after being driven off by a storm. The site was rediscovered by fishermen in 1968 and within a period of about 6 weeks, about 45,360 kg (100,000 lb) of red snapper were caught (Wilcove, 1975). The name Red Snapper Sink was given to the sinkhole and the site was located on chart No. 11486 (U.S. National Ocean Survey, 1976).

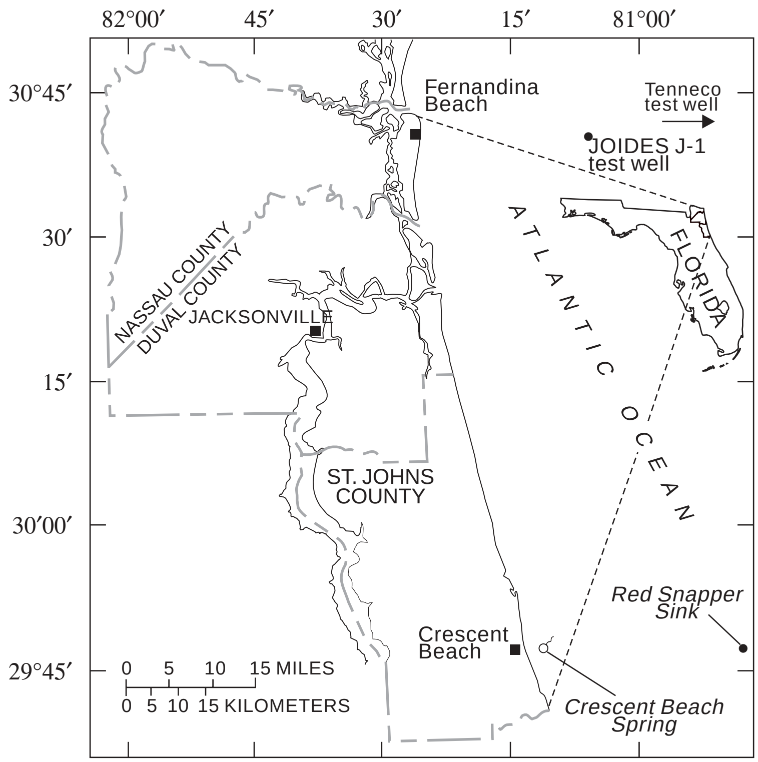

Figure 1: Location of Red Snapper Sink.

Several attempts have been made to learn more about the hydrogeology and stratigraphy of the sinkhole since it was rediscovered. In 1970, the U.S Geological Survey (USGS) conducted expeditions to the sinkhole to determine its exact location, depth, and hydrologic characteristics. Using a stainless-steel multiconductor wire operated over a registered sheave, soundings indicated that the depth of the sinkhole ranged from 131 to 141 m (430 to 464 ft) (Popenoe and others, 1984). Water samples taken by a sampling device lowered to the bottom showed normal seawater salinity and temperature indicating no freshwater outflow from the Floridan aquifer system. A diver descended to a depth of 91.5 m (300 ft) but could not proceed further because of the physiological limitations of compressed air. At 76 m (250 ft), fluorescein dye released into the water showed a slight downward movement, indicating the possibility of salt water intrusion into the Floridan aquifer system (Popenoe and others, 1984). A rock sample was collected at 61 m (200 ft) and was determined to be of Pliocene age (Popenoe and others, 1984).

National Oceanic and Atmospheric Administration (NOAA) and USGS investigators in 1974 used a fathometer to accurately map the sinkhole for the first time. Although the sinkhole was determined to be at least 133 m (437 ft) in depth, side echos from the steep wall may have caused interference, so the depth determined could be somewhat less than the true depth (Wilcove, 1975).

HYDROGEOLOGIC FRAMEWORK

Northeastern Florida is underlain by a thick sequence of sedimentary rocks that overlie a basement complex of metamorphic rocks. The primary water-bearing sediments are composed of limestone, dolomite, shell, clay, and sand that range in age from late Paleocene to Holocene (figure 2). Stratigraphic units in ascending order, are: the Cedar Keys Formation of late Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, the Ocala Limestone of late Eocene age, the Hawthorn Group of Miocene age, and the undifferentiated deposits of late Miocene to Holocene age.

Marine seismic reflection profiles show that the continental shelf off the northeastern coast of Florida is underlain by dissolution-deformed limestone of Late Cretaceous to Eocene age (Meisburger and Field, 1976; Popenoe and others, 1984). Dissolution and collapse features, which are widely scattered throughout the area, are expressed as sinkholes that presently breach the sea floor (Red Snapper Sink and Crescent Beach Spring), sinkholes that breached the sea floor in the past and are now filled with sand, and collapse structures that originated deep within the section and have deformed the overlying units (Popenoe and others, 1984). The deep dissolution-collapse features probably originate in the Upper Cretaceous or Paleocene rocks (Popenoe and others, 1984).

METHODS

During 1991, Deep Breathing Systems, Inc., Sevierville, Tennessee, privately sponsored four, 1-day diving expeditions to Red Snapper Sink for the purpose of exploring and studying the sinkhole. Advanced technical-diving techniques, including the use of mixed gas (oxygen/helium/nitrogen) for deep diving, were used to put a diver on the bottom of the sinkhole for the first time, and allowed divers to collect rock and water samples. Approximately 13 people participated in each dive at the sinkhole. Generally, four divers, in teams of two, were used to collect rock and water samples. Additional divers set up safety lines, placed extra gas bottles for divers for decompression, and provided safety support. A crew of three served as surface support.

Rock samples were collected from 27 to 122 m (88 to 400 ft). Most samples from 27 to 73 m (88 to 240 ft) were collected at intervals of about 3 m (10 ft). Rock samples below 73 m (240 ft) were collected approximately every 7.5 to 15 m (25 to 50 ft).

SUBSURFACE INVESTIGATION

Underwater observations in Red Snapper Sink were restricted by the physical dimensions and depth of the sinkhole. Because of the extreme depth, time for data collection was severely limited. During each dive, a descent line was placed along the walls of the sinkhole. The character of the walls and stratigraphy were identified at those sites where safety lines were lain. Water visibility ranged from 9 to 18.5 m (30 to 60 ft) during the study and artificial light was not needed for observations above a depth of 49 m (160 ft).

The top of Red Snapper Sink is located at a depth of about 27 m (88 ft). At a depth of 27.5 m (90 ft), the sinkhole is nearly circular

Series	Stratigraphic unit		Lithology	Hydrogeologic unit			Hydrogeologic properties
Holocene to Upper Miocene	Undifferentiated surficial deposits		Discontinuous sand, clay, shell beds, and limestone	Surficial aquifer system			Sand, shell, limestone, and coquina deposits provide local water supplies.
Miocene	Hawthorn Group		Interbedded phosphatic sand, clay, limestone, and dolomite	Intermediate confining unit			Sand, shell, and carbonate deposits provide limited local water supplies. Low permeability clays serve as the principle confining beds for the Floridan aquifer system below.
Eocene	Upper	Ocala Limestone	Massive fossiliferous chalky to granular marine limestone	Floridan aquifer system	Upper Floridan aquifer		Principal source of ground water. High permeability overall. Water from some wells shows increasing salinity.
	Middle	Avon Park Formation	Alternating beds of massive granular and chalky limestone, and dense dolomite		Middle semiconfining unit		Low permeability limestone and dolomite.
					Lower Floridan aquifer	Upper zone	Principal source of ground water. Water from some wells shows increasing salinity.
						Semiconfining unit	Low permeability limestone and dolomite.
	Lower	Oldsmar Formation				Fernandina permeable zone	High permeability; salinity increases with depth.
Paleocene	Cedar Keys Formation		Uppermost appearance of evaporites; dense limestones	Sub-Floridan confining unit			Low permability; contains highly saline water.

Figure 2: Generalized geology and hydrogeology of northeastern Florida (modified from Spechler, 1994).

and is approximately 122 m (400 ft) in diameter (figure 3). The ocean floor immediately adjacent to the sinkhole is flat and is covered by loose quartz sand and shell. The sinkhole slopes downward at an angle of about 15 to 26 degrees from the ocean floor to a depth of about 41 m (134 ft). Holocene sediments of sand and shell (figure 4) are present from 27 to 34.5 m (88 to 113 ft). Outcrops of green Pleistocene sand and clayey sand are present from 34.5 to 41 m (113 to 134 ft). A very hard layer of dolomitic sandstone about 0.3 m (1 ft) thick crops out at 41 m (134 ft). The sandstone occurs as very pronounced ledges, and extends out 0.6 to 1.8 m (2 to 6 ft). From 41 to 116 m (134 to 380 ft), the sinkhole is a vertical shaft measuring about 45.5 m (150 ft) in width to *52* m (170 ft) in length. The upper walls of the shaft are developed in slightly indurated Pliocene shelly sand from about 41 to 50 m (134 to 164 ft). The walls are composed of moderately indurated silty sands and sandy silts from 50 to 63 m (164 to 206 ft). From 63 to 102 m (206 to 335 ft), the walls of the shaft are developed in clayey sands and sandy clays of the Upper Hawthorn Group (Miocene). Ledges were observed at depths of 73 and 97.5 m (240 and 320 ft). The ledge at 73 m (240 ft) does not reflect a change in lithology, therefore, it could be a wave cut terrace associated with a lower stand of sea level. The Lower Hawthorn Group consists of dolomitic limestone with phosphate pebbles and carbonate interclasts with phosphatic rims from 102 to 116 m (335 to 380 ft). From 116 m (380 ft) to the bottom of the sinkhole, the walls of the shaft are undercut. A rock sample collected at 114 m (375 ft) was identified as Hawthorn Group and another sample collected at 122 m (400 ft) was identified as Ocala Limestone (Eocene age.) A change in lithology was observed at 116 m (380 ft), and is assumed to be the top of the Ocala Limestone.

Depths to the bottom of the sinkhole were determined during two separate dives. The floor of the sinkhole on the south side (at a depth of 132.5 m (434 ft)) is relatively flat and sandy. Though visibility at the time of the dive was about 9 m (30 ft), the walls of the sinkhole were not visible. An attempt was made to locate the wall, but it was unsuccessful. A gently sloping sand floor occurs at a depth of 140 m (460 ft) on the northwest side. Further exploration indicated that the sinkhole floor continued to slope downward to a depth of 147 m (482 ft). Though no attempt was made to go deeper, the slope was seen and estimated to continue to a depth of 151 m (495 ft), where the floor terminated at the wall of the sinkhole.

The shape of the sinkhole at the base of the shaft was not determined in detail. Below a depth of 116 m (380 ft), divers observed that the northwest wall of the sinkhole is undercut about 24.5 m (80 ft). The diameter at the base of the shaft is estimated to be at least 91.5 m (300 ft) based on the assumption that the wall is undercut 24.5 m (80 ft) around the entire base of the sinkhole.

Of significant hydrologic importance was the observation of suspended particles in the seawater moving slowly toward small limestone caves in the Floridan aquifer system at the bottom of the sink. The velocity of the suspended particles was estimated to be 0.03 m/s (0.1 ft/s). The tidal cycle during the dive was at or near high tide, so inflowing seawater at this tidal stage seems hydrologically normal. Other divers also have reported observing a slight downward movement of water in the upper parts of the sinkhole (Wilcove, 1975). Currently, it is not known whether water discharges from these caves at low tide; however, this seems likely based on observations of discharge from other submarine caves such as the blue holes in the Bahama Islands (Palmer, 1989). The presence of these small

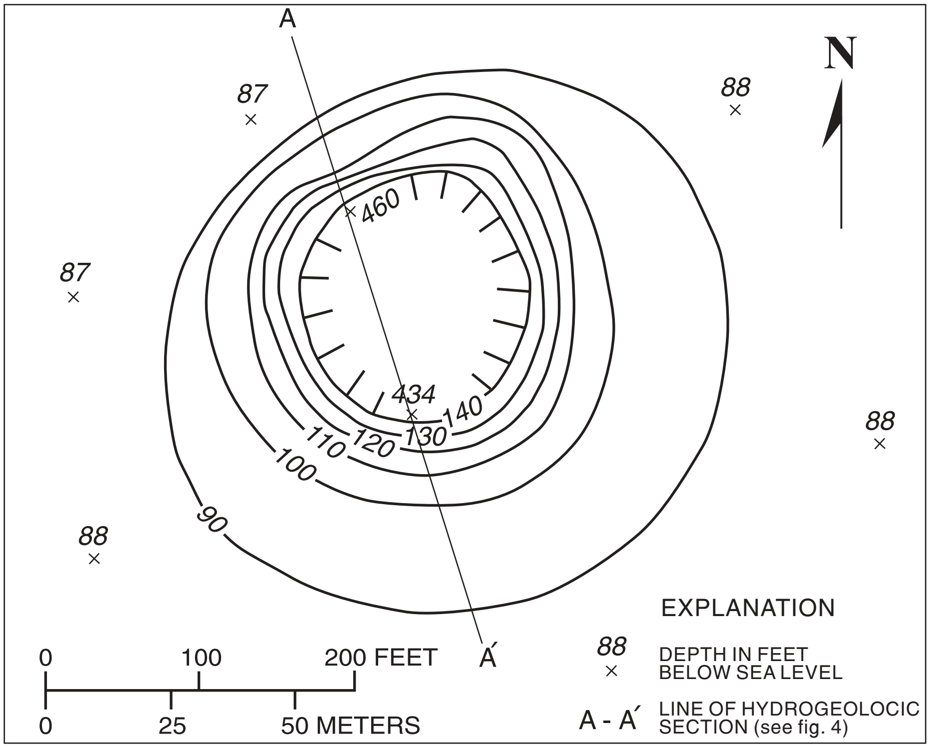

Figure 3: Bathymetric survey of Red Snapper Sink (modified from Popenoe and others, 1984).

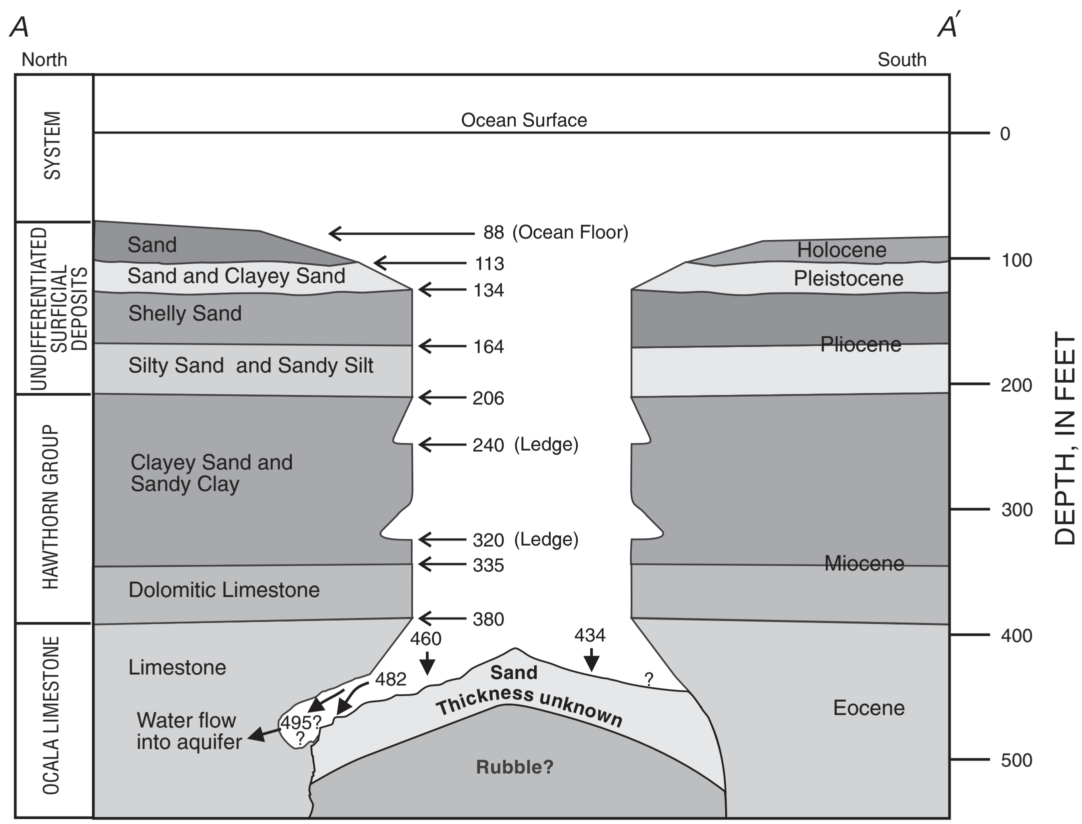

Figure 4: Profile and stratigraphy of Red Snapper Sink.

caves at the bottom indicates that the sinkhole is a high permeability pathway that can allow saline water to enter the Floridan aquifer system.

WATER QUALITY

A considerable volume of relatively fresh water is known to exist in the Upper Floridan aquifer off the coast of northeastern Florida. Analyses of water samples collected from the JOIDES J-1 test well (figure 1), 32 km (20 mi) east of Fernandina Beach and the Tenneco test well, 89 km (55 mi) east of Fernandina Beach, indicate that chloride concentrations in the Upper Floridan aquifer ranged from 675 to 1,025 mg/L and 1,000 to 7,000 mg/L, respectively (Wait and Leve, 1967 and Johnston and others, 1982). Chloride concentrations in recent water samples collected from the Crescent Beach Spring were about 3,600 mg/L (unpublished data in files of the U.S. Geological Survey, Altamonte Springs, Fla.). Freshwater springflow from Red Snapper Sink has been reported by mariners, but scientific expeditions to the sinkhole have confirmed no evidence of freshwater discharge.

Water samples were collected at the surface, 18.5, 91.5, 132.5, and 140 m (60, 300, 434 and 460 ft) to determine variations in the chemical quality of the water in the sinkhole with depth. All water samples were analyzed for chloride and sulfate in the laboratory (table 1). Specific conductance was determined in the field and in the laboratory.

Table 1: Chemical and physical analysis of water from Red Snapper Sinkhole. --, no data

Depth (feet below mean sea level)	Field specific conductance (microsiemens per centimeter)	Laboratory specific conductance (microsiemens per centimeter)	Chloride (milligrams per liter)	Sulfate (milligrams per liter)
Surface	52,000	52,300	20,500	2,900
60	52,000	52,500	20,600	2,900
300	53,600	52,400	20,700	2,900
434 (bottom)	53,600	52,400	20,700	2,900
460 (bottom)	--	52,400	20,500	2,900

Analyses of the water showed normal seawater salinities and little change in the chemical and physical properties with depth. Field specific conductance increased slightly with depth and ranged from 52,000 microsiemens per centimeter in the upper part of the water column to 53,600 microsiemens per centimeter at 132.5 m (434 ft). Laboratory values, however, showed no significant change with depth. Chloride concentrations ranged from 20,500 to 20,700 mg/L and sulfate concentrations were uniform at 2,900 mg/L.

CONCLUSIONS

Red Snapper Sink is a submarine collapse sinkhole on the continental shelf about 42 km (26 mi) east of Crescent Beach, Florida. The rim of the sinkhole is at a depth of 27 m (88 ft) and is about 122 m (400 ft) in diameter. Rock samples collected in the sinkhole show the top of the Pleistocene at 34.5 m (113 ft), the Pliocene at 41 m (134 ft), the Miocene (Hawthorn Group) at 63 m (206 ft), and the top of the Eocene (Ocala Limestone) at 116 m (380 ft). The sinkhole is a vertical shaft measuring about 45.5 m (150 ft) in width to 52 m (170 ft) in length at depths of 41 to 116 m (134 to 380 ft). The maximum recorded depth in the sinkhole is 147 m (482 ft). Although the bottom of the sinkhole was not explored in detail, it is estimated that the base of the shaft is at least 91.5 m (300 ft) in diameter. Water samples collected at the bottom of the sinkhole show normal seawater specific conductance and chloride and sulfate concentrations, indicating the absence of significant freshwater or brackish water discharge. During a dive to 147 m (482 ft), sea water was observed flowing into small caves along the base of the wall, indicating that during the dive period, the sinkhole conveyed saltwater into the Floridan aquifer system. Seismic profiles indicate that Red Snapper Sink is the surficial expression of a dissolution collapse feature possibly originating in Upper Cretaceous or Paleocene rocks. Similar, but buried, features on the Florida Peninsula could provide a hydraulic connection between freshwater zones and deeper, more saline zones of the Floridan aquifer system. The presence of such collapse features could help explain the anomalous distribution of elevated chloride concentrations in northeastern Florida, particularly in eastern Duval County.

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