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# Submarine karst belt rimming the continental slope in the Straits of Florida

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**Abstract** Nine submarine sinkholes have been surveyed and mapped with side-looking sonar and echo-sounder profiles in the Straits of Florida. These structures are irregularly distributed across the surface of the South Florida Margin, forming a discontinuous belt along the edge of the slope. The sinkholes occur in water depths too great to have ever been exposed above sea level, and some are several times larger than any known subaerial sinkholes in North America. Because most karst morphologies are the product of groundwater circulation, the distribution of submarine sinkholes in the Florida Straits may be directly related to the paleohydrology of the South Florida Platform.

## Introduction

Sinkholes, or dolines, are circular depressions which typically range from 10 to 1000 m in diameter and which are about 2 to 100 m deep (Sweeting 1973). They commonly result from dissolution by meteoric groundwater in subaerially exposed carbonate strata (Esteban and Wilson 1993). For this reason sinkholes are often used as indices of subaerial exposure (e.g., Schlanger and Silva 1986; Lincoln and Schlanger 1987; Van Waasbergen and Winterer 1993). Thus, when Jordan (1954) first reported submarine sinkholes on the Pourtales Terrace south of the Florida Keys (Fig. 1), he assumed that they formed during a Tertiary sea-level lowstand. Burnett and Gomberg (1977) concluded from petrologic and geochemical evidence that Tertiary limestones of the Pourtales Terrace had been subjected to freshwater diagenesis, and that submarine karst features observed there must have been caused by Miocene subaerial exposure.

Although Malloy and Hurley (1970) proposed a marine origin for the South Florida submarine sinkholes, based on their interpretation of regional subsidence history, until recently most workers have accepted this subaerial interpretation. However, the origin of these features has been controversial since they were first discovered, because they are at the maximum possible depth for exposure to have occurred given any combination of tectonic subsidence and eustatic sea-level fall (Fig. 2; Malloy and Hurley 1970; Mullins and Neumann 1979).

Because the calcium carbonate saturation curve is non-linear, dissolution of carbonate rocks can occur when two fluids of different salinities combine even if both parent fluids are supersaturated with calcium carbonate (Runnells 1969; Plummer 1975; Hanshaw and Back 1979; Sanford and Konikow 1989a, b). Thus, submarine sinkholes may be the products of freshwater/saltwater mixing. Limestone corrosion resulting from the mixing of fresh and saline waters is well documented at groundwater discharge sites in shallow-water areas (e.g., Back et al. 1984; Smart et al. 1988). The lack of unequivocal evidence for active carbonate dissolution in deeper submarine environments is the principal reason for the controversy over the origins of karst-like features in the Florida Straits.

### South Florida Slope

The continental slope off southeast Florida is interrupted by an intermediate-depth terrace, the surface of which coincides with a regional unconformity developed on Eocene–middle-Miocene strata. This erosional surface is exposed in the northern Straits of Florida as the Miami Terrace, and to the southwest as the Pourtales Terrace (Fig. 1). A post-Miocene sediment drape

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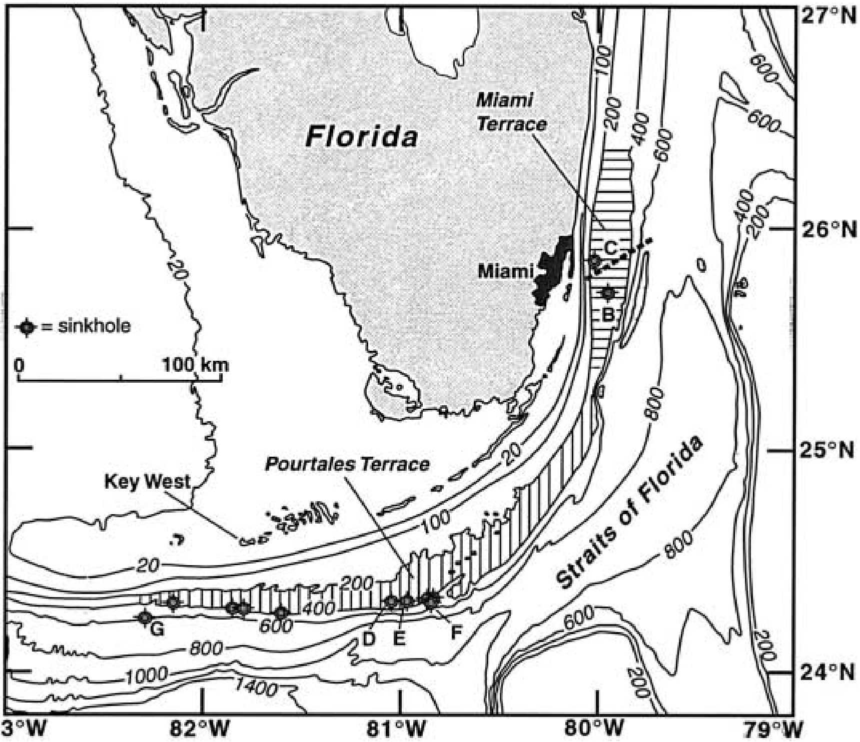


**Fig. 1** Bathymetry of the Straits of Florida and adjacent areas (contours in m at variable intervals). *Horizontal and vertical lines* Miami and Pourtales terraces, respectively. *B–G* Locations of sinkhole surveys in Fig. 4. *B* Key Biscayne Sinkhole, *C* Miami Sinkhole, *D* Jordan Sinkhole, *E* Jordan East Sinkhole, *F* Marathon Sinkholes, *G* NR-1 Sinkhole. Locations of other sinkholes are extracted from Jordan (1954), Jordan et al. (1964), and Malloy and Hurley (1970). *Closed contours* at the eastern end of the Pourtales Terrace indicate karst-like knolls (Jordan et al. 1964). *Dashed line* across Miami Terrace indicates location of Fig. 3

separates the two terraces off Key Largo. Eocene/Oligocene strata beneath these terraces are offshore extensions of the Floridan Aquifer (Fig. 2), an important artesian aquifer in the southeastern United States which also hosts the sinkholes of the north central Florida karst terrane (Stringfield 1966; Meyer 1989).

The Miami Terrace occurs at 200–400 m water depths at the foot of a slope of post-Miocene sediment offshore Miami. The surface of the terrace consists of Oligocene–Miocene phosphatic limestone (Uchupi and Emery 1967), and is marked by a very irregular karst-like topography (Fig. 3; Malloy and Hurley 1970; Neumann and Ball 1970; Mullins and Neumann 1979). The Pourtales Terrace, in the southern Straits of Florida, is the drowned southern end of the Florida carbonate platform, located at 200–450 m water depths (Fig. 1; Jordan et al. 1964; Burnett and Gomberg 1977). Eocene limestones of the Floridan Aquifer system are presumed to crop out at the margin of the Pourtales Terrace, based on correlation with exploratory boreholes drilled on Marquesas and Big Pine Keys (Maher 1971; Puri and Winston 1974). Several submarine sinkholes occur along the southwest margin of the terrace (Jordan 1954; Jordan et al. 1964; Malloy and Hurley 1970).

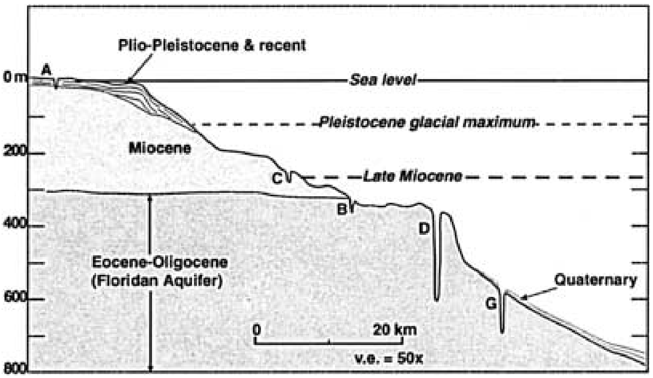


**Fig. 2** Idealized cross section of the Miami and Pourtales terraces, extracted from Malloy and Hurley (1970), and Miller (1986). *A–D*, *G* Depth (or elevation) of sinkholes in Figs. 1 and 4 (sinkhole A is not shown in Fig. 1). Because of the 50× vertical exaggeration (*v.e.*), relative depths only can be compared. The gentle slope of the escarpment is characteristic of the extreme western end of the Pourtales Terrace where the NR-1 sinkhole (*G*) occurs near the base of the escarpment in a Quaternary sediment drape

In the 1960s through 1980s, Kohout and others published a series of papers (Kohout 1965, 1967; Kohout et al. 1977, 1988) documenting evidence for a type of open-cycle thermal convection occurring within artesian aquifers of south Florida, now commonly referred to as Kohout convection (Simms 1984). According to Kohout's model, cool seawater in the Florida Straits invades highly permeable limestones of the Tertiary Floridan Aquifer at its submarine outcrop and flows inland. Geothermal heating increases the buoyancy of the encroaching seawater, causing it to migrate upwards where it becomes entrained with regional flow of fresh groundwater toward the coast. The mixture of fresh and saline waters ultimately discharges from submarine springs on the shelf and along the shelf edge. Kohout hypothesized that submarine karst phenomena in the northern Straits of Florida are the result of

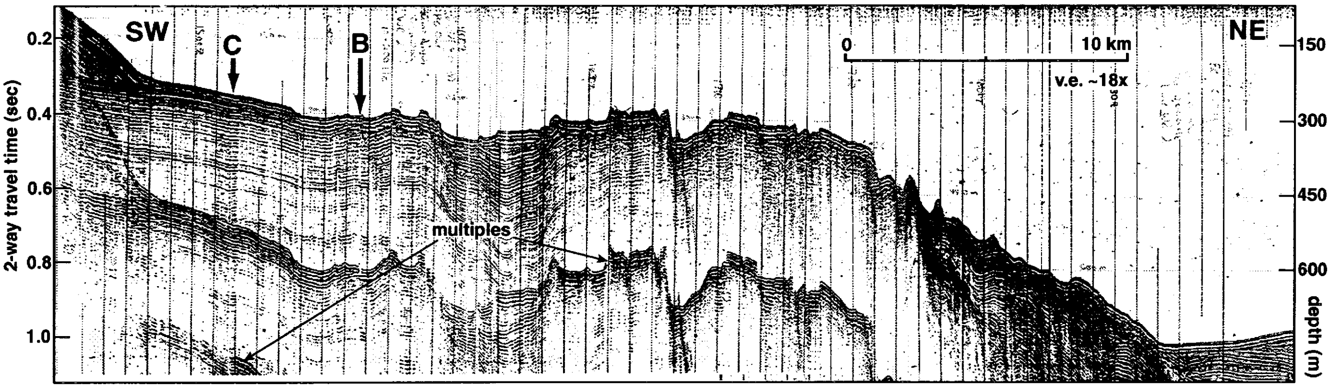


**Fig. 3** Seismic reflection profile WR-2 (RV Gyre, 1980, US Geological Survey) illustrating the irregular, karst-like morphology of the Miami Terrace (see Fig. 1 for location of profile). *Arrows* Approximate positions of Key Biscayne (*B*) and Miami (*C*) sinkholes along the profile. *v.e.* Vertical exaggeration

mixing-zone dissolution at sites of groundwater discharge. However, Kohout's model is based primarily on negative geothermal gradients observed in onshore boreholes, and there is little hydrologic information available on the discharge end of his hypothetical circulation system.

Land et al. (1995) identified a sinkhole at the foot of the Pourtales Escarpment (now named the NR-1 Sinkhole) at water depths greater than 600 m – too deep to have been subaerially exposed at any time during the Neogene. This discovery supports a marine origin and was the stimulus for additional surveys, the principal objective of which has been to investigate the role of submarine groundwater discharge in creating and maintaining these sinkholes. If submarine sinkholes in the Florida Straits are the product of groundwater advection, they may provide fundamental information about the paleohydrology of the South Florida Platform.

## Data acquisition

A series of seafloor surveys were conducted in October 1994 and May 1995, using the US Navy NR-1 nuclear submarine. The NR-1 is equipped with 177.5 kHz side-scan sonar, 7 kHz seismic profiler and a 25 kHz narrow-beam echo-sounder which are displayed on a paper record produced by a Raytheon flat-bed recorder. The NR-1 also has an obstacle avoidance sonar (OAS) display which provides a detailed three-dimensional picture of the surrounding topography on a CRT screen. However, except for an occasional frame which is captured on video film, the OAS data are not recorded. The NR-1 operates with an inertial navigation system but OAS images were used for reconnaissance. After a depression on the seafloor was identified with OAS (appearing as a circular or oval feature on the monitor), the NR-1 collected side-scan sonar, seismic and echo-sounder data in a grid, maintaining a constant depth along each profile of ~50 m above the seafloor adjacent to the sinkholes. The NR-1 is equipped with a large bow wheel which allows it to roll along the bottom in areas of moderate current and gentle topography. Visual observations of the seafloor are made from the three forward viewports of the submersible, and documented with an electronic still camera, 8 mm film and VHF videotape.

Conductivity-temperature-depth (CTD) data were collected throughout the surveys. Because the CTD sensor is positioned on the sail of the NR-1, it records relatively low-resolution water-column data, and it is not well located or calibrated for making precise measurements of temperature or salinity near the seafloor. No marked variations in temperature or salinity were observed during crossings over any of the sinkholes. Representative temperature and salinity values for each survey are given in Table 1.

## Results

### Miami Terrace

Two sinkholes were surveyed and mapped on the Miami Terrace (Fig. 1). The one is located ~17 km east of Key Biscayne, and is referred to hereafter as the Key Biscayne Sinkhole. The other, located ~8 km east of Miami Beach, is referred to as the Miami Sinkhole (locations, water depths, and dimensions of all surveyed sinkholes are shown in Table 1).

### *Key Biscayne Sinkhole*

The Key Biscayne Sinkhole has an asymmetrical outline and overall teardrop shape (Fig. 4B), with a deep, funnel-shaped center and an elongate, shallow extension to the north. The seafloor around the margin of the sinkhole has a soft sediment cover ~1 m thick, based on observations made above outcropping strata at the edge of the hole. The gentle north flank is defined by angular outcropping ledges with ~1–5 m of relief (Fig. 5). Undercutting of the outcrop has resulted in the slumping of angular blocks into the sinkhole. The NR-1 submarine traversed down the north flank to a depth of 348 m, at

**Table 1** Sinkhole dimensions and properties

| Sinkhole | Latitude | Longitude | Water depth (m) | Relief (m) | Long axis (m) | Short axis (m) | Asymmetry[a] | Salinity[b] (‰) | σ (‰) | Temperature[b] (°C) | σ (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Key Biscayne | 25°42.2′N | 79°58.6′W | 335 | 35 | 350 | 190 | 1.84 | 35.29 | 0.10 | 8.15 | 0.16 |
| Key Biscayne, interior | | | | | | | | 35.21 | 0.07 | 8.16 | 0.11 |
| Miami | 25°51.5′N | 80°01.9′W | 244 | 31 | 480 | 340 | 1.41 | 35.34 | 0.10 | 8.46 | 0.22 |
| Jordan, west lobe | 24°16.4′N | 81°02.2′W | 350 | 260 | 680 | 560 | 1.21 | 35.49 | 0.11 | 9.87 | 0.34 |
| Jordan, east lobe | 24°16.4′N | 81°01.9′W | 350 | 170 | 800 | 720 | 1.11 | | | | |
| Jordan East | 24°16.1′N | 80°58.9′W | 378 | 61 | 960 | 640 | 1.5 | 35.59 | 0.11 | 10.52 | 0.69 |
| Marathon North | 24°15.4′N | 80°54.1′W | 460 | 64 | 480 | 280 | 1.71 | 35.32 | 0.10 | 8.74 | 0.46 |
| Marathon South | 24°15.2′N | 80°54.3′W | 460 | 61 | 860 | 400 | 2.15 | | | | |
| NR-1 | 24°13.9′N | 82°18.2′W | 575 | 120 | 440 | 400 | 1.1 | ~35.1 | | 8.25 | |
| Unnamed | 24°15.5′N | 80°55.1′W | 495 | 32 | | | | | | | |
| Winter Park | 28°35′N | 81°21′W | Subaerial | 30 | 106 | | | | | | |
| Dean's Hole | 23°30′N | 75°W | | 202 | | | | | | | |
| Cay Sal Bank bluehole | ~23°55′N | ~80°20′W | ~125 | 100 | | | | | | | |

[a] Asymmetry is the ratio long axis/short axis

[b] Salinities and temperatures are mean values for each survey (with standard deviation σ)

**Fig. 4A–G** Bathymetry of selected sinkholes (all sinkholes are at the same horizontal scale; contour interval (*CI*) is 10 m except in **D** where *CI* is 25 m). **A** Winter Park Sinkhole, a subaerial sinkhole located in Orange Co., Florida, about 300 km north of Miami, is shown for comparison (contours in meters above sea level; topographic data from Jammal 1984). **B** Key Biscayne Sinkhole, **C** Miami Sinkhole (slump blocks are shown by *closed contours* around the margin of the hole), **D** Jordan sinkhole complex (note that the easternmost sinkhole is only defined by one survey line), **E** Jordan East Sinkhole, ***F*** Marathon Sinkholes, **G** NR-1 Sinkhole (locations of sinkholes **B**–**G** are shown in Fig. 1). *Faint dashed lines* Path of the NR-1 submarine during survey operations. *Heavy dashed line* Location of Fig. 6

which point the sinkhole narrows significantly and investigations at greater depths became impossible. No evidence of significant infilling was observed during the descent.

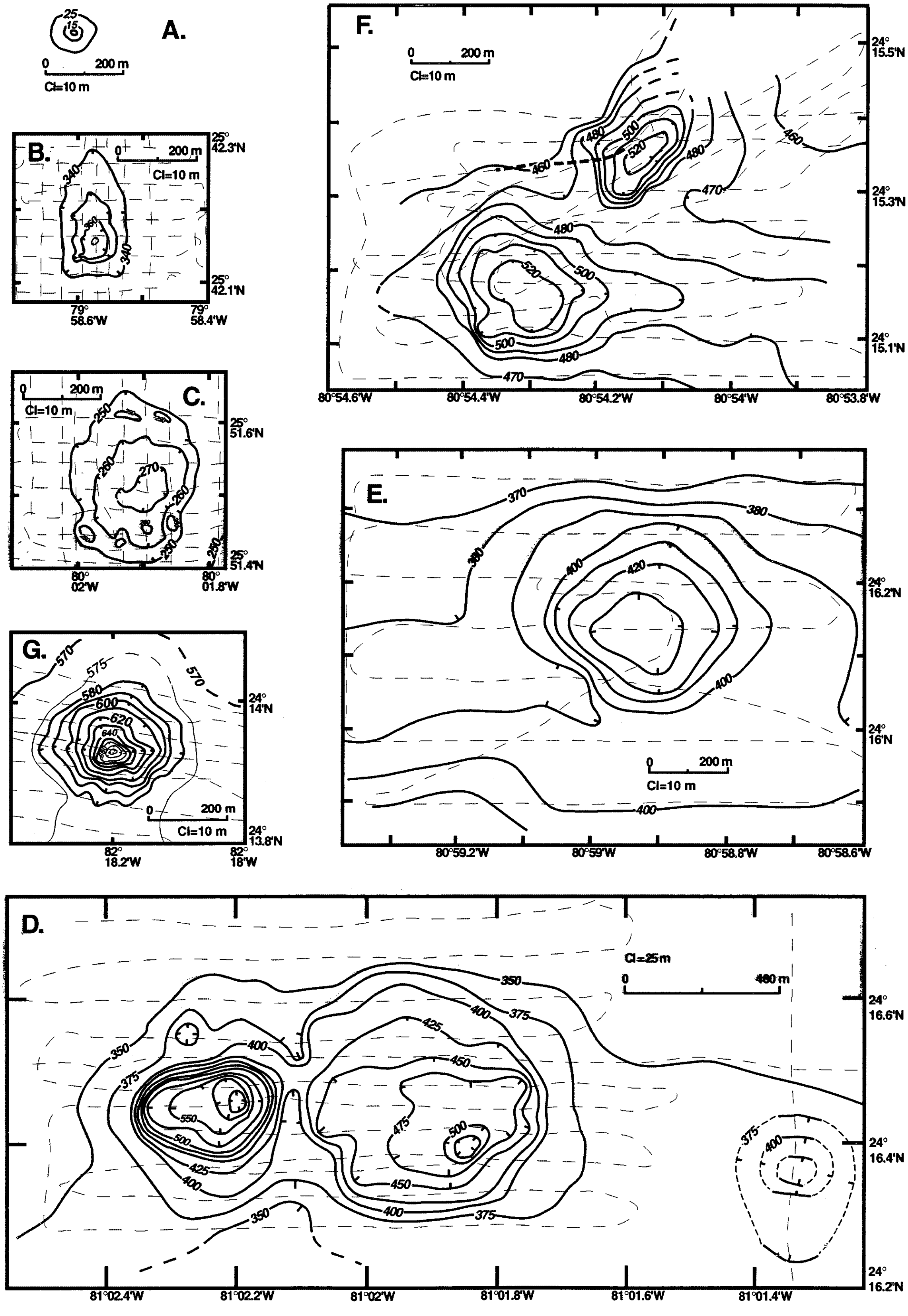
## *Miami Sinkhole*

The margin of the Miami Sinkhole (Fig. 4C) is sharply defined around most of its perimeter by an abrupt scarp with ~2–5 m of relief, below which the inner flanks have a fairly gentle slope. The outcrop along the edge of the sinkhole consists of angular ledges which have a pitted, vuggy texture in places, suggestive of bioerosion (Neumann 1968) although few benthic organisms were observed. Some of the ledges had been significantly undercut. Several large blocks of limestone, some up to 10 m in length, had evidently broken off the upper ledges and fallen into the sinkhole. The floor of the sinkhole is nearly horizontal, and largely covered with sediment. Northward sediment transport is indicated by sediment drape over the south flank, and also by a layer of metal beverage cans which have accumulated parallel to the northwest margin of the sinkhole and just below the outcropping scarp.

## Pourtales Terrace

Four sinkholes were surveyed on the Pourtales Terrace, about 50 km south of Vaca Key (Fig. 1). The Jordan Sinkhole, so named because it was first reported by Jordan et al. (1964), is located near the apex of the Pourtales Terrace. The Jordan East Sinkhole (our nomenclature) is located about 5 km east of the larger Jordan Sinkhole. Two additional sinkholes, referred to as the Marathon Sinkholes because of their location ~60 km south of the town of Marathon on Vaca Key, were first identified by Malloy and Hurley (1970) in their bathymetric map of the southern Straits. In addition, at least half a dozen sinkhole-like depressions (not surveyed) were observed in OAS records at the margins of these survey areas and during transits between the sites.

The NR-1 Sinkhole (Fig. 1) is located near the base of the Pourtales Escarpment about 40 km south of Marquesas Keys at the extreme western end of the southern Florida Straits (US Geological Survey and


A.
25
15
0 200 m
CI=10 m
B.
0 200 m
CI=10 m
340
360
25° 42.3'N
25° 42.1'N
79° 58.6'W
79° 58.4'W
C.
0 200 m
CI=10 m
250
260
270
25° 51.6'N
25° 51.4'N
80° 02'W
80° 01.8'W
G.
570
575
580
600
620
640
0 200 m
CI=10 m
24° 14'N
24° 13.8'N
82° 18.2'W
82° 18'W
F.
0 200 m
CI=10 m
460
470
480
500
520
24° 15.5'N
24° 15.3'N
24° 15.1'N
80°54.6'W
80°54.4'W
80°54.2'W
80°54'W
80°53.8'W
E.
370
380
400
420
0 200 m
CI=10 m
24° 16.2'N
24° 16'N
80°59.2'W
80°59'W
80°58.8'W
80°58.6'W
D.
CI=25m
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350
375
400
425
450
475
500
550
24° 16.6'N
24° 16.4'N
24° 16.2'N
81°02.4'W
81°02.2'W
81°02'W
81°01.8'W
81°01.6'W
81°01.4'W

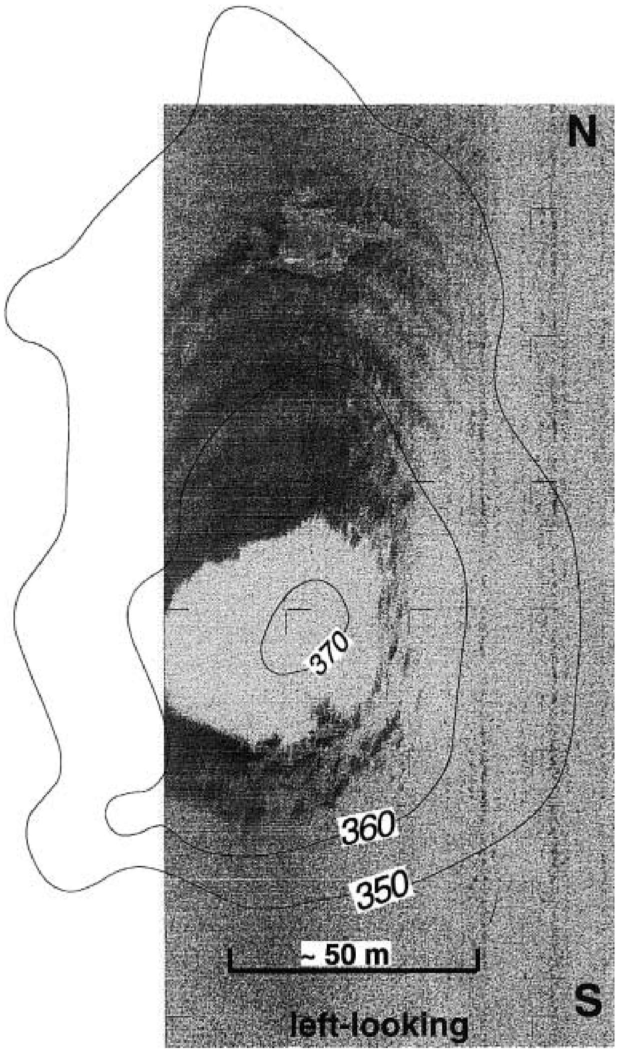

**Fig. 5** Side-scan sonar image of Key Biscayne Sinkhole. *Concentric reflectors* on the northern margin of the hole are caused by stratified outcrop, presumably limestone. The *light circular area* in the center of the sinkhole is caused by sonar shadow due to increased steepness of the interior walls, an indication of its funnel-shaped morphology

National Ocean Service 1989a). This sinkhole was originally surveyed in October 1994, and is described in Land et al. (1995).

### *Jordan Sinkhole*

Data acquisition across the Jordan Sinkhole (Fig. 4D) was complicated by the size of the feature which is several hundred meters wider than the NR-1's side-scan sonar footprint (~200 m). Because of the depth and steep interior walls of the hole, echo-sounder records taken during central crossings show numerous side echoes which obscure the actual bottom reflections. Thus, the observed bathymetry of the sinkhole should be considered as representing minimum depths.

The Jordan sink lies directly beneath the Gulf Stream and, coupled with powerful updrafts of ~0.5 knots (25 cm/sec) from the hole (NR-1 officers, personal communication), strong currents prevented operations being conducted closer than 50 m above the seafloor. Preliminary observations suggest that the updrafts are probably a turbulence effect caused by current flow across the mouth of the sinkhole. Thus, visual observations were impossible during most of the survey because of our inability to make a close approach to the sinkhole. However, some seafloor lineations were observed oriented perpendicular to the margin on the west edge of the sinkhole complex.

The general morphology of the Jordan Sinkhole, similar to a 1.2-km-long, E-W-oriented figure eight, indicates that it consists of two partially merged sinkholes (Fig. 4D). Within the broad outer depression are two roughly circular, steep-walled inner depressions, separated by a narrow ridge which rises to within 30 m of the surrounding seafloor. The west lobe is narrower and deeper (Table 1), and has a more pronounced funnel shape than the east lobe. Side-scan sonar records indicate the presence of secondary ledges at intermediate depths within the west lobe.

The Jordan complex includes a third sinkhole ~500 m east of the main depression (Fig. 4D). Since it was crossed by one survey line only, its shape was not well established in the present study.

### *Jordan East Sinkhole*

The Jordan East Sinkhole has a shallow, bowl-shaped profile (Fig. 4E), contrasting strongly to the deep, steep-walled depressions of the Jordan Sinkhole complex. The margins slope gently down to a relatively flat bottom which is partially covered with rippled sand. Sediment cover is patchy and, in places, the sinkhole floor consists of a rubbly pavement. The margin of the sinkhole consists of a <1-m-thick bed, presumed to be limestone, which has a weathered appearance and appears to be manganese-phosphate coated. The outcrop is covered in places by unconsolidated sediment.

### *Marathon Sinkholes*

The North and South Marathon sinkholes (Fig. 4F) occur at the outermost edge of the Pourtales Terrace, near the slope break at ~500 m water depth (US Geological Survey and National Ocean Service 1989b). The seafloor at the southwest margin of the North Marathon Sinkhole is marked by a pronounced NW-SE fabric (Fig. 6) which probably represents outcropping strata on the outer edge of the terrace. Strong updrafts were again experienced during crossings, which caused erratic movements and degraded the quality of the side-scan sonar records. An abrupt loss of buoyancy occurred during the final crossing over the South Marathon Sinkhole.

During the transit to the Marathon site, another sinkhole was identified ~900 m west of North Mara-

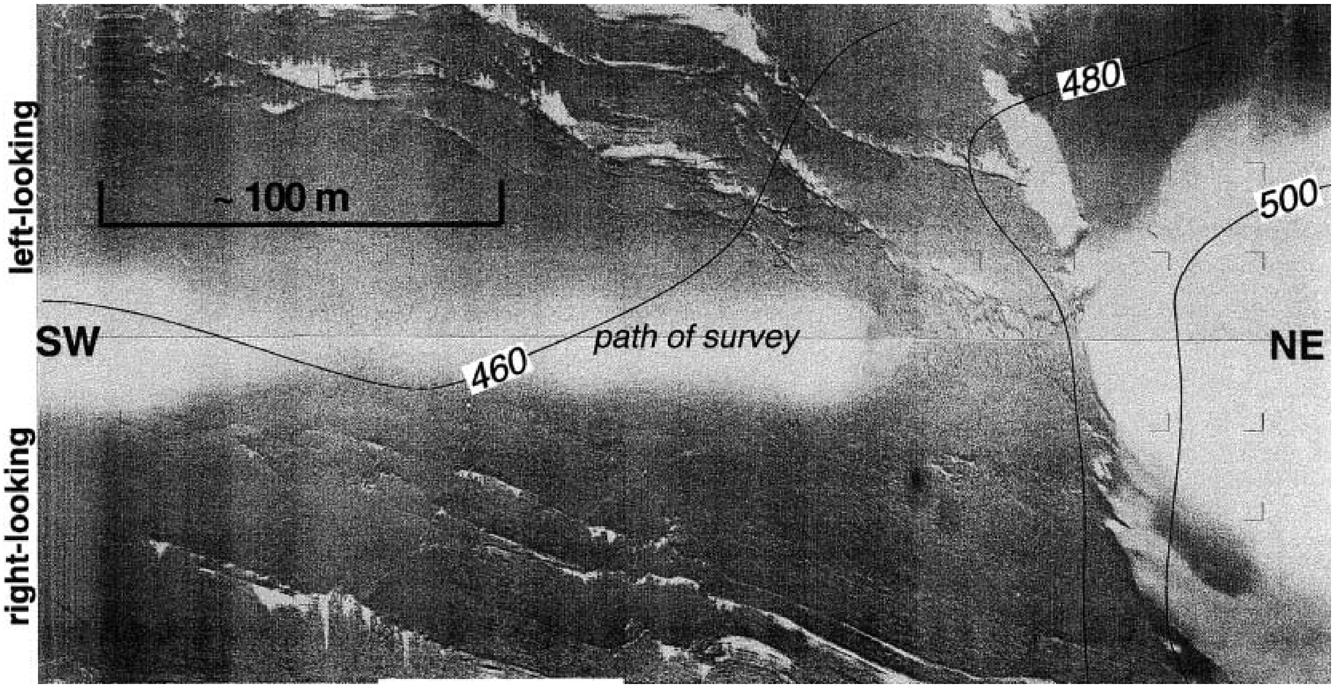

**Fig. 6** Side-scan sonar image of the seafloor adjacent to the Marathon Sinkholes. The southwest margin of the northern sinkhole is indicated by the *light area* on the right, caused by sonar shadow in the interior of the hole. The *bright*, *subparallel linear features* trending NW-SE probably represent bedded limestone outcrop

thon. Although there was insufficient time to conduct a detailed survey, approximately four additional sinkholes were observed on the OAS screen as the NR-1 submarine lifted off bottom and prepared to surface.

### *NR-1 Sinkhole*

The NR-1 Sinkhole (Fig. 4G) is developed in a late-Quaternary drape of pelagic carbonate sediment ~10 m thick on the gentle lower slopes of the Pourtales Escarpment (Figs. 1, 2; Brookes and Holmes 1989). The interior of the sinkhole consists of outcropping ledges, expressed as a series of concentric reflectors on the side-scan sonar record (Land et al. 1995). Regional stratigraphic correlations (Maher 1971; Puri and Winston 1974) indicate that the NR-1 Sinkhole is probably rooted in Eocene strata of the lower Floridan Aquifer (Fig. 2).

## Discussion

The southwest margin of the Pourtales Terrace is ornamented by a chain of sinkholes which extends for ~100 km off the lower Florida Keys. The eastern end of the terrace is marked by a band of karst-like topography consisting of paired knolls and depressions extending an additional 55 km to the northeast (Jordan et al. 1964; Malloy and Hurley 1970). If the smaller sinkholes surveyed on the upper Miami Terrace are genetically related to the karst features on the Pourtales Terrace, their presence suggests that a discontinuous belt of submarine karst extends along the southeast margin of the Florida Platform for over 350 km.

### Sinkhole morphology

The surveyed sinkholes vary in size, shape, and geological setting. Sinkholes on the Miami Terrace are similar in size to subaerial sinkholes of central Florida (e.g., the Winter Park Sinkhole), whereas sinkholes on the Pourtales Terrace are wider and deeper than onshore sinkholes (cf. Table 1, Fig. 4). The Jordan Sinkhole, with 206 m of vertical relief, is an order of magnitude deeper than most subaerial sinkholes currently exposed on the Florida Platform, which average only 8 m in depth (Troester et al. 1984). For example, the notorious Winter Park Sinkhole (Fig. 4A), which swallowed a house and several cars when it breached the surface northeast of Orlando in 1981, is only 30 m deep (Jammal 1984). The difference in size may result in part from thickness of overburden. All sinkholes on the Florida Platform are rooted in Tertiary limestones, but the majority of onshore sinkholes are formed in a siliciclastic mantle up to 150 m thick overlying the Tertiary strata (Arrington and Lindquist 1987). Most of the Florida Straits sinkholes (with the exception of the NR-1 sinkhole) are developed in Tertiary limestone outcrop covered by a thin (<3 m) veneer of post-Miocene sediment. The circular shape and high degree of symmetry of the NR-1 Sinkhole may be related to its occurrence in an unconsolidated pelagic sediment drape (Brooks and Holmes 1989).

Although sinkholes formed in tropical karst regions (e.g., Puerto Rico, Jamaica) tend to be somewhat larger and deeper than those found in temperate areas, they still average < 30 m in depth (Troester et al. 1984). The only subaerial karst features in North America comparable to the Pourtales Terrace sinkholes are vertical solution shafts in caves, some of which are reported to exceed 100 m in depth in the Appalachian Mountains of the southeastern United States (Troester et al. 1984).

The Pourtales Terrace sinkholes are similar in scale to blueholes which are common features of the Bahamas Platform and Caribbean islands. The deepest reported bluehole in the Bahamas, Dean's Hole on Long Island, is 202 m deep (Shinn et al. 1996). Blueholes are thought to be subaerial solution features which formed on the edge of carbonate platforms during Pleistocene sea-level lowstands (Gascoyne et al. 1979). The platform-margin position of most blueholes may be the result of fluid circulation through "free-face" extensional fractures which are formed by uncompensated lithostatic pressure at the near-vertical face of the margin (Daugherty et al. 1986). Blueholes along the margins of carbonate platforms can result in complex hydrological variations within the platform. On Andros Island, Bahamas, Whitaker and Smart (1990, 1997) demonstrated that blueholes are an important component of the coastal hydrological system, providing conduits for fluid exchange between groundwater and oceanic waters. The submarine sinkholes on the opposite side of the Straits of Florida may play a similar role in the hydrology of the South Florida Platform.

## Sinkhole history

All of the surveyed sinkholes occur at water depths too great to have been exposed during the Pleistocene when maximum sea-level lowstand was ~125 m below present (Vail and Mitchum 1978; Fairbanks 1989). The last significant global regression prior to the onset of Plio-Pleistocene glaciation occurred ~10 Ma ago in late-Miocene times (Hallam 1992) when sea level was 75–125 m below present (Lincoln and Schlanger 1987). Freeman-Lynde et al. (1981) estimate that regional subsidence during the Cenozoic was 20 m/Ma. This combination of subsidence and sea-level history places the late-Miocene shoreline ~300 m below its present position. Most of the sinkholes discussed in this paper would be a few tens to hundreds of meters below Miocene sea level, and arguably too deep to have originated in a subaerial setting.

The morphology and sedimentation record of the surveyed sinkholes suggest that some of these features are still active. Some of the sinkholes are deep, narrow and steep-walled, a morphology which implies recent activity, while others have relatively flat floors carpeted with sediment, indicating that they are now acting as sediment catchment areas. If the sinkholes are simply relicts of Tertiary subaerial exposure, they must have remained unfilled during and after subsequent Plio-Pleistocene transgressions across the exposed terrace, which we think is unlikely. Shinn et al. (1996) surveyed a sinkhole formed in Pleistocene limestone off Key Largo at 5–7 m water depths which is completely filled with sediment, and calculated a fill rate of ~25 m/ka. If this value is typical of sedimention rates in a shallow platform setting, then the absence of complete infilling of the Florida Straits sinkholes supports a marine origin for these features, and possibly recent activity.

## Sinkhole distribution and origin

During our survey of the Pourtales Terrace, we identified a chain of at least seven sinkholes lining the rim of the terrace. At the end of the dive series we transited 20 km to the northwest across the surface of the terrace, yet no sinkholes were observed in the OAS records. Almost all previously reported sinkholes (Jordan 1954; Jordan et al. 1964; Malloy and Hurley 1970) also occur near the edge of the Pourtales Terrace, indicating that sinkholes in the southern Straits of Florida are not randomly distributed but are preferentially located at the terrace margin.

The presence of a belt of sinkholes rimming the slope in the Straits of Florida may reflect past or present hydrological patterns on the South Florida Platform. Potentiometric maps of the upper Floridan Aquifer suggest groundwater flow to the south and southeast (Meyer 1989). At the downgradient end of the flow system, zones of freshwater/saltwater mixing should develop within the aquifer at discharge sites along the South Florida Slope. Submarine karst morphologies on the Miami and Pourtales terraces may thus represent past or present mixing zones where limestone dissolution and solution-collapse processes are enhanced (e.g., Plummer 1975; Back et al. 1984). This model is supported by the linear distribution of sinkholes in the southern Straits. While karst terranes which form on land above a near-horizontal water table are laterally extensive, submarine karst which forms within a mixing zone should produce a relatively narrow, linear belt of solution features.

If groundwater discharge is occurring along the south Florida continental slope, advective rates are probably modest given the present relatively low hydraulic head (Meyer 1989). However, late-Miocene or Pleistocene sea-level lowstands would result in an elevated head, stimulating artesian flow of groundwater out of the aquifer (Meisler et al. 1984; Land 1999). Some of the larger sinkholes may thus have originated in a submarine setting in late-Miocene times, and continue to serve as conduits for fluid exchange between the Floridan Aquifer and seawater in the Straits of Florida. Mixing-zone dissolution at sites of fluid exchange would serve to maintain and enlarge pre-existing sinkholes, as well as forming new ones. The smaller sinkholes surveyed on the Miami Terrace may be younger features, formed during the Pleistocene or Holocene.

Seawater encroachment into onshore aquifers is presently occurring in parts of south Florida (Meyer 1974; Kohout et al. 1988). Thus, regardless of their age, the Florida Straits sinkholes represent potential entry points for saltwater invasion of south Florida aquifers.

## Conclusions

We infer that the submarine sinkholes identified in the Straits of Florida formed entirely in the submarine environment. Since the Florida Straits sinkholes are rooted in Tertiary limestones of the Floridan Aquifer, they may be an important component of the discharge end of the south Florida hydrological system.

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