SEDIMENTOLOGICAL EFFECTS OF STRONG SOUTHWARD FLOW IN THE STRAITS OF FLORIDA

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Abstract


Periodic southerly currents along the western side of the Straits of Florida are sufficiently strong to erode the seafloor and create large sand waves and coral mounds up to several meters high. Mapping with side-looking sonar and visual observations from the Nuclear Research Submarine NR-1 show that the sand waves are confined to an area about 2 km wide, but over 70 km long. Southerly currents in excess of 50 cm s⁻¹ were measured during our dives, and the size of the bedforms and grain size of sediments suggests currents could attain velocities of 100 cm s⁻¹. The eastern boundary of the sand waves terminates abruptly with an erosional cliff or a series of erosional steps, grades to a zone of nondeposition and then to an area of sediment accumulation. In the central Straits are regions of ripples, megaripples and small coral mounds that indicate persistent flow to the north.

Chemical as well as current erosion appears to be altering the seafloor on the southern side of the Northwest Providence Channel, which feeds into the Straits of Florida. Relict lithoherms are abundant in this channel, but they are much smaller than those observed further north in the Straits of Florida. Bedforms and current measurements show a strong northwest flow in the channel along the south wall.

Introduction

Since the first suggestion by Pillsbury (1891) of deep-current reversals in the Straits of Florida, several studies have confirmed the existence of periodic southward flow. Use of the dynamic method by Wüst (1924) indicated a deep, southward flow in the straits. Photographs on the central floor of the straits showed sand ripples which could only have been formed by southward flow (Hurley and Fink, 1963). Submersible observations revealed well-defined ripples and sedimentary structures indicative of southward flow that were further confirmed by short-term current measurements (Newmann and Ball, 1970), although early measurements suggested the southward flow was weak (Richardson et al., 1969). Using profiling current meters, a periodic, deep, southward flow has been confirmed and, as Pillsbury had suggested, was found to occur only on the western side of the straits (Düing and Johnson, 1971, 1972; Düing, 1973, 1975).

Southward currents reached a maximum speed of 87 cm s⁻¹ at a water depth of 750 m (Station P, Fig.1), while the maximum northward speed at that depth was 30 cm s⁻¹ (Düing, 1975). The period of flow reversal was typically four to six days, and the fluctuations appear to be caused by barotropic continental shelf waves generated by atmospheric forcing.
Despite the high southward velocities during the flow reversals (Fig.2), the net northward transport of the Florida current decreased by less than 10% (Düng, 1975). This agrees well with the ±10% seasonal and interannual variability measured in the total transport of the Florida current (Schmitz and Richardson, 1968; Schott and Zantopp, 1984). No evidence of southward flow has been found in studies to the north of our area along 27°N (Molinari et al., 1983; Lee et al., 1984).

The volume transport may not be drastically affected by the flow reversals, but the strong southward velocities and resulting bed shear stresses are sufficient to cause significant sediment transport. When transport occurs, evidence can be left in the form of ripples, sand ribbons, sand waves, and other bedforms. Mapping these features provides information about the extent, direction and intensity of flows sufficient to cause sediment transport.

Methods

The Nuclear Research Submarine NR-1 was used in the northern Straits of Florida to identify and map bedforms while acquiring acoustic, optical, hydrographic, and current velocity data. The greatest advantage of the NR-1 over submersibles is its ability to conduct longer dives and to cover greater horizontal distances while taking underway measurements (Gardner et al., 1979). Sonographs from side-looking sonar (SLS) are generated while traversing a fixed distance above the seafloor (usually 50 or 100 m) simultaneously with 25 kHz and 3.5 kHz bottom and subbottom echosounders. The paper advance rate of the SLS recorder is proportional to the ship’s speed to remove distortions in the sonographs. Bottom-Doppler navigation allows the submarine to return to specific targets on the SLS for further investigation. A total of 42 dives were made to the seafloor in 8 days. Dives lasted between 0.5 and 7 h for a total of 79 h of bottom observations.

Instantaneous current velocities were measured with an electromagnetic (EM) sword mounted on the NR-1. Bottom-Doppler navigation recorded movement of the submarine with respect to the seafloor. Vector subtraction yields true horizontal water velocities with respect to the seafloor. The electromagnetic sword was calibrated by running a measured mile in opposite directions. The speed error at low cruising speeds (3%) was corrected by the instrument’s sensitivity function; errors at higher speeds (12–17%) were handled by a mathematical correction factor (General Dynamics, 1970). No estimate of the direction error is available; however, the EM sensor
is positioned to minimize errors due to turbulence around the submarine.

Position, direction, depth, height off bottom, velocity, water velocity, and many other parameters were recorded every 6.7 s. Sonographs and echosounding were continuous between dives. Photographs were taken through the viewports and external video cameras were actuated during dives to the

bottom. Throughout the operation, the USS Pensacola conducted surveys including XBT sections and camera and coring stations.

**Regional setting**

The Florida peninsula, including the Straits of Florida, is part of a subsiding carbonate platform (Malloy and Hurley, 1970). Strati-
Fig. 3. Track lines of the NR-1. Numbers indicate bottom stations. Note the regions of the Miami Terrace, Escarpment and Trough, depositional anticline (dive 10), and the central straits (dives 1-7, 30). Lettered segments are side-looking sonographs referred to in the text. Solid lines across the submarine track are boundaries between fields of different bedforms as shown in Fig. 24. Line A down the Escarpment is the track of DSRV Aluminaut dive by Newman and Ball (1970).

Graphic data from wells near Miami indicate that the Miami Terrace is composed of Oligocene to Miocene limestone (Uchupi, 1966). The unconsolidated sediments found throughout most of the Straits of Florida are fine-grained (sand size and smaller) carbonates over a hard substrate. Carbonate sands (pteropod and foraminiferal) are found in the western portions of the straits. Limestone rock outcrops are seen along the escarpments.

The Northern Straits are a continuation of the Southern Straits, being a passage for water from the Gulf of Mexico into the Atlantic. The origin of the Northern Straits has been attributed to tectonics, erosion, subsidence and bank accretion with nondeposition in the axis, whereas the main means of formation of the Southern Straits between Florida and Cuba is tectonic (Malloy and Hurley, 1970). Some faulting may occur in the Northern Straits.
Fig. 4. Bottom photographs taken through the submarine viewports. a. Coral on top of coral mounds in both the central straits and in the large coral mounds in the Miami Trough; white coral is living, dark coral has died and is being buried by sand trapped by the coral. b. Between the coral mounds the bottom is current swept with streaks of sand covering a hard bottom. c. and d. Ripped sand ribbons ended abruptly and changed to current-swept bottom. e. The depositional anticline (dives 8 and 10) has a soft bottom with animal mounds and burrows.
causing the steep scarp at the edge of the Miami Terrace (Uchupi, 1966) but the previously mentioned means of formation are dominant.

The Northern Straits of Florida form a passage which separates Florida from the Bahamas. The bathymetric features of the Straits of Florida from east to west consist of the Bimini Escarpment, the central floor of the straits, a depositional anticline, the Miami Trough, the Miami Escarpment, and the Miami Terrace (Figs. 1 and 3).

Results

Although the major large-scale features of the Straits of Florida have been described in the literature, only occasional data exist on the distribution of small-scale surface bedforms. These small-scale bedforms can be valuable in determining the intensity and direction of near-bottom currents (Hollister and Heezen, 1972). Mapping the distribution of small-scale bedforms in the Straits of Florida has been made possible by the unique capabilities of the NR-1 and has provided new information on flow through the straits. The principal bedforms we mapped in the straits and the Northwest Providence Channel (NWPC) are flat bed, ripples, sand waves, coral mounds, lithoherms, and erosional outcrops, and will be described by region.

Central area of the straits

The central area of the straits south of Bimini is broad and relatively flat as seen from surface echosounders. The area near dive 1 showed featureless SLS returns and was devoid of bedforms, but slight current lineations were visible. The hard, carbonate substrate also appeared to be fractured. Further south the region is covered with low-lying coral mounds (Fig. 4) (dives 2–5 and 7). These mounds are up to 1 m in height (Fig. 5) and appear to have been created by a “snow fence” effect caused by coral (probably *Dendrophyllia*; see photographs in Stetson et al., 1962) growing up from a hard, carbonate seafloor between the mounds. With time, new coral attaches itself to the carbonate substrate in front of the mound. the older coral is buried and dies, and the mound moves slowly upstream. Streaks and ribbons of brownish-gray, medium to coarse-grained sand filled the area between mounds (Fig. 4b). The SLS revealed the mounds were aligned perpendicular to the northward flow of water (Fig. 6, sonograph A). Distinct lineations parallel to the flow between the mounds were also visible on the side-sonar records (Fig. 6, sonograph A and Fig. 7, sonograph F). Further south, mounds became less regular and gave way to a featureless bottom (Fig. 6, sonographs C and D). The only objects seen visually from the submarine which could have caused the lineations were the sand ribbons and streamers. Although their vertical relief (1–2 cm) was below the detection level of the SLS, their cumulative abundance appears to have been sufficient to cause aligned reflective patterns (Fig. 7, sonograph F). Velocities near the seafloor during our dives in this region ranged from 10–40 cm s⁻¹.

Between dives 6–7 and 30–31 enough coarse sediment exists on the hard substrate to form ripples, but they were confined to sheets 10–50 m wide and at least hundreds of meters long (Fig. 7, sonographs E and N). The ripple crests were perpendicular to the long axis of the sheets and terminated abruptly at the edge of the ripple field (Fig. 4c and d). The ripples were generally 1–5 cm high with a spacing of 10–20 cm and were formed by a N-flowing current. Between the ripple sheets were current-smoothed strips which were lineated longitudinally and had about the same spacing of 10–100 m. Again, the height of individual ripples is below the detection level of the SLS but the change in surface texture caused by alternating patches of ripples and current-lineated areas made it possible to detect these features on SLS while traversing 50 m above the seafloor.

The SLS near dives 6 and 8 again shows a
featureless bottom (identical to the right-hand side of sonograph G in Fig.8), but visual observations on the bottom showed that in less than 2 km, the bottom appearance had changed from current swept to tranquil with soft, cohesive sediment covered by mounds and holes created by the benthos (Fig.4c). We conclude that the strongest northward bottom flow is on the eastern side of the Straits of Florida. North of Bimini the straits become narrower, but based on SLS and visual observations, the strongest northward flow is still confined to the eastern side. Lineations on the SLS cease at a water depth of 590 m along the northern track. By dive 32 the bottom sedi-

Fig.5. Bathymetric profile over coral mounds in the central Straits of Florida during dive 2. Direction is normal to crests of mounds.

Fig.6. Sonographs of segments A, C and D shown in Fig.3. The vertical and horizontal scales are always equal. Oriented features are coral mounds which have trapped carbonate sand.
ments are softer, more cohesive and burrowed, but the presence of lee deposits behind protruding objects still indicates a strong northward flow.

**Depositional anticline**

Between the central portion of the Straits of Florida and the Miami Trough is a ridge identified as a depositional anticline based on seismic profiles (Malloy, 1968). This ridge, which is shaped like a broad saddle, parallels the axis of the straits with the deepest part of the saddle occurring at the latitude of Bimini.

All sonographs along the ridge are featureless (Fig.8, sonograph G). Sediments at dive 8 were soft, highly burrowed, and showed no evidence of currents. At dive 10 the sediment was also burrowed, though somewhat firmer, but still there were no indications of past currents in the surface sediment.

**Miami Trough**

The trough at the base of the Miami Terrace is 90 km long, but only 2–6 km wide, yet within this band are several narrower zones with distinct boundaries.
Erosional steps

The first zone is the contact between the depositional anticline and the trough. This zone, which is anywhere from 20–500 m wide, consists of one to several steps from less than 0.5 to 7 m high eroded into the consolidated sediment of the depositional anticline (Figs. 8 and 9). The largest steps are outcrops forming nearly vertical cliffs (Figs. 9 and 10a) but most are rounded into the shape of a quarter cylinder and do not have the stratified appearance of outcrops. The rounded steps continue uniformly for at least hundreds of meters. Between the steps the bottom formed flat benches covered with ripples and sand waves. These bedforms began abruptly at the bottom of each step and usually ended just as abruptly within a meter of the next downward step. The crests of the ripples and sand waves were oriented perpendicular to the steps, but occasionally the ripple crests bent gently northward, eased their way down the step and were lined up across the next step. These steps and cliffs were seen on the SLS on every crossing of the trough for the 65 km of trough surveyed. At the southernmost crossing near dive 11 the SLS return of the steps was not very distinct (Fig. 8, sonographs G and H), but it increased towards the north and was strongest between dives 16–22 (Fig. 11, sonograph II). The northernmost crossing showed definite but diminished returns from the steps (Fig. 12).

Sand waves

At the base of the steps is a zone from 600 to 1500 m wide covered with sand waves. The wavelength varied from 30 to 60 m with amplitudes of less than 1 m to 6 m. The asymmetry of the waves and southern slip faces could only be caused by a strong southward flowing current.
Fig. 9. Ship’s track and bathymetry section during dive 9 (Fig. 3). Sand waves about 5 m high lie on top of the erosional steps between H and L and are migrating south (out of the page). Smaller sand waves are crossed obliquely in the trough.

(Fig.13). Ripples were always seen on the back slopes of the sand waves and were generally parallel to the wave crests. They had a spacing of 10–15 cm and an amplitude of 1–3 cm. Ripples usually started within 50 cm of the wave crest and continued down the back of the wave to the trough. As the trough was approached (Fig.10b), the ripple crests would often arc northward into the slipface of the wave, continue up the slipface perpendicular to the wave crest, and stop within 50 cm of the top (Fig.10c). These ripples tended to be very long crested with a single crest often continuing up the entire face. In the southern portion of the trough, the ripples appear to have been active recently and current velocities were measured around 25 cm s⁻¹. As we moved north, however, some ripples had an "older" appearance with animal burrows and a fine sediment dusting on their flanks.

The sand waves and ripples were formed from a coarse carbonate sand composed of foraminifera and pteropod shells as well as other shell hash and coral fragments. Very few fines were in the sediment as was evidenced from the minimal dust cloud when we dropped a pronged cylinder and dragged it half to three-quarters buried through the sediment (Fig.10d). The sediment was totally incohesive as the sand quickly slumped to its angle of repose after the cylinder passed through the sediment. It was common to see *Thalassia* (sea grass from shallow waters) collecting on the slipface of the sand waves and occasionally moving on the slip face parallel to the wave crest.

While most sand waves had a sinuous orientation perpendicular to the axis of the Miami Trough, there was an occasional field where wave crests bifurcated and ripples became confused or where wave crests curled around nearly 180° and terminated in a horse-shoe formation. Near the erosional steps at the northern end of the sand wave field there was an occasional block of semiconsolidated sediment partially buried or eroded.
Fig. 10. Bottom photographs taken through the submarine viewports. a. Ripples cover the backs of the sand waves and at the trough of the wave the ripples often turn 90° and continue up the slip face of the wave, indicating strong secondary flow along the slip face parallel to the wave crest. b. Ripples end abruptly at the edge of the erosional cliff, which drops nearly vertically as much as 7 m. Burrowing animals speed up the current erosion (dive 20). c. Ripples extend to the top of wave crests (photograph at dive 24 looking south-southeast). At the northern end of the Miami Trough the ripples had been reformed by a northerly flow and had more dark organic fluff in the ripple troughs than at the southern end of the trough. d. Dragging the anchor through the sand on the wave slip faces showed there are few fines in the incohesive sand. e. and f. The south wall of the Northwest Providence Channel and the lithotherms within the channel showed similar patterns of sheet erosion or dissolution with only a moderate number of attached organisms.
Coral thickets

A third zone within the Miami Trough is composed of large coral thickets stretching along about 65 km between dives 15 and 24 in a band up to 2.8 km wide. The region is separated from the sand waves by a band of current-swept semiconsolidated sediment ten–tens of meters wide that rises 10–20 m from the sand waves to the coral thickets (Fig.14). The coral thickets are similar in nature to the coral mounds on the east side of the Straits of Florida but are much larger and have more lateral continuation forming E–W rows. There is periodicity to the rows with wave lengths ranging from 60–120 m and amplitudes between 3–5 m. The dense coral growth on these features forms thickets and coral mats of dead and living
coral with the live coral concentrated near the upstream end of the mound. The coral thickets provide strong sonar reflectors which initially appear as steep walls, but the lack of shadow behind these "walls" would be confusing had we not made visual observations (Fig.11, sonographs I, II and J; Fig.12, sonograph K). Between the coral thickets are shallow troughs of clean, fine-grained cohesive sediment.

The coral mounds described by Newmann and Ball (1970) while diving in Aluminaut are located in the southern part of the coral thicket zone mapped here. These also appear to
Fig. 13. Bathymetry profile over sand waves at dive 16. Track from J to O (north is up) corresponds to profile J–O and shows the asymmetry of the sand waves.

Fig. 14. Bathymetry along track K (Figs. 3 and 12). Coral mounds (a–b) are up to 7 m high, separated from the field of sand waves (c–d) by a steep slope (c–b). See Fig. 12 for corresponding sonograph.

be similar to those described in shallower water by Stetson et al. (1962).

**Miami Escarpment**

The western boundary of the Miami Trough is a steep escarpment rising up to the Miami Terrace. Some seismic evidence suggests this feature may be structurally controlled by faulting (Uchupi and Emery, 1967; Sheridan et al., 1981). The numerous outcrops and vertical walls of consolidated sediment support this view. The boundary between the coral thickets and the Miami Escarpment is not always distinct. They fade out on the SLS rather than terminating abruptly as do the other zones in the trough. The bottom slopes up gently at the base of the Miami Escarpment and there are numerous shallow (10–100 cm high) outcrops which are often undercut and composed of hard limestone. Many small rocks between the outcrops and some of the outcrops themselves appear to have manganese coatings because of their gray coloring and nodular appearance.

In some places the sonographs are filled with reflections from these outcrops and trend parallel to the regional contours (Fig. 12, sonograph K). Frequently there are flat benches up to hundreds of meters wide between vertical steps. Some benches are featureless, but others are current swept or covered with ripples and small sand waves as between dives 24 and 25. Along the deeper portions of the escarpment, all bedforms indicate southerly flow, whereas the evidence is less conclusive at depths less than 700 m.

**Miami Terrace**

This feature is a flat carbonate plateau paralleling the Florida coast off Miami. We traversed only the southern portion with the NR-1, but that area was totally featureless on the SLS. Visual observations on dive 12 revealed a light carbonate ooze with no indications of strong currents. As we moved east towards the Miami Escarpment, the bottom sloped downward but at the edge of the terrace a coral–algal reef rose abruptly with occasional overhangs supporting living corals. Coral mats and thickets contained carbonate sediments mixed with coral debris. Branching coral, probably *Dendrophyllia*, was most common and there were numerous glass sponges. *Langusta* were common and small white crabs were often climbing on the coral. The flow was from the north-northeast but was highly influenced by the complex topography. The eastern side of the ridge dropped 10 m nearly vertically onto a 30 m wide flat bench covered with sediment and coral debris and then sloped steeply (30°–40°) down the escarpment. Little coral was seen on the Miami Escarpment.

**Northwest Providence Channel (NWPC)**

Three different regions were examined in the NWPC: the spur at the junction with the Straits of Florida, the south wall of the channel, and the channel floor (Fig. 15).
Fig. 15. Submarine track from the central Straits of Florida to the Northwest Providence Channel with dive locations (numbers) and sonograph segments (letters). Area within small box is expanded in Fig. 17.

Spur
At 610 m between dives 31 and 32 the lineations ceased and the SLS sonograph was uniformly featureless. At 240 m between dives 32 and 33 the SLS sonograph changed texture. There were no specific targets, but the bottom appeared rougher (Fig. 16, sonograph O). The same type carbonate sediment was found at dive 33 as at dive 32, but the bottom was criss-crossed with echinoid trails. The vertical relief on the disturbed sediment was only 0.5–2.0 cm, below the normal detection level of the SLS, but it appears that their ubiquity, like the rippled areas, cumulatively caused a change in the SLS echo character.

The new textured SLS echo character persisted past dive 35 as did the abundance of echinoid trails at dives 34 and 35. At dive 34 the bottom current was around 20 cm s⁻¹, yet the animal tracks looked fresh. Occasionally, however, several incipient ripples were seen downstream of some of the larger tracks. Presumably the flow was not sufficiently great to cause instantaneous ripples everywhere in the existing sediment and flow regime. With the perturbation of the animal tracks, however, an instability generated ripples downcurrent as shown by Southard and Dingler (1971).

South wall of channel
The detailed bathymetry map of Malloy and Hurley (1970) shows what appears to be three small canyons incising the south wall of the NWPC. We dived where the mouth of one of the canyons was indicated with the intent of moving up the canyon for investigation. No canyon-like feature was observed. The sediment at the bottom during dive 39 was very soft as indicated by the 20 cm penetration of our pronged cylinder. Moving northwest we encountered a steep wall over 30 m in height. The echoes on the SLS showed hard returns which did not seem consistent with the existence of a canyon. A survey was then made at constant depth to ascertain whether any canyons existed. A rough bathymetry map of a 7 h survey suggested the possibility of a single canyon and we descended to its head. Rather than finding any canyon or gully-like features, we found mounds of lithified limestone rising above the sediment to a height of 10–15 m and tens of meters across. A subsequent careful study of the bathymetric data and SLS records showed that there was indeed a single canyon-like feature, the mouth of which we crossed during dive 39 and the head of which we explored during dive 40 (Fig. 17), but this was not a typical continental slope submarine canyon.

The walls and mounds examined consisted of a light-colored limestone on the bottom which was not stratified and was very rounded. The upper layer was darker and contained more solution pitting. Towards the top of mounds the limestone often seemed peeled away somewhat like an onion skin in that the erosion was in 10–20 cm layers parallel to the surface of the outcrop with undercutting and solution erosion where layers had been removed (Fig. 10e). Attached organisms on the mounds were limited to an occasional coral, sponge, or sea anemone (Fig. 10f).

Axis of Northwest Providence Channel
The axis of the NWPC has areas with mounds rising about 10 m out of the sediment (Fig. 16, sonograph P and Fig. 18). During dive 41 we found that, as on the south wall, these
features rise abruptly from the seafloor with slopes of 60°–80°. The mounds are composed of lithified limestone and are very rounded. Solution pits as much as two feet deep occur near the top. These mounds have an occasional live attached organism, but do not have the coral thickets collecting sediment as seen in the Straits of Florida and in the Miami Trough. No talus piles were seen at the bottom. Between areas with mounds the bottom was current-swept and sonographs indicate that flow was strong to the northwest based on lineations downstream of point reflectors (Fig.16, sonograph Q). A temperature section across the NWPC also indicates strong flow to the northwest during our study (Fig.19).
Fig. 17. Detailed bathymetry of south wall of Northwest Providence Channel. The map of Malloy and Hurley (1970) indicated a series of submarine canyons in the area. However, most of the region appears to be buried lithoherms which are re-emerging as a result of erosion and dissolution (see Fig. 10e and f).

Fig. 18. Lithoherms in Northwest Providence Channel outlined with 3.5 kHz echosounder on the NR-1. Records were made while traversing 50 m above the seafloor.

**Currents**

Stick diagrams of the current velocities were plotted along the submarine's track (Fig. 20). North or northwest flow is seen across the Straits except in the Miami Trough. In the trough and along the Miami Escarpment the flow is predominantly to the south. Some of the variability in the direction of flow in areas such as the Miami Escarpment may be due to the complex topography. The strongest northward flows observed (64 cm s⁻¹) were on the eastern side of the Straits and at the intersection of the Florida Straits and the NWPC.
Because current velocity is recorded every 6.7 s, it was possible during descents and ascents to obtain a vertical current profile between about 50 m and 3 m above the seafloor. Previous measurements by Weatherly (1972) in the bottom 30 m of the Straits (just north of dive 1, Fig.1) revealed a mean Ekman veering of \( \approx 10^\circ \), but all of the veering occurred in the lowest 3 m of the water column where velocity decreases logarithmically (the log layer). We obtained only a few measurements below 3 m, but during the 84 descents and ascents, veering in the correct sense for Ekman veering (counterclockwise looking down) was observed in twenty cases. All but one case had northward flowing water. The best examples of veering, dives 30 through 33 (Fig.21), occurred in crossing the eastern side of the Straits across the spur to the NWPC. These examples occur beneath the Florida current over a largely featureless, current-swept seafloor. The veering measured in profiles ranged from \( 1.2^\circ \) to \( 109^\circ \), which is much more than the \( 10^\circ \) measured by Weatherly (1972) and, at the upper range, is more than can be attributed reasonably to the Ekman veering caused by frictional interaction with the seafloor.

Kundu (1977) measured veering angles of \( 25^\circ - 40^\circ \) off the coast of Spanish Sahara in northwest Africa, and Weatherly and Van Leer (1977) reported near-bottom direction changes of \( 30^\circ - 75^\circ \) on the western Florida shelf during periods of along-isobath geostrophic flow. Weatherly and Martin (1978) suggested that large veering angles observed in the benthic boundary layer of the western Florida shelf

Fig.19. XBT section across the southern end of Miami Trough (see Fig.1 for location). Tilt of isotherms suggests strong northward flow in the trough.
Fig. 20. Current vectors (relative to north) measured on the NR-1 during traverses 50 m above the seafloor.

were directly related to stratification of the water column.

Examination of the cross section of current velocities (Fig. 2) made by Düing (1975) during deep southward flow shows extremely sharp gradients in the velocity field. It appears likely, based on sections of both U and V components shown in Düing (1975), that, in a vertical profile, as the current decreases in strength and, in some places reverses from north to south, there is a downward counterclockwise veering in the current direction. The E-W boundary between north and south flow must shift during the 4-6 day cycle when the transient southward flow occurs. This may account for the veering observed at some times and not others. A temperature section made with XBTs across the trough (locations in Fig. 1) is shown in Fig. 22.

Discussion

The highest velocity northward flow of bottom water is on the east central side of the Straits of Florida as indicated by in situ currents measured across the straits (Fig. 20) and in agreement with the pattern of bedforms (Fig. 24), with current velocities in excess of 50 cm s$^{-1}$. The slope of isotherms in the temperature section indicates the main surface flow of the Florida current was on the western side of the straits (Fig. 22), as is normally the case (Düing, 1975).

Because the Florida Straits form a conduit for large volumes of warm water moving northward at high velocities, it is not unusual to find well-developed, large-scale bedforms in them. However, the size and extent of the features we mapped are greater than previously reported. Furthermore, the largest bedforms are produced by a southward flow.

To interpret the bedforms it is important to know what factors control their formation and size. Considerable experimental work has been done in recirculating flumes to recreate conditions suitable for the formation of different types of bedforms (Kennedy, 1963, 1969; Southard, 1971). The important parameters controlling bed state are flow depth, flow velocity, fluid density, fluid viscosity, particle density, and mean size of sediment. To a first approximation fluid density, fluid viscosity and particle density are constant in the Straits of Florida since there is little significant seasonal change in bottom water properties and all the sediment is nearly 100% carbonate. It is therefore possible to make three-dimensional plots of depth versus velocity versus sediment size as discussed by Southard (1971) and Rubin and McCulloch (1980). Two-dimensional plots of flow depth versus velocity can be made for sediments of different sizes to delineate the flow regimes in which different bedforms exist. Most flume experiments are limited to flow depth of less than 50 cm for practical reasons. Boothroyd and Hubbard (1975), Dalrymple et al., (1978) and Rubin and McCulloch (1980) used field data to extend the observations of
bedforms under known conditions to water depths of nearly 100 m (Fig.23). Presumably at some point the total water depth is no longer a controlling factor, but is replaced by some dimension of the benthic boundary layer, e.g., the Ekman layer thickness, $\delta = 0.4 \frac{u_*}{f}$, where $u_*$ is the bed shear velocity and $f$ is the Coriolis parameter. Under most flow conditions the maximum Ekman layer thickness should be around 30 m, but there is an enigma in that thermally well-mixed layers up to 100 m above the seafloor have been observed (Armi and Millard, 1976).

The diagrams in Fig.23 are derived from bedforms with quartz sands in the size range 190–600 $\mu$m. Although we did not take any samples with the submarine, grab samples analyzed by Hathaway (1971) indicate that about 70% of the sediment is between 125 and 500 $\mu$m. Sand in the sand waves may be even better sorted. The density of calcite ($2.72$ g cm$^{-3}$) is close to that of the quartz ($2.65$ g cm$^{-3}$) used in the experiments shown in Fig.23, but the hollow structure of shells and animal tests can bring the density down to $1.5$ g cm$^{-3}$.

Depth–velocity diagrams assume there is unlimited sediment available to create bedforms, which is often not the case in the natural environment. In many places bedforms, particularly rippled areas, are sediment starved, resulting in thin sheets of ripples. Fines are carried downstream in suspension. Boundaries of ripple fields are abrupt and are parallel to the main flow suggesting that secondary circulation maintains the sediment in long rows rather than irregularly shaped patches.

The seafloor in the central Straits of Florida is very compact and appears to be somewhat indurated. The carbonate in this area was $62\%$ Mg calcite (Hathaway, 1971), a good indication of recrystallization (Milliman, 1966). The hard bottom makes it possible for branching coral to attach itself, trap sediment, and create coral/sediment mounds. The regular
Fig. 22. XBT section on southwest wall of Northwest Providence Channel (see Fig. 1 for location). Steeply dipping isotherms suggest strong bottom flow to the northwest in agreement with the currents measured from the NR-1 (Fig. 20). This is contrary to the flow proposed by Richardson and Finlen (1967).

The spacing of mounds suggests a hydrodynamic effect in determining which coral fences are successful in collecting sediment but the added effect of the coral makes it impossible to place these mounds on the Fig. 23 depth–velocity diagrams. Areas between the mounds are current swept and relatively clean of debris, which may be due to high bed shear stresses as the flow reattaches to the seafloor downstream from a mound.

The surface sediments of the depositional anticline were very soft and cohesive, indicative of a tranquil area. This area is a transition zone between the strong northward flow on the eastern side and the periodic strong southward flow in the Miami Trough. Current velocities were only 5–15 cm s\(^{-1}\) near the bottom on the eastern portion of the anticline during our transit, which appears consistent with long-term data (Düing, 1975). As a result, sedimentation rates are higher along the depositional anticline than on either side of it.

The Miami Trough marks the contact between the Straits of Florida, which on a long time scale is a net depositional regime, and the uplifted Miami Terrace whose fault scarp is the Miami Escarpment. Seismic profiles show that the northern end of the terrace is being covered by prograding sediments (Uchupi, 1966). The terrace consists of Oligocene to Miocene indurated limestone, while the sediments in the trough are recent. In the past the
depositional anticline extended down to the bottom of the trough but is now being eroded. The erosion leaves the sand size sediment while the fines are winnowed and carried downstream (south). At some point the fines are either deposited or mixed in the northward flow of the Florida current.

The most obvious question about the bedforms in the Straits of Florida is whether or not they are in equilibrium with the maximum flows presently observed there. Wimbush and Lesht (1979) photographed ripple movement in the vicinity of our northern traverse of the straits (Fig.1). Comparisons between currents (Figs.2 and 20), distribution of bedforms (Fig.24) and phase diagrams of bedforms (Fig.23) clearly indicate that the bedforms found in any part of the Straits of Florida could be formed by the currents that have been measured in each region. Our instantaneous current measurements in the northern portion of the Miami Trough were weak (about 10 cm s\(^{-1}\)) to the north, but these currents have been shown to be periodic and variable (Düing, 1975), and strong southward flow has been recorded in the northern trough (Figs.1 and 2).
Profiles in the Miami Trough indicate the waves in the southern trough are more asymmetric than in the north, indicating that either the southward flows are stronger in the southern trough or the periods of northward flow in the trough are competent to reshape the sandwaves only in the northern trough.

Although the Miami Trough at the base of the Miami Escarpment is a long (~90 km), narrow (2–6 km) feature, it is unusual to have such distinct and continuous subzones of bedforms (Fig.24). SLS sonographs indicate sand waves begin near the southernmost traverse (Fig.8, sonograph G) and are still distinct at the northernmost traverse (Fig.12, sonograph L). In the Miami Trough between dives 16 and 24 there is a narrow transition band between the sand waves and coral mounds. The transition is current swept and may represent upper flat bed, as there are no bedforms
The coral mounds in the Miami Trough are similar to those in the central Straits of Florida, but larger. The trough mounds tend to form long, E–W rows and are almost walls rather than rounded mounds (Fig. 11, sonographs I and J). North of dive 24 and south of dive 16 coral mounds are absent, so the sand wave field directly abuts the base of the Miami Escarpment (Fig. 8, sonograph H, Fig. 12, sonograph L, and Fig. 24). At the base of the escarpment numerous small outcrops trending parallel to the axis of the trough appear in SLS sonographs (Fig. 8, sonograph H and Fig. 12, sonograph K). Between dives 16 and 24 the coral fields likewise phase into the escarpment outcrops, but the coral mounds may occur as much as 100 m up the escarpment. The large coral mounds may have been initiated because escarpment outcrops provided a solid substrate on which the coral could attach and trap sediment. The periodicity of the coral thickets (Fig. 11, sonograph J and Fig. 12, sonograph K) again suggest a hydrodynamic influence, since the trend of the thickets is perpendicular to the trend of limestone outcrops seen everywhere around the thickets.

Northwest Providence Channel

Newmann et al. (1977) have suggested that lithoherms start out as coral mounds similar to those observed in the central Straits of Florida. With time the captured sediments become cemented and recrystallize and they build up into very large mounds covered with living coral. In the axis of the NWPC we found numerous mounds which, though not as large as those described by Newmann et al. (1977) in the northern Straits of Florida, were very similar in shape. Three such mounds are outlined in 3.5 kHz records in Fig. 18. A major difference, however, was that little coral was found on these features and there appeared to be more dissolution occurring than accretion (Figs. 10e and f).

Similar indurated, nearly lifeless mounds were found on the south wall of the NWPC. These mounds, which seemed to have been sculpted out of the wall, appeared to have been lithoherms that were buried, and were now being uncovered. The unusual karst-like topography contributed to the difficulty in contouring the bathymetry in Fig. 17, though the SLS sonographs aided contouring considerably.

Current reversals

Newmann and Ball (1970) suggested that the strong southward flow in the Miami Trough may be caused by a pile up of water at the sill north of the NWPC which then moves southward. Schott and Düng (1976) and Düng et al. (1977) suggest that southward flow is related to atmospherically driven baroclinic shelf waves. A contributing factor may be pulses of water from the NWPC. The net transport of the NWPC was measured at $1.5-2.5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ at a time when the transport in the Florida current was $32 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Richardson and Finlen, 1967). During that 2 day study the flow was always to the west on the north side of the NWPC and to the east on the south side. Our measurements clearly show a strong westward flow (up to 45 cm s$^{-1}$) on the south side. It is possible that flow reversals also occur in the NWPC that significantly alter the net transport through this passage. Future studies of variations in the Florida current should include long-term measurements of the transport in the NWPC.

Conclusions

A wide variety of bedforms have been mapped in the Straits of Florida. Currents measured during this study and others suggest that the bedforms are in dynamic equilibrium with the present-day flow patterns when they are at their maximum. When a hard substrate is available, branching coral can attach itself and act as a snow fence to trap sediment in mounds. Hydrodynamic effects create periodic spacing of the mounds. The largest bedforms are found in the Miami Trough and result from strong southward, not northward, flow. The sediment is
being eroded slowly in the Miami Trough, although on geologic time scales, the majority of the Straits of Florida is a depositional regime. In the Northwest Providence Channel lithoherms are being eroded by strong currents and dissolution, causing some karst-like topography.

Veering in current direction was measured in the lowermost 50 m of the water column, but is probably related to transition from northward to southward flow in the Straits of Florida and to the confluence of the Florida current with water entering the straits from the Northwest Providence Channel as opposed to Ekman veering. Future studies should consider the input of water from the Northwest Providence Channel as a cause for the flow reversals in the deep western Straits of Florida.

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References


General Dynamics, 1970. EM log calibration on NR-1 Sea Trial Form #NO.80.02, Rev. C. Electr. Boat Div., Groton, Conn.


