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SHELF MARGIN REEF MORPHOLOGY: A CLUE TO MAJOR OFF-SHELF SEDIMENT TRANSPORT ROUTES, GRAND CAYMAN ISLAND, WEST INDIES

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Abstract

Side-scan sonar, high-resolution seismic, and echo-sounder data, coupled with the results of other reef-related studies on Grand Cayman Island, show that abundant sediments have accumulated on the deep fore-reef shelf. The most important accumulation sites are on the downdrift northwest and southwest flanks of the island, where gradients from high to low energy are maximized.

Shelf-margin reef morphology along the lee or western side changes from a continuous sill-like structure that impounds sediment along most of this sector to a discontinuous reef along the southwestern flank. Isolated reef buttresses, separated by wide sediment-floored channels, characterize this area, where abundant sediments are stored on the lower forereef shelf. The wide channels between reef buttresses provide avenues through which sediments produced in shallow-water environments can be transported to deep off-shelf sites of deposition. Echo-sounder traces off the shelf at the southwestern corner of the island display characteristics suggesting depositional slopes. Shelf-margin reef morphology strongly indicates that off-shelf sediment transport is occurring along the southwestern flank of the island. Side-scan sonar data were extremely valuable for rapidly evaluating the morphological variability of reefs on the forereef shelf.

Introduction

Recent studies of physical processes interacting with island reef systems in trade-wind settings suggest that around-the-island gradients in both wave energy and current energy favor transport and accumulation of sediment along the lee coast and adjacent shelf (Roberts et al., 1975; Murray et al., 1977; Davies, 1977; Roberts, in press). Both observations and theory show that zones of intense currents (jets or rips) and zones of weak currents (stagnation zones) are systematically distributed around the shores of islands and that prisms of shelf sediment accumulate in response to the deceleration of high-speed currents (Murray et al., 1977). Within quasi-unidirectional wind and wave systems, major low energy or sheltered zones around islands generally correspond to regions where nearshore current fields display minimal velocities. In the northeast trade-wind setting of the Caribbean, these low-energy zones occur on the western sectors of islands.

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Carbonate research conducted on the reefs and sediments of Grand Cayman (West Indies), a trade-wind island that fits the above observations concerning energy distribution (Fig. 1), indicates that sediments have accumulated in abundance on the deep forereef shelf along the western (lee) side of the island (Rigby and Roberts, 1976; Roberts, 1977). Although shallow fringing reefs, which are abundant sediment sources, are not evident along the leeward coast, flourishing mid-shelf and shelf-margin reefs are present. Higher energy shelves, compared to low-energy shelves of Grand Cayman, tend to support more coral cover and less open areas of sediment accumulation in both shallow and deep environments (Roberts, 1974). Sediments produced by both physical and biological degradation of the reef framework in these higher energy shelf areas appear to be largely trapped in the reef matrix and thereby diverted from primary routes of off-shelf sediment transport. Meaney (1973), Moore et al. (1976), Land and Moore (1977), Ginsburg and James (1973), and Hanna and Moore (1979) have studied various aspects of shelf to basin sedimentation, including sediment budgets, facies relationships, and stratigraphic history of off-shelf deposits. The study reported in this paper provides additional data from side-scan sonar, subbottom, and echo-sounder surveys (Fig. 1) concerning identification of optimal sites for shelf-to-basin sediment transport associated with a low-relief Caribbean island.

Objectives of this investigation were twofold. Firstly, from previous geological and physical process studies of Grand Cayman, the location of important sediment sinks and general areas of maximum sediment input to the shelf were identified. It then became important to determine if these areas of accumulation are also sites of significant sediment transport and if reef morphology is linked to this process. Secondly, the usefulness of side-scan sonar for reef-related studies was tested.

Instrumentation

Three instruments were used in conjunction with accurate location control. These instruments included a side-scan sonar system, a 3.5-kHz subbottom profiler, and a linear chart recording fathometer. All instruments were deployed on an 11-metre boat, which served as a research vessel. Instrumentation was operated simultaneously, and event marks indicating position fixes were automatically recorded on all records at 1-minute intervals. The position fix numbers and distances from known points were recorded on paper tape as a permanent record. Each instrument is discussed below, with more emphasis being given to side-scan sonar because of its usefulness in this study and its recent importance to marine geology in general.

Side-Scan Sonar

The first operable side-looking sonars were made by the British in the early 1960s. Side-scan did not become a valuable instrument for marine surveys until the late 1960s. In the 1970s it has become increasingly important as standard instrumentation in marine survey work. For the marine geoscientist, the development of side-scan sonar must be considered a major technological milestone. Through the use of this instrumentation, which is now readily accessible, it is possible to map sea-floor surface features with complete coverage, a task very similar to mapping from aerial photography. Previously, our understanding of sea-floor morphology was derived primarily from profile data such as is generated by a precision depth recorder. Between survey lines extrapolations must be made, whereas adjacent side-scan sonar lines may be spaced so that records overlap for continuous sea-floor coverage. Recent development of systems that digitally acquire side-scan data and play it back in an undistorted analog form is yet another major improvement in this valuable instrumentation. In an undistorted format spatial distributions of bottom features, textures, and shapes can be easily assessed in a quantitative way, much like mapping and form analyses using air photos.

The area of sea floor covered is a swath, commonly to 1,000 metres (500 metres on each side of the source), rather than a line, as is the case with profiling techniques. Objects on the sea floor reflect the acoustic energy, which is received by the towed sonar source. Returned signals are then amplified and printed as various tones on either wet or dry paper. Precise measurements of distances between the vessel and a reflector, as well as shapes, heights, and other relationships, are not possible with conventional side-scan without corrections (Flemming, 1976). The new digital system offers a method for obtaining distortion-free images and therefore the possibility of easily employing this instrumentation for precise topographic mapping (Prior et al., 1979).

A conventional side-scan sonar system consists of three basic units: (1) a transducer (or "fish"), which is the underwater transmitting unit, (2) a steel-reinforced cable, which is used for towing the fish and transmitting signals to the third component, (3) the recorder.

For optimum results from a side-scan sonar survey, precise navigational control is needed, and track lines should be arranged so that adjacent records overlap on one channel. Without accurate navigational control, both conventional and the new digital side-scans are of limited use as instruments for collecting quantifiable data from the sea floor.

For research in coral reef environments side-scan sonar may be used to collect data on reef shape, orientation, and general configuration which may then be compared to physical expressions of the environment such as wave direction and wave power. Density changes on the side-scan sonograph may also represent well-defined facies changes, e.g., muds to sands. This method is invaluable for the study of shelf reefs that are too deep to be recorded by aerial photography. Other uses in carbonate environments include the determination of sediment transport routes and sediment sinks in deep shelf areas where other methods of observation may be difficult and time consuming.

The Klein side-scan system used in this study was coupled to the 3.5-kHz subbottom profiler, and records from both sensors were printed on a single wet-paper recorder, which has three channels. The side-scan has a frequency of 100 kHz with lookout ranges from 25 to 600 metres. We found the 100-metre range to be optimal for the Grand Cayman study.

Subbottom Profiler

The subbottom profiler is designed so that it fits on the nose of the side-scan sonar fish (Fig. 2). This unit operates at a frequency of 3.5 kHz and is designed to produce details of reflection events in the upper 100-200 feet of the stratigraphic column, depending on the type of sedimentary material. Unfortunately, the acoustic energy is transmitted at relatively low power. In reef and reef-associated areas, the sea floor is generally very hard, which causes much of the acoustic energy to be reflected without penetrating the bottom. Only a few of our records contained useful subbottom information. These records, however, provided additional data concerning sediment thickness on the forereef shelf.

Fathometer Depth Recorder

A Raytheon Model DE-731 depth recorder was used in conjunction with other instrumentation. This particular instrument was selected for use because of its linear chart, versatile depth ranges, and portability. Although both the side-scan sonar and the 3.5-kHz subbottom profiler records a bottom trace, the fathometer is a much more accurate and convenient method of generating a bathymetric profile. The fathometer was run on all survey lines during this study.

Our unit is equipped with a narrow-beam transducer, which gives the best resolution of the sea floor. However, in rough seas this transducer does not function well. The system will record in both feet and fathoms (0-410 feet or fathoms is the depth recording range). The operating frequency is 41 kHz, and the sounding rate is 270 pulses per minute in FEET mode and 45 pulses per minute in FATHOMS mode.

Survey Position Fixing Instrumentation

A Decca Del Norte electronic range-range locating system which employs advanced microwave and digital techniques was used for survey control. This system has a "line of sight" capability, with maximum ranges in the order of 80 km when both remotes and the master receiving antenna are elevated. Distance is obtained by measuring the round-trip travel time of signals transmitted between the master and the remote. Then, 10 or 100 path lengths, selected by digital filtering, are averaged to determine each distance displayed. Ranges are obtained in a matter of milliseconds. Positions can be resolved with this equipment to an accuracy of 1-3 metres. The instrumentation is very lightweight, easy to install, and reliable under a full range of field conditions. The system used in this study consisted of two remote stations (land based), a master receiving station (boat based), and a printer. All units are powered by two 12-volt car batteries. The remotes are deployed at known survey control points along the coast (Fig. 3). These stations are interrogated by the master unit on the boat, and the distance in metres from each remote to the master antenna on the boat is printed out on paper tape, along with position fix number and time. A 1-minute rate for these position checks was used in the Grand Cayman study. As position fixes are taken every 1 minute, an event mark is simultaneously triggered on the side-scan sonar, subbottom, and bathymetric records.

Shelf Morphology

The shelf surrounding Grand Cayman is narrow, ranging in width from approximately 0.5 km to 2.0 km. Geomorphically, the most distinctive features of any given shelf profile are two persistent submarine terraces which can be traced around the entire island (Fig. 4). Although differential reef growth and other generally slower forms of shelf accretion account for a moderate degree of variability in terrace topography, the seaward break in slope of the shallow terrace generally occurs at a depth of 8-10 metres. The base of this shallow terrace averages 15 metres where the deep terrace is encountered. Except for the seaward margin, most of the shallow terrace is a hardground surface with very little, if any, sediment cover. It is sparsely colonized by reef-building organisms, and is commonly dissected by shallow grooves (Fig. 5). On the lee side, however, localized areas of sediment accumulation are associated with adjacent hardgrounds. Spurs and grooves are not characteristic of the shallow terrace of the central lee shelf (Fig. 6).

The seaward margin of the shallow shelf break in slope supports a prolific growth of coral superimposed on a distinct spur and groove structure. Well-defined ridges or spurs of living coral are prograding seaward and building toward the surface. The linear depressions in the shallow terrace surface are sometimes discontinuous and therefore do not always extend to the seaward margin of the terrace. Most well-defined grooves either reach the lower terrace or intersect other grooves until the network extends across the upper shelf. It is clear, however, that whether these grooves terminate upslope in actively growing fringing reefs, as is generally the case, or in a limestone sea cliff, common on lee side, they function as pathways for sediment transport to the lower shelf.

Spur and groove structure is also typical of the deep shelf terrace. However, the landward portion of this terrace is frequently an area of sediment accumulation (Fig. 7). Extremely coarse carbonate material (cobble- to coarse-sand-sized sediment) is concentrated at the base of coral-covered spurs of the shallow terrace. Particle size generally decreases to a bimodal sediment of coarse sand-sized constituents in a silt- to clay-sized matrix near the shelf margin. Spurs of living coral that extend landward from the actively growing shelf edge reef tend to break the continuity of the lower shelf sediment belt. Considerable variability is displayed in sediment plain characteristics, in terms of both geometry and sediment properties. High-energy sectors of the shelf tend to have coarse sediment plains that are highly segmented by spur growth. Contrasting low energy shelves tend to have broader unbroken areas of sediment accumulation. Most of these sites occur on the lee (western) side of the island, where sediments can be quite fine grained in localized areas. Depending on relationship to dominant wave direction, spurs that extend into the sediment plain may not be oriented normal to the shelf edge. Roberts (1974) has shown that differences in orientation between spurs and grooves on the shallow and deep terraces are related to progressive changes in direction of dominant waves as they intersect the shelf and refract across it.

A thriving reef community is present at the seaward edge of the deep shelf terrace where an abrupt break in slope separates the shelf from deeper off-shelf environments. Morphologically, the shelf margin reef can vary from an unbroken ridge, through regularly spaced massive coral buttresses separated by narrow sediment-floored grooves, to irregularly spaced and widely separated coral buttresses. The degree to which the deep reef morphology is exaggerated or amplified appears to depend greatly on the wave energy conditions under which it developed (Roberts, 1974). Along high-energy sectors of the shelf, massive and regularly spaced living coral buttresses protrude into deep water (Fig. 8). These huge coral spurs occasionally coalesce, forming a wide variety of tunnel and cavern structures. The massive buttresses generally have a steep to overhanging seaward profile, with as much as 20-30 metres of relief. Low-energy shelf-margin reefs support thriving coral communities (Fig. 9) but display less exaggerated buttress formation and less steep offshelf profiles. Morphological elements of the reef at these depths have coalesced to form a semicontinuous ridge at the shelf edge which has grown to a height of 3-5 metres above the adjacent deep terrace sediment plain. Inasmuch as this linear topographic feature is infrequently dissected by narrow grooves, it essentially forms a sill that causes sediment to be impounded behind it.

Sediment Transport Routes and Variability of Deep Reef Morphology

Previous research on Grand Cayman (Roberts, 1974; Roberts et al., 1975; Murray et al., 1977) has demonstrated that strong westerly directed currents exist along both the northern and the southern flanks of the island (Fig. 1). At Grand Cayman's southwestern extremity, where much of the research reported in this paper was concentrated, the combined effects of shoaling waves, tidal currents, and westward-flowing backreef lagoon currents from South Sound (Fig. 1) result in the transport of sedimentary particles to the lee shelf, where they accumulate.

As discussed in a recent paper by Roberts (in press), continuous reefs separating shallow backreef lagoons from the open shelf can be abundant sources of sediment to deeper shelf and off-shelf environments. Reefs of this description function as continuous sources of sedimentary particles, first to backreef environments and subsequently to deeper depositional settings outside the lagoon. Coarse sediment bodies tend to accumulate behind the reef as a result of wave overwash processes and at the adjacent backreef shoreline by swash action. Strong currents develop in the downdrift ends of these systems, transporting sediment outside the confines of the lagoon. Such flow is driven by both wind stress on the lagoon and constant input of water to the backreef by breaking waves that generate strong shore-normal surge currents at the reef crest (Roberts and Suhayda, 1977; Suhayda and Roberts, 1977). These processes provide the driving forces for creating a significant flow out of the lagoon. The combined result is to export reef-derived and lagoonal sediment to the adjacent forereef shelf. Although mean conditions produce flows sufficient to move sand-sized sediments, storm events create proportionately higher velocities and thereby become important sediment transport events.

Even though the movement of sediment to deep shelf environments is reasonably well understood, processes responsible for transporting sediments off the shelf to deeper depositional sites have not been studied in detail. Investigations of off-shelf sediment transport by Meaney (1973), Moore et al. (1976), Land and Moore (1977), Ginsburg and James (1973), and Hanna and Moore (1979), among others, have focused primarily on the products of the transport process. They demonstrate that sediments generated in shallow reef and reef-associated environments are moved off the shelf and into deepwater sedimentary environments. The conditions responsible for displacing sedimentary particles from a shelf domain to a basinal environment are not well understood. Most recently, Hine and Newmann (1977), Hine et al. (in press), and Mullins et al. (in press) have shown, from research on the margins of the Bahama Bank, that large volumes of shallow-water sediments have engulfed Holocene shelf-margin reefs and now reside on the deep flanks of the Bahamian platform. They have attributed much of this off-bank transport to storm-related processes. Islands such as Grand Cayman are somewhat more limited in areas available for sediment generation as compared to vast shallow-water platforms such as the Bahama Banks. There are, however, favored sites where sediment accumulation around islands is focused by the physical dynamics of the island system (Murray et al., 1977; Roberts, in press).

Side-scan sonar data indicate that the morphology of Grand Cayman's shelf-margin reefs provides important clues to interpreting the location of significant off-shelf sediment transport routes. On the lee or western shelf, where sediments collect more abundantly than on higher energy flanks of the island, there are long sections of shelf-margin reef which have coalesced to form a relatively coherent ridge. Sediments are impounded in the lee of this structure and can be transported over the shelf edge only through narrow grooves (Fig. 10).

Grooves are active transport routes (Meaney, 1973) especially on high-energy flanks of the island, where they are kept open by tidal exchange at the shelf edge and wave-related forces (Roberts et al., 1975, 1977). However, only limited amounts of sediment can be fluxed through these narrow passageways to deeper sedimentary environments. Higher energy shelves seem to maintain the integrity of a basic spur and groove structure (Fig. 6), and sill-like structures do not generally develop. The southwestern extremity of Grand Cayman is a site where maximum energy gradients favor sediment deposition. Figures 11 and 12 illustrate the large area of sediment deposition on the deep shelf, as well as the discontinuous nature of the adjacent shelf-margin reef. Rather than a coalescence of reef elements to form a sill at the shelf edge, which is typical of the Grand Cayman lee side, along the downdrift southwestern flank of the island the shelf-margin reef breaks into irregularly spaced reef masses or buttresses separated by wide channels. These wide channels provide free access for shelf sediments to deeper off-shelf environments. Such shelf-margin reef morphology has probably developed in response to a constant input of sediment to this accumulation site since sea level rose above the level of the shelf edge (approximately 20-24 metres). Assuming that Grand Cayman has been subject to the same general unidirectional wind and wave system since sea level was at the level of the shelf edge, the island's southwestern flank has been a favored site of sediment deposition. An abundant supply of sediments has probably inundated once-living shelf-edge reefs and produced a mobile sediment substrate that restricts coral attachment and growth. Apparently only the highest topographic points have been able to perpetuate themselves by continued reef growth.

Figure 13 summarizes the general sediment sinks and transport routes associated with the southwestern flank of Grand Cayman Island. Shallow-water accumulation zones are found in the sheltered areas of the backreef lagoon. Over-the-reef currents, modulated by the tide and wind stress, drive lagoonal water from east to west. Strong axial currents capable of transporting sand-sized particles to the adjacent shelf develop at the downwind end of the system. Significant shelf sediment accumulation takes place only on the deep shelf terrace. Our 3.5-kHz subbottom profiles show that these deposits are at least 5 metres thick. High-resolution seismic data, showing more penetration from neighboring Caribbean islands with similar shelf morphology, suggest that these deposits may be up to 20 metres thick. Recent studies from the shelf and shelf margin of Little Bahama Bank (Hine et al., in press) illustrate Holocene sediment thicknesses in this range at preferred sites.

Shelf-margin reef morphology suggests that along high-energy flanks of the island sediments move off the shelf through narrow, well-defined groove systems. In contrast, the lee shelf-margin reef has fused to essentially prohibit off-shelf transport of significant volumes of sediment. Very narrow (1-3 metres), irregularly spaced grooves offer a few minor pathways through which sediments may be carried off the shelf (Fig. 10). Only at the northwest and southwest extremities of the island where energy gradients are maximized do sediments accumulate in such abundance that reef growth on the shelf edge is affected. At these locations the shelf-margin reef becomes discontinuous (Fig. 12). Large breaks in this sill-like structure are interpreted as major routes for the movement of shallow-water sediments to deep sedimentary environments. Echo-sounder profiles of the southwestern island margin tend to support the depositional nature of this site over steeper higher energy flanks of the island (Fig. 14). Additional high-resolution seismic work, coupled with a coring program, needs to be accomplished in order to verify the extent of off-shelf deposits and to calculate a budget for sedimentation during Holocene times at this preferred site.

Conclusions

Side-scan sonar, high-resolution seismic, and echo-sounder data, coupled with results from previous studies on Grand Cayman, have led to the following conclusions linking shelf-margin reef morphology and off-shelf sediment transport:

1. Sediments accumulate in abundance on the down-drift southwestern flank of Grand Cayman, where gradients in wave and current energy are maximized. An abundant source of sediments to the southwestern shelf is associated with the east to west flushing of South Sound, which is forced primarily by strong reef overwash caused by breaking waves.

2. Shelf-margin reef morphology along the island's southwestern flank changes from a continuous sill-like structure which impounds sediments to a discontinuous reef characterized by isolated reef buttresses. Wide avenues exist between reef buttresses through which sediments produced in shallow-water environments can be transported to deep sites of deposition off the shelf. Echo sounder profiles of windward to leeward island margins suggest that the island's southwestern flank is a zone of deposition, as evidenced by less steep "depositional" slopes and slump-like topography.

3. Side-scan sonar data proved to be particularly useful in this study for determining details of shelf and shelf margin reef morphology. This method of acquiring morphological details of bottom features is rapid and quantitative, and allows the geomorphic variability of large areas of sea floor to be compared without making direct underwater observations.

Acknowledgements

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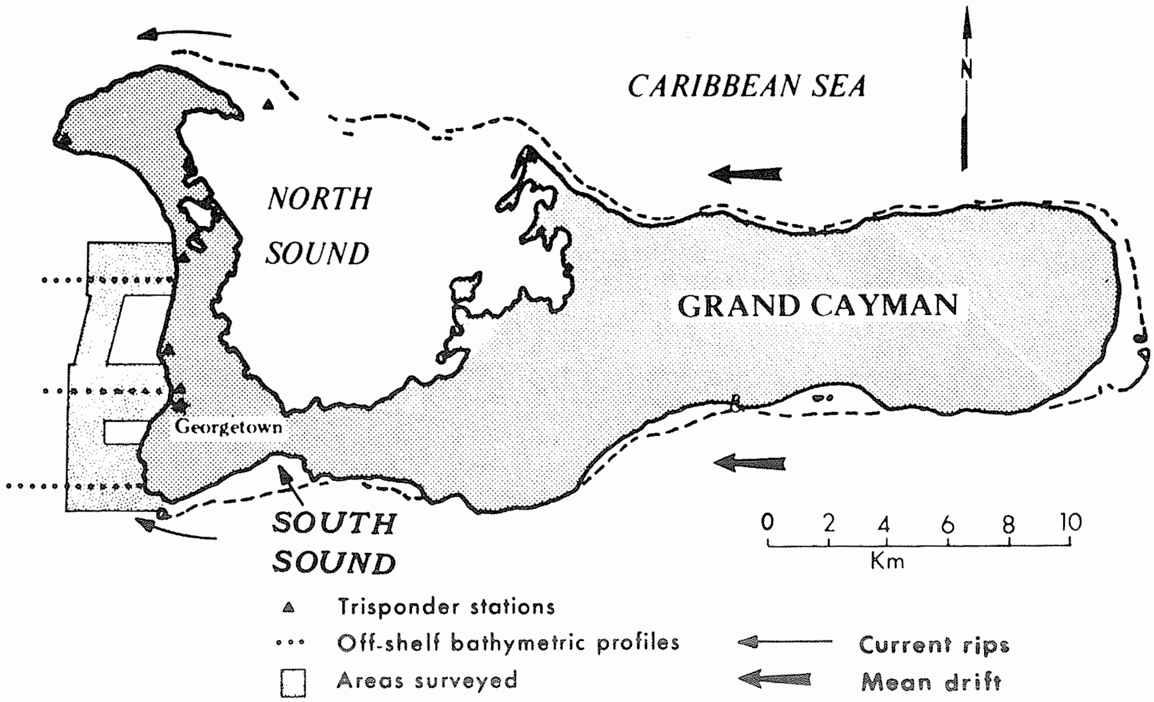


Figure 1. Location map of Grand Cayman Island showing the survey areas.

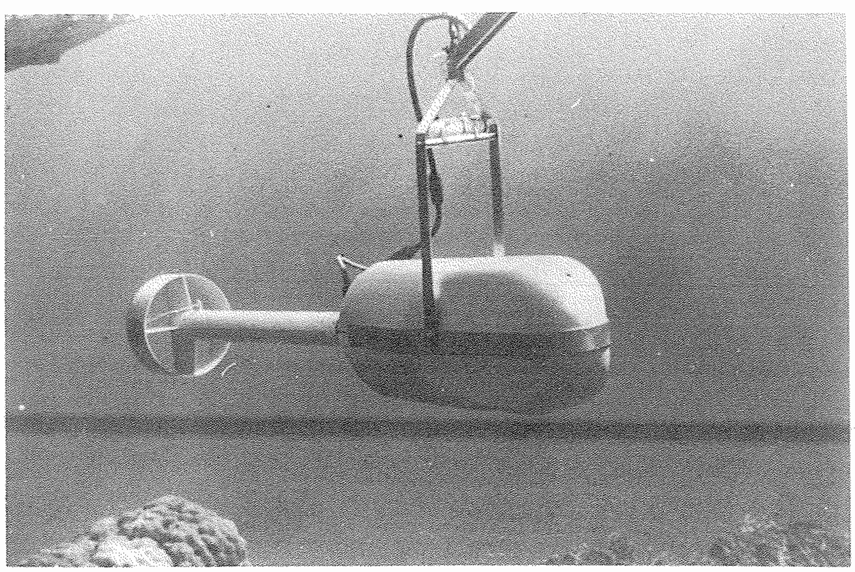
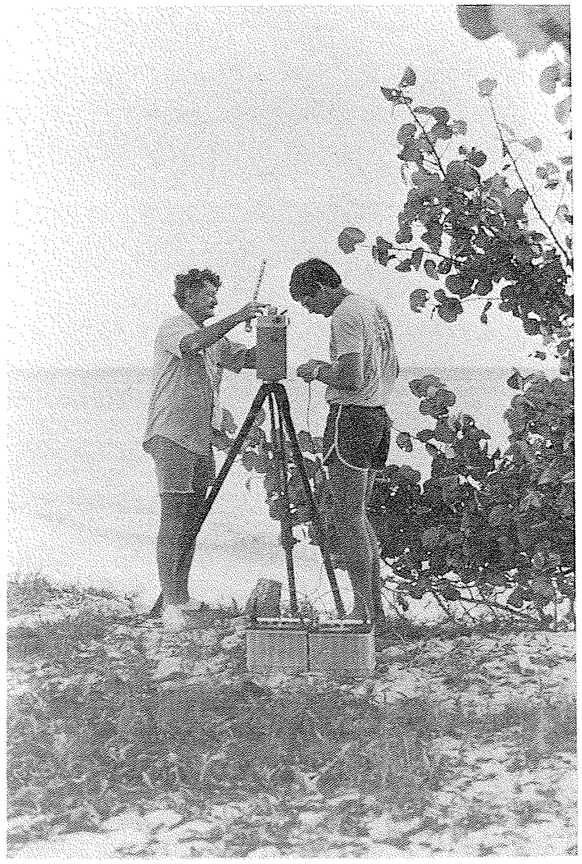


Figure 2. The Klein side-scan sonar fish plus 3.5-KHz subbottom profiler used in this study.

Figure 3. Trisponder shore location being installed in preparation for an offshore survey.



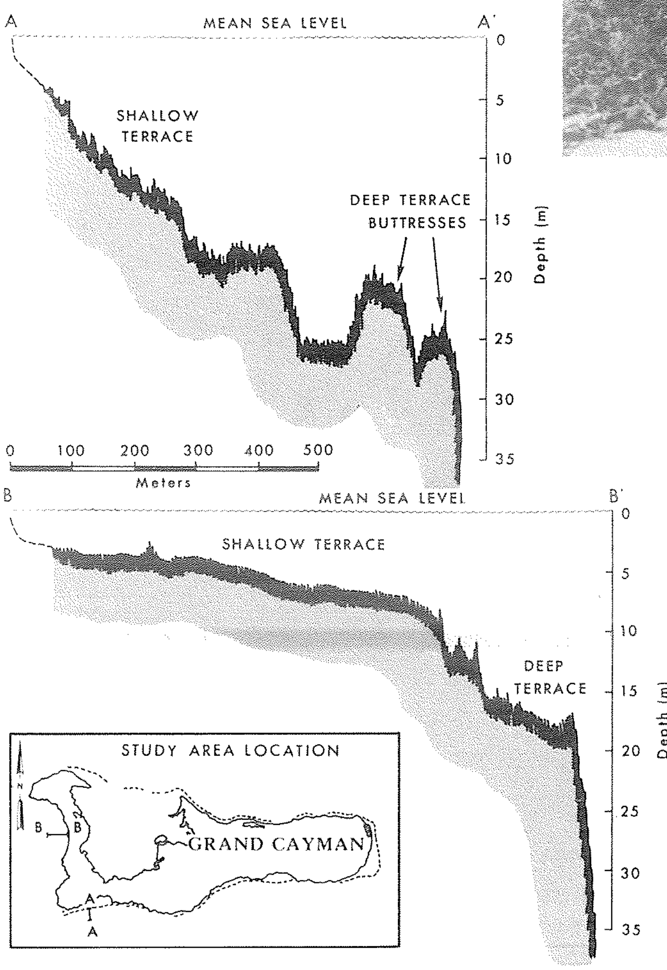


Figure 4. Echo-sounder traces across Grand Cayman's narrow southern forereef shelf (profile A-A') and somewhat wider western shelf (profile B-B'). Shallow and deep terraces are characteristic of each profile. Large coral buttresses with intervening grooves are common along high-energy flanks of the island (A-A'). A rather continuous shelf margin reef is the norm on the lee or western side of the island (B-B').

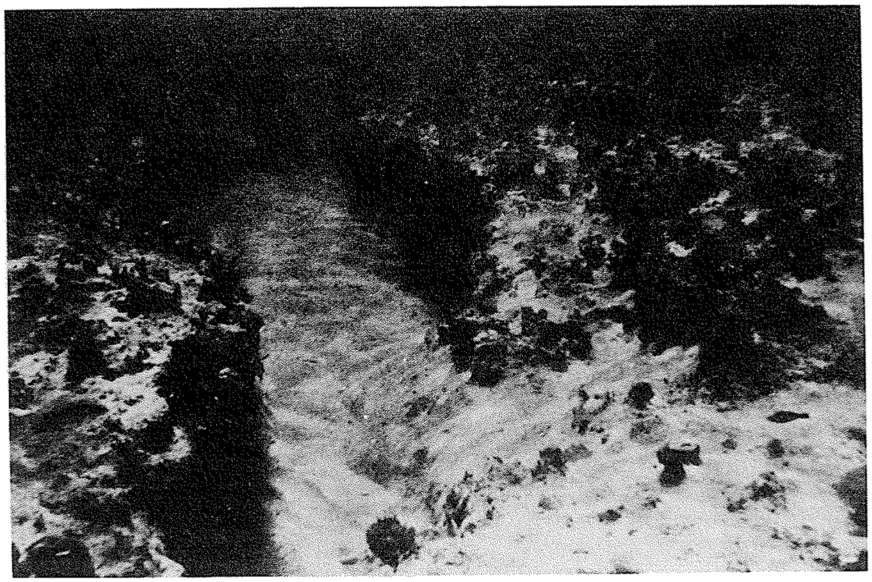


Figure 5. Surface of shallow terrace (depth ~3 metres). Note the lack of sediment cover, sparse colonization of reef-building organisms, and shallow groove.

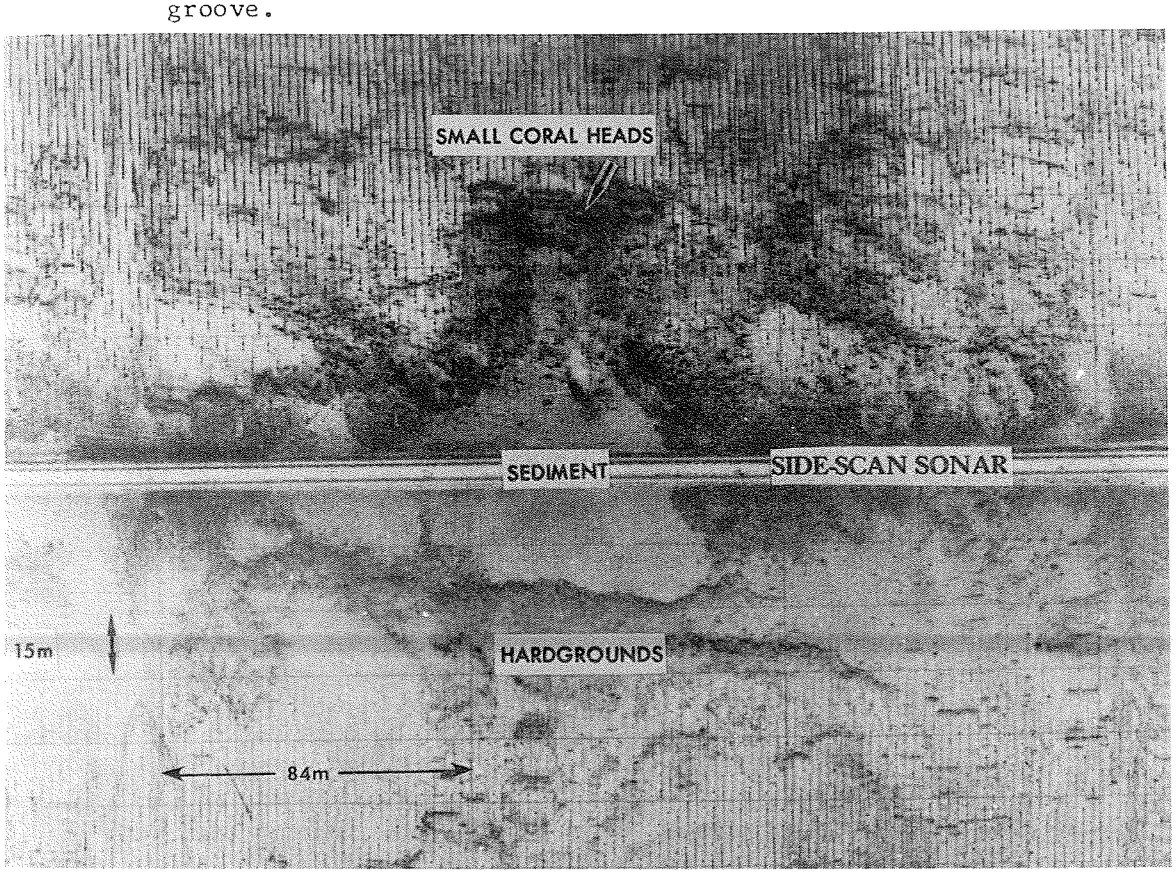


Figure 6. Side-scan sonograph of the shallow shelf terrace on the lee side of the island. Note the lack of spur and groove structure, isolated areas of sediment accumulation, and hardgrounds. Water depth is 5-7 m.

Figure 7. Deep shelf terrace sediment plain that is dissected in this locality by a linear spur constructed by a thriving reef community. Note the rippled sediment. These structures are oscillation ripples from recent storm waves (water depth 24 metres).

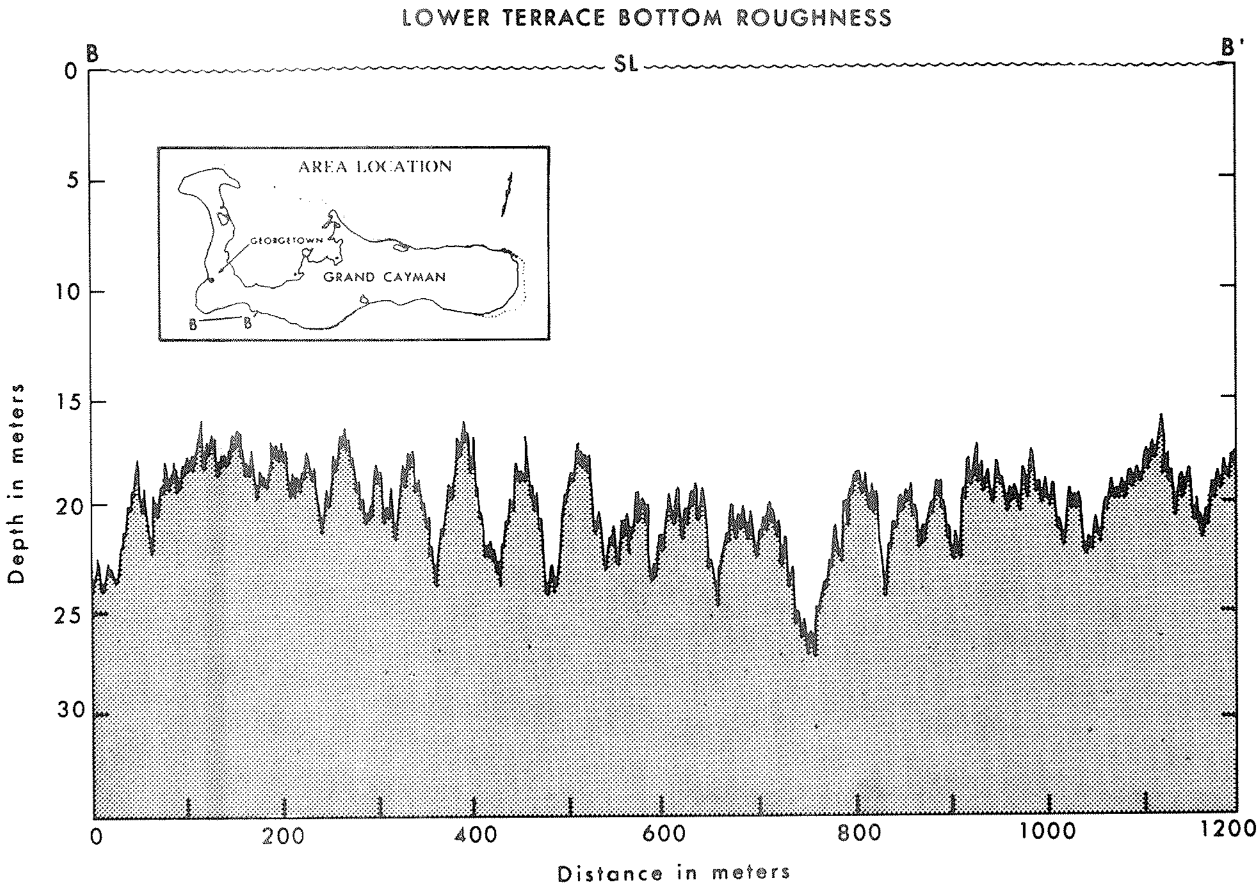


Figure 8. Echo-sounder trace along the shelf edge of a high-energy sector of the shelf showing the regularly spaced coral buttresses separated by narrow sediment-floored grooves.

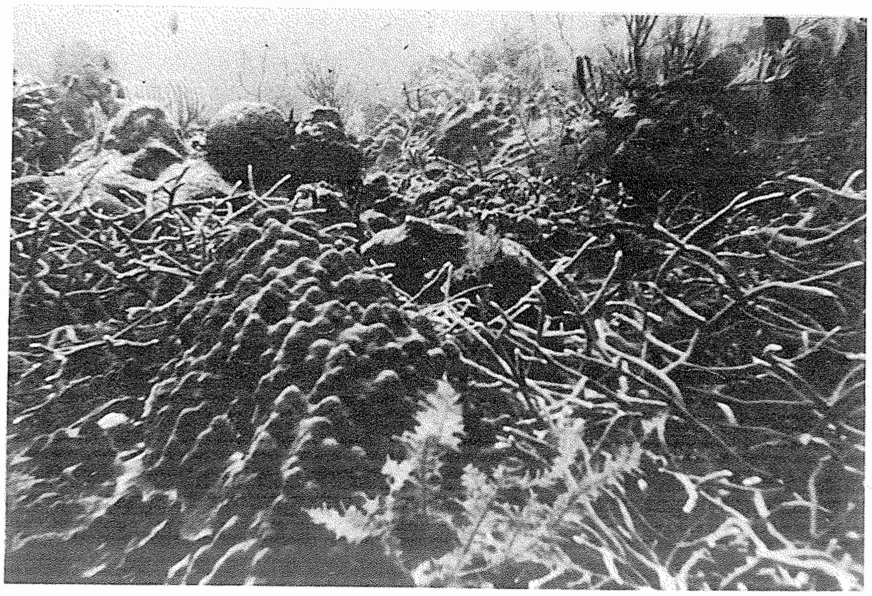


Figure 9. Diverse coral community typical of the shelf-margin reef (water depth 22 m).

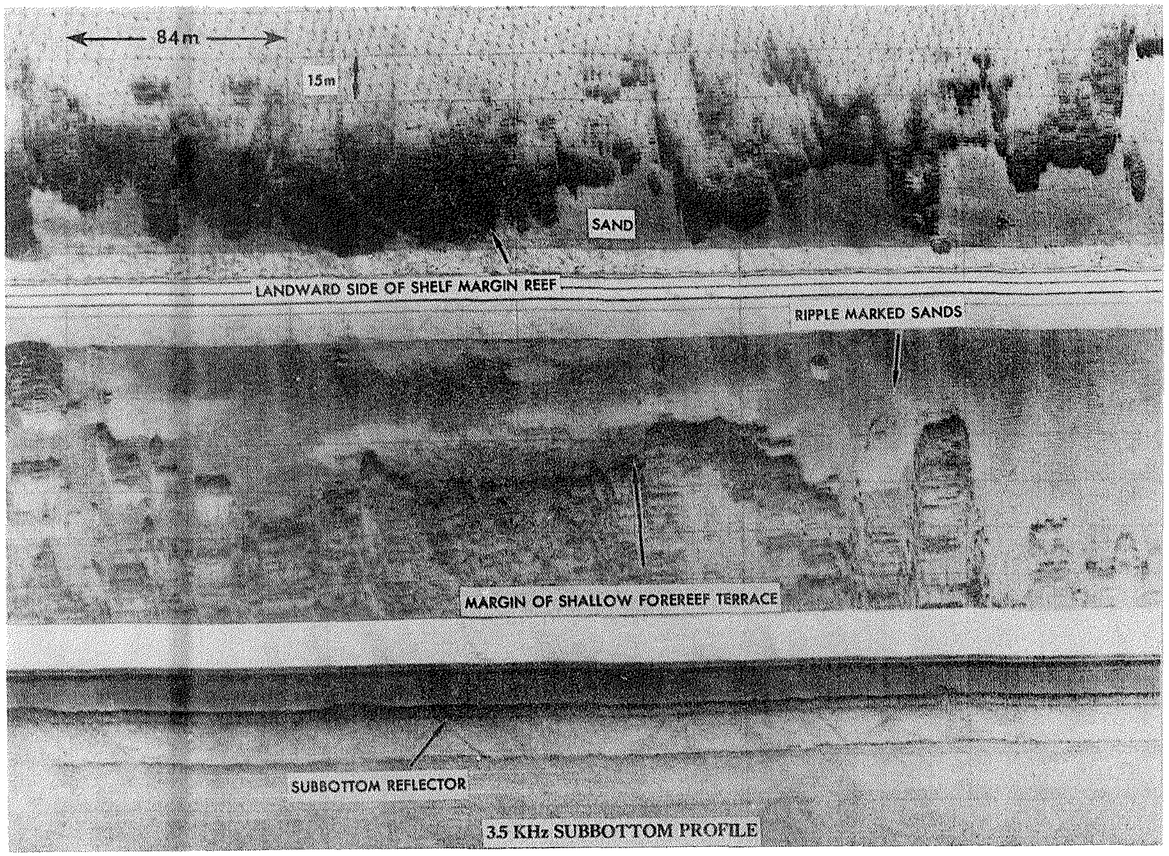


Figure 10. Side-scan sonograph and subbottom profile run parallel to the rather continuous shelf-margin reef (water depth ~22 metres) along the western part of the island. Note the well-developed spurs and grooves and extension of the shelf-margin coral spurs across the adjacent sediment plain. This configuration of extended spurs and a compartmentalized sediment plain is typical of higher energy shelves around the island. The shelf edge is represented by the area of "no return" at the top of the figure.

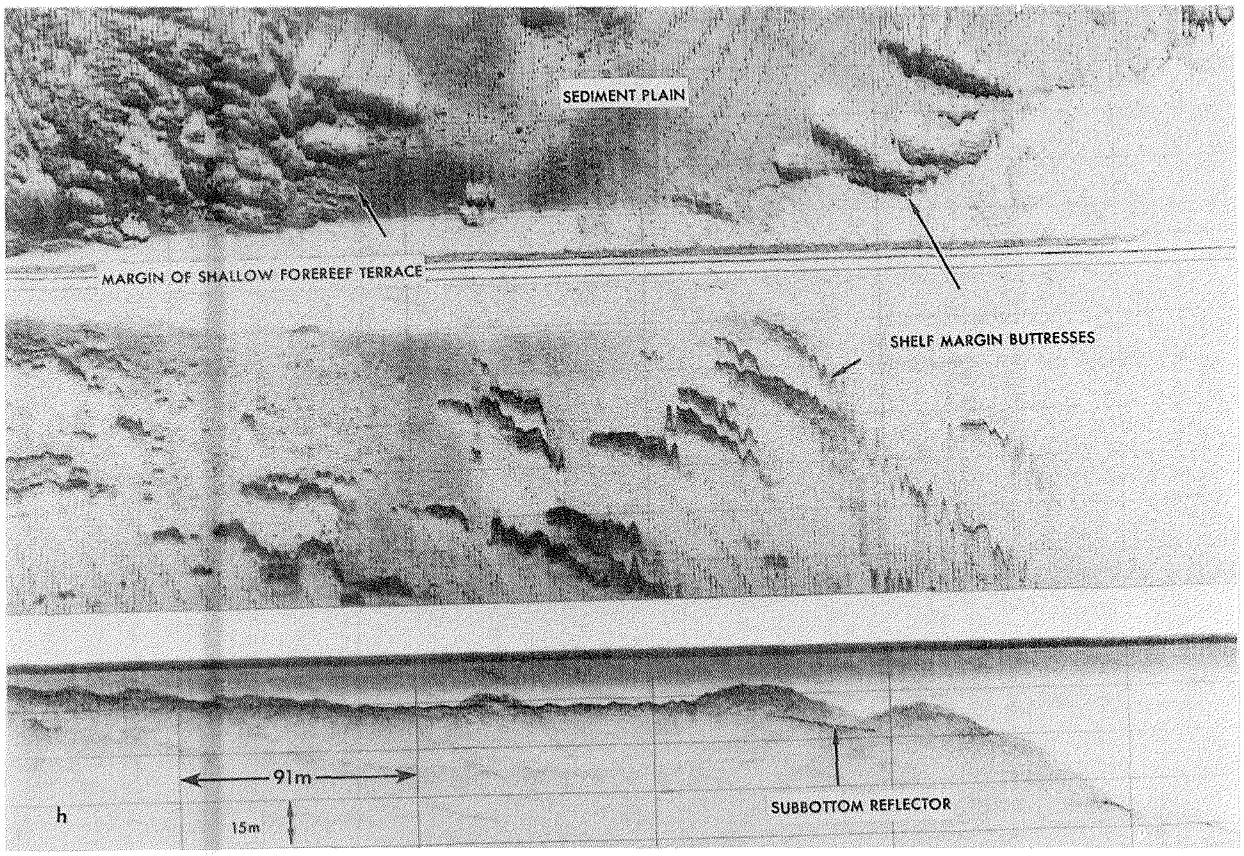


Figure 11. Side-scan sonograph and subbottom profile run across the shelf near the sediment-rich area of the island's southwestern flank. Much of this sediment was generated from shallow reefs acting as the seaward boundary for South Sound. Back-reef lagoon currents carry this material to the west, where it eventually reaches the lower shelf. Note the widely spaced and well-defined coral spurs or buttresses at the shelf edge.

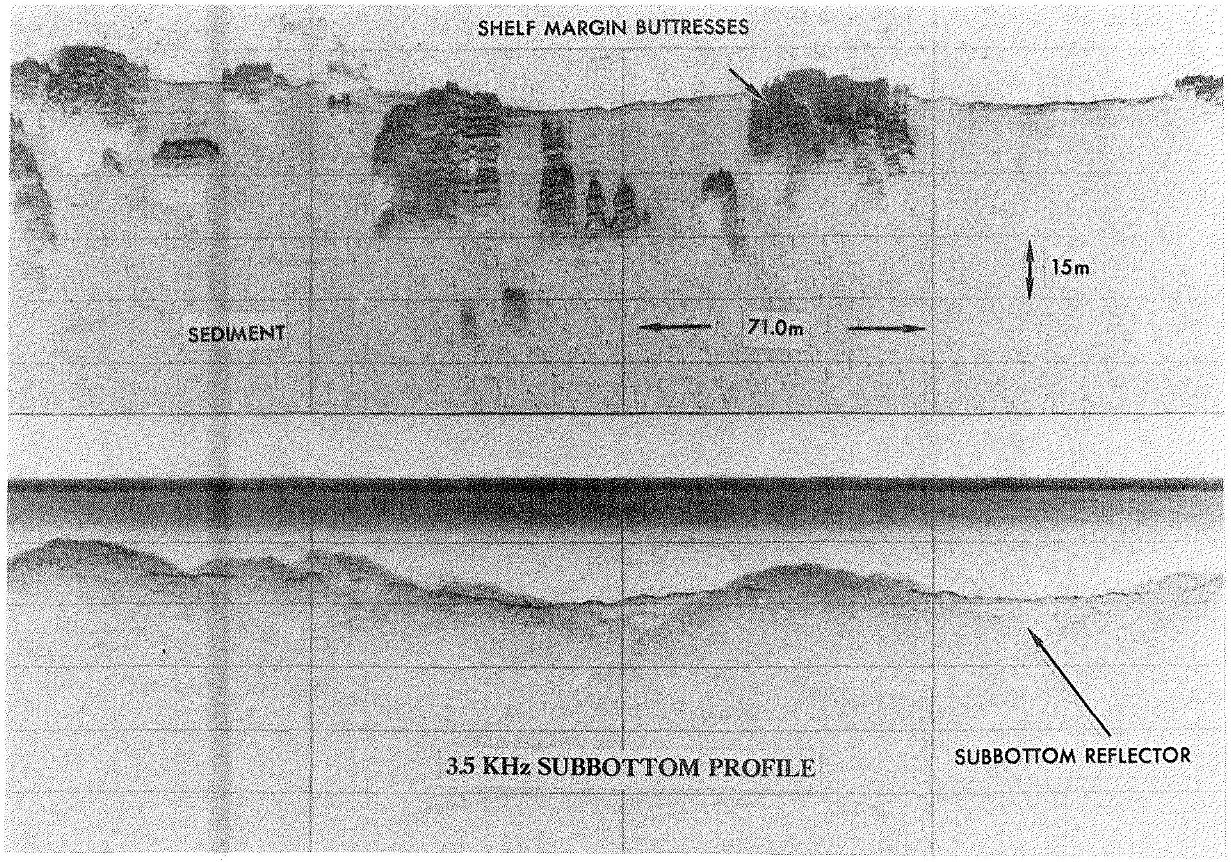


Figure 12. Side-scan sonograph (only one channel) and subbottom profile of the shelf margin opposite Southwest Point, where shelf sedimentation rates are relatively high. The shelf margin in this area consists of a few localized coral buttresses separated by wide paths for off-shelf sediment transport, clearly delineated. The side-scan sonar channel omitted was facing deep water and therefore no images were recorded.

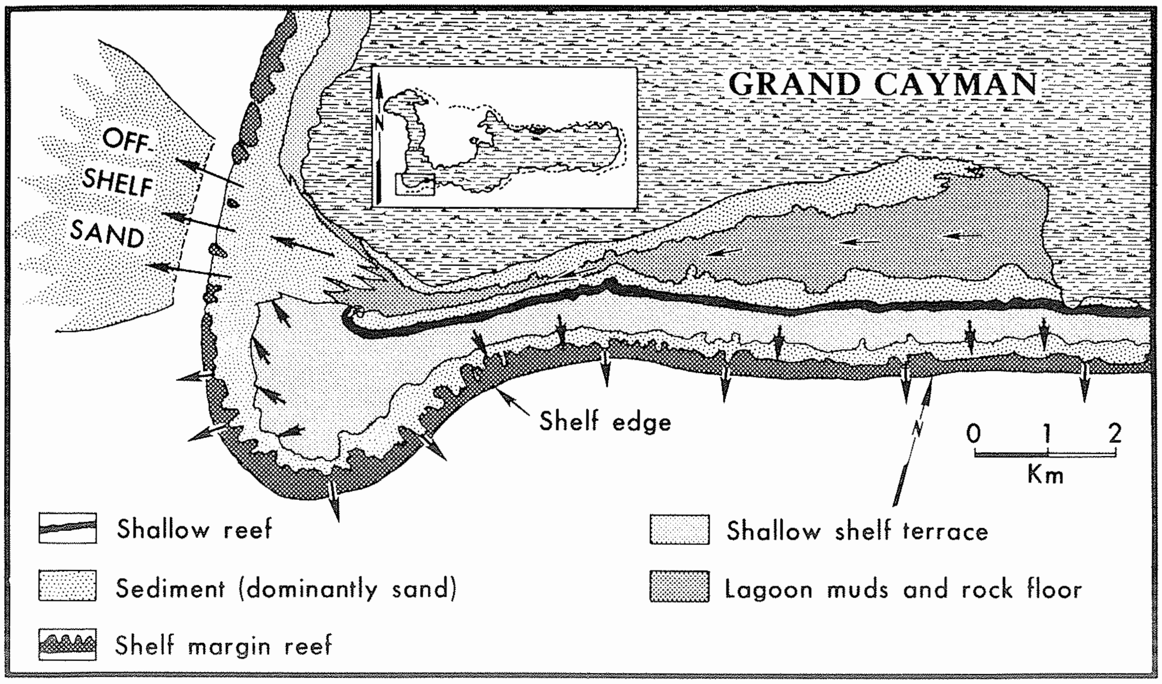


Figure 13. Sediment sinks and transport routes associated with the south western flank of Grand Cayman Island (South Sound and adjacent shelf areas). Arrows indicate sediment transport directions.

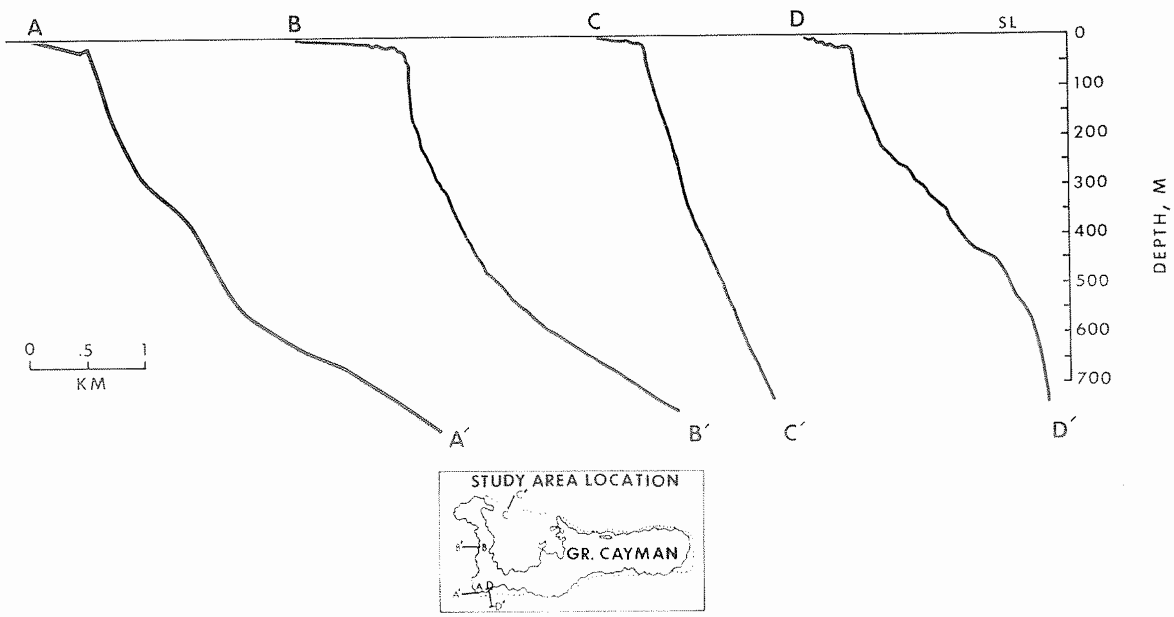


Figure 14. Echo-sounder profiles showing the variability in shelf and shelf-margin slope morphology around the western end of the island. Note the less steep and more "depositional" configuration to the lee side profiles.