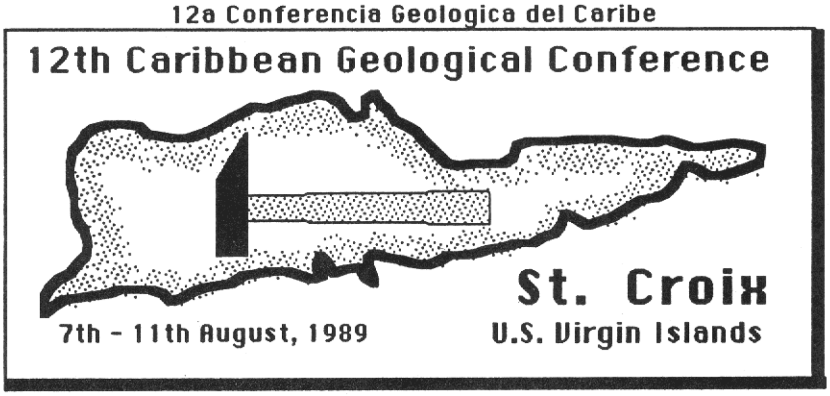
TRANSACTIONS OF THE 12TH CARIBBEAN GEOLOGICAL CONFERENCE

ST. CROIX, U.S. VIRGIN ISLANDS

August 7th - 11th, 1989

12a Conferencia Geologica del Caribe



12me Conference Geologique de Caraibes

Edited by

David K. Larue
Department of Geology, University of Puerto Rico
Mayagüez, PR 00708, Puerto Rico

and

Grenville Draper
Department of Geology, Florida International University
Miami, FL 33199
U.S.A.

Additional copies of this book may be purchased from

Miami Geological Society
P.O. Box 431552
South Miami, FL 33243, U.S.A.

December 1990

MORPHOLOGY AND DEVELOPMENT OF MODERN CARBONATE FORESLOPES, TONGUE OF THE OCEAN, BAHAMAS

G. M. Grammer, R. N. Ginsburg, and D. F. McNeill
Comparative Sedimentology Laboratory
University of Miami/RSMAS
Fisher Island Station
Miami Beach, Florida

ABSTRACT

Using a small research submersible, we have found that the upper slopes surrounding the southern portion of the Tongue of the Ocean exhibit a distinctive morphology characterized by a near-vertical escarpment followed by steeply dipping hard rock slopes with declivities of 35-45^{o}. These slopes are believed to be modern counterparts to the clinoforms often observed in outcrop and seismic sections of fossil carbonate platforms.

Our observations indicate that the slopes formed by the synsedimentary amalgamation of localized, linear trains of sediment and talus derived from the marginal escarpment and not through the emplacement of large-scale mass flow deposits. Pervasive submarine cementation subsequently lithified the slope deposits resulting in the preservation of the steep slope angles. Distinct variations in the patterns of sediment accumulation along the foreslopes depending upon the windward or leeward orientation of the margin were also observed. These variations result from the increased sedimentation rates associated with open leeward margins.

INTRODUCTION

Carbonate foreslopes define an important transitional zone between shallow-water platform carbonates and deeper-water basinal and distal slope deposits. Because of its position adjacent to the margin, knowledge of the depositional and early diagenetic processes acting on the foreslope and how they influence overall slope morphology may provide valuable insight into the mechanisms by which carbonate platforms evolve. A review of the more recent literature on modern platform to basin transitions, however, indicates that with the exception of a very few studies utilizing research submersibles (e.g. Moore et al., 1976; James and Ginsburg, 1979), this part of the slope has been mostly overlooked.

Recent work in the southern portion (or cul-de-sac) of the Tongue of the Ocean has shown that the foreslopes on both windward and leeward margins are characterized by a consistent overall morphology. The profile is dominated by a near-vertical escarpment extending down from approximately 50 to 140 meters, followed by steeply dipping (35-45^{o}) hard-rock surfaces that may extend down to depths greater than 300 meters. These steeply dipping slopes are notable because of their similarity to the inclined beds or clinoforms (Rich, 1951) often observed in outcrop or seismic profiles of fossil platform margins (e.g. Sarg, 1988). The major emphasis of this study is to document the morphologic features characteristic of the foreslope and to discuss the mechanisms responsible for the development of the slope.

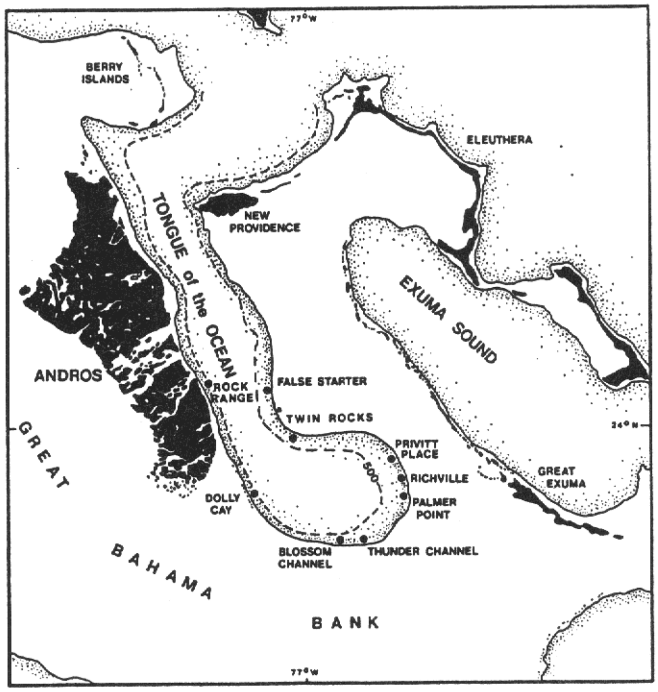


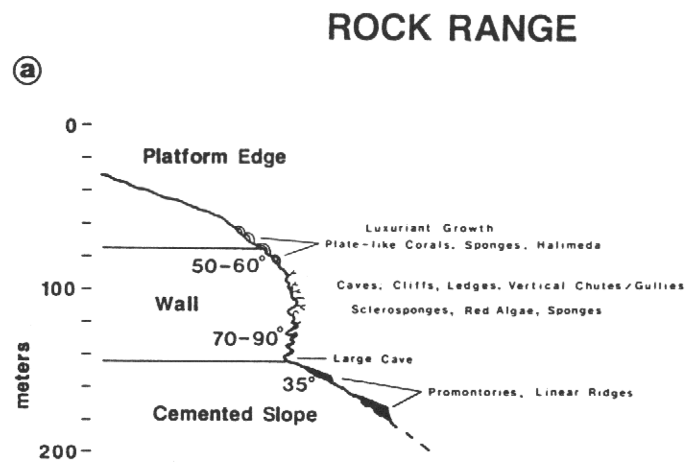
Figure 1. Map showing location of submersible dive sites in the Tongue of the Ocean, Bahamas. Depth in fathoms.

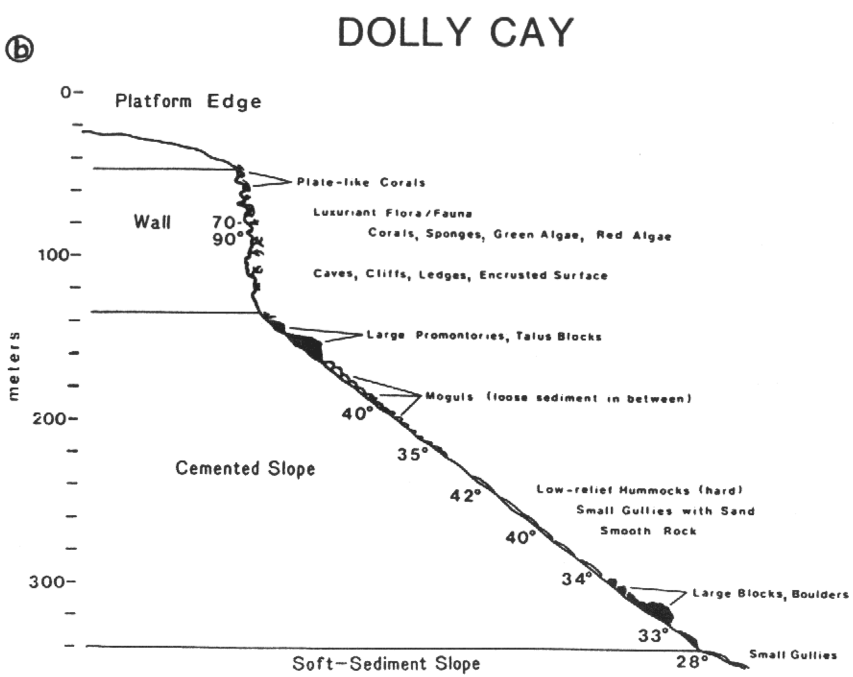
METHODS

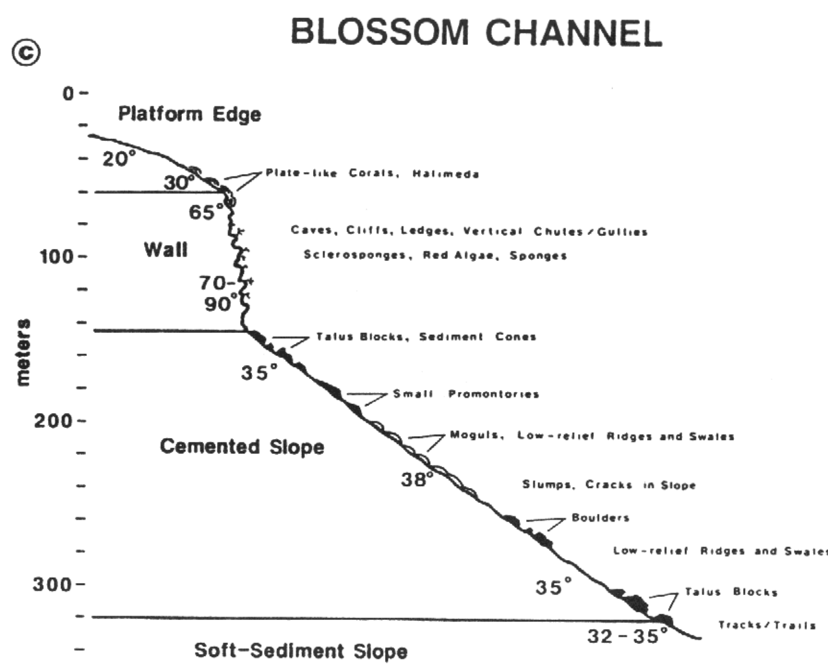
A total of 94 dives with the research submersible DELTA were made at nine locations around the southern portion of the Tongue of the Ocean (Figure 1). Utilization of the DELTA enabled us to observe first hand the morphological features of the slopes, to document our observations via videotape and still photography, and to collect both sediment and rock samples from known locations along the slope. Slope profiles were constructed from a synthesis of initial dive observations combined with the evaluation of videotape documentation from all dives. Slope angles were measured using an inclinometer from inside the submersible.

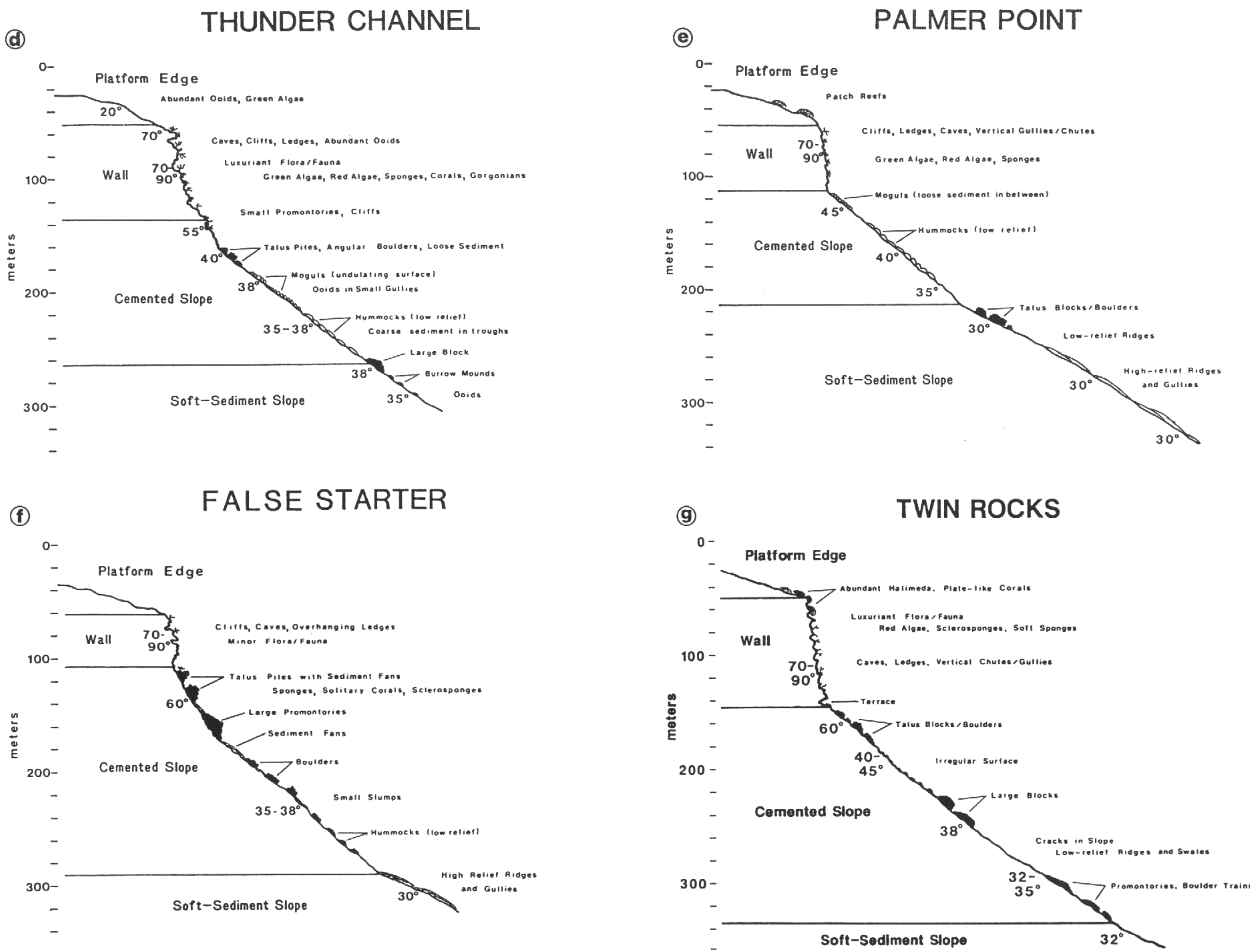
Larue, D.K., and Draper, G. (eds.),
Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S.V.I., Miami Geological Society, P.O. Box 431552, South Miami, FL 33243, U.S.A

Figure 2a-g. Profiles of upper slope from representative dive sites. Profiles were constructed from a synthesis of data accumulated during a total of 94 dives in the Tongue of the Ocean during 1987 and 1988. No vertical exaggeration.









THUNDER CHANNEL
d
Platform Edge
Abundant Ooids, Green Algae
20°
70°
Caves, Cliffs, Ledges, Abundant Ooids
Luxuriant Flora/Fauna
Green Algae, Red Algae, Sponges, Corals, Gorgonians
Wall
70-90°
Small Promontories, Cliffs
55°
Talus Piles, Angular Boulders, Loose Sediment
40°
Moguls (undulating surface)
Ooids in Small Gullies
38°
Cemented Slope
Hummocks (low relief)
Coarse sediment in troughs
35-38°
Large Block
38°
Burrow Mounds
Ooids
35°
Soft-Sediment Slope
meters
0
100
200
300
PALMER POINT
e
Platform Edge
Patch Reefs
Cliffs, Ledges, Caves, Vertical Gullies/Chutes
Wall
70-90°
Green Algae, Red Algae, Sponges
Moguls (loose sediment in between)
45°
Hummocks (low relief)
Cemented Slope
40°
35°
Talus Blocks/Boulders
30°
Low-relief Ridges
Soft-Sediment Slope
High-relief Ridges and Gullies
30°
30°
meters
0
100
200
300
FALSE STARTER
f
Platform Edge
Cliffs, Caves, Overhanging Ledges
Minor Flora/Fauna
Wall
70-90°
Talus Piles with Sediment Fans
Sponges, Solitary Corals, Sclerosponges
60°
Large Promontories
Sediment Fans
Boulders
Cemented Slope
Small Slumps
35-38°
Hummocks (low relief)
High Relief Ridges and Gullies
30°
Soft-Sediment Slope
meters
0
100
200
300
TWIN ROCKS
g
Platform Edge
Abundant Halimeda, Plate-like Corals
Luxuriant Flora/Fauna
Red Algae, Sclerosponges, Soft Sponges
Wall
Caves, Ledges, Vertical Chutes/Gullies
70-90°
Terrace
60°
Talus Blocks/Boulders
40-45°
Irregular Surface
Large Blocks
Cemented Slope
38°
Cracks in Slope
Low-relief Ridges and Swales
32-35°
Promontories, Boulder Trains
Soft-Sediment Slope
32°
meters
0
100
200
300

RESULTS AND INTERPRETATION

Morphology

Observations of the slopes around the Tongue of the Ocean indicate that the upper slope, or foreslope, is characterized by a distinctive morphology that may be subdivided into four zones (Figures 2a-g):

1. The platform edge, which consists of a Holocene sediment wedge, is situated in shallower water behind one or more areas of deep (40-60m) reef growth. These reefs, where present, are dissected by a series of sediment chutes that may extend to the edge of the platform. The sediment composition of the platform margin varies depending upon its windward or leeward positioning (see Figure 3).

2. The near-vertical wall, with slopes ranging from 70° to 90°, begins at water depths of 40-60 meters. This zone consists of variable types of deep-water corals, encrusting coralline algae, soft sponges, sclerosponges, and green algae. The surface of the wall is characterized by numerous small pits, caves, ledges, and vertical overhangs. Unconsolidated sediment derived both from the edge of the platform and the wall rests on all horizontal and sub-horizontal surfaces. Our observations suggest that the wall is capable of producing copious amounts of sediment, through both biological production (primarily *Halimeda* sp.) and bioerosion, which is subsequently transported further downslope.

The wall extends down to a depth of 135 to 145 meters except along the leeward margins where higher rates of sedimentation have effectively buried the lowermost portions. The base of the wall is commonly marked by near-horizontal ledges extending for tens of meters and flat-floored caves, suggesting that this may mark a previous lowstand of sea-level. The transition from the wall to the underlying cemented slope is often characterized by the presence of large talus blocks, some up to 30m high, that have apparently been derived through mass-wasting of the wall above.

3. The cemented slope is found at the base of the wall and is characterized by relatively consistent slope angles between 35° and 45°. The surface of the cemented slope often exhibits an irregular morphology of rounded to elliptical topographic highs (moguls) separated by trains of unconsolidated sediment in the adjacent troughs. Near the base of the wall, the moguls are mostly rounded and range in height from a few decimeters to over a meter. Downslope, the moguls are progressively more elongate.

In some areas, large promontories that are a few meters in height and up to several meters or tens of meters long project outward from the slope. These promontories may have been formed by the repeated deposition and subsequent cementation of numerous generations of sediment piled-up behind talus blocks.

The cemented slope is notable for its well-lithified surface, internal bedding, and steep slope angles. Only a thin veneer of unconsolidated sediment is present, primarily in localized topographic lows. Petrographic analysis of rock samples from this zone indicates pervasive submarine cementation dominated by micritic Mg-calcite cements. Lesser amounts of isopachous bladed Mg-calcite along with pore-filling fibrous and botryoidal aragonite cements are also present.

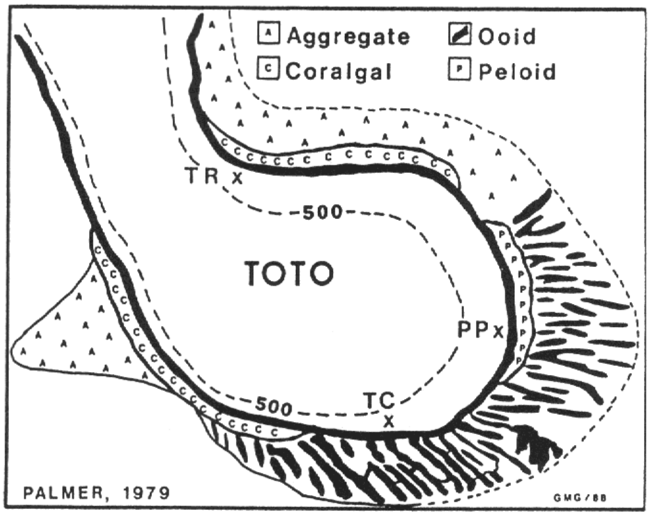


Figure 3. Map showing distribution of surface sediments in the southern portion of the Tongue of the Ocean. Thick dark line indicates slope break at top of wall. Depth in fathoms. TR - Twin Rocks; PP - Palmer Point; TC - Thunder Channel. Modified from Palmer (1979).

4. The soft-sediment slope is a wedge of unconsolidated sediment with slope angles of 25° to 30° that onlaps the overlying cemented slope. This sediment wedge exhibits varying surface morphologies ranging from a smooth sediment blanket to a series of large sediment ridges and erosional troughs that may be several meters high and extend downslope for many tens of meters. Active bioturbation in this zone is suggested by the presence of numerous tracks, trails and apparent burrows on the surface of the unconsolidated sediment. The transition between the cemented slope and the soft-sediment slope is often marked by an accumulation of talus blocks and reefal material derived from above. The soft-sediment slope consists of a mixture of platform-derived sands and muds, and deep water planktic material and defines the uppermost portion of the present-day, active depositional slope.

Development

The questions of how and when the cemented slope formed are of primary interest because of the similarity to steeply dipping slope deposits seen in the fossil record. Carbonate slopes from the Permian of West Texas/New Mexico (Yurewicz, 1977; Ward et al., 1986), the Devonian of Western Australia (Playford, 1980, 1989), and the Triassic Dolomites of northern Italy (Bosellini, 1984; Harris, 1988) all exhibit primary depositional slopes of 35-40°. This type of slope profile is also frequently observed in seismic profiles from ancient carbonate platforms in the subsurface (e.g. Sarg, 1988). Researchers working on both modern and ancient carbonate slopes have suggested a myriad of downslope, gravity-induced mechanisms for the deposition of sand-size and coarser sediments. On modern carbonate slopes, Cook and Mullins (1983) and Enos and Moore (1983) indicate that relatively large-scale turbidity currents and debris flows appear to be the dominant mechanisms for the downslope transport of coarse detritus.

Observations from the Tongue of the Ocean, however, suggest that the foreslopes formed by an alternative mechanism. In particular, the cemented slope appears to have formed in large part by the progressive amalgamation of localized, linear trains or lobes of coarse sands and gravels rather than by emplacement of large-scale mass flow deposits. These sediment lenses are decimeters thick and average a few meters wide by a few tens of meters long and are oriented with their long axes parallel to the slope. They appear to form by the damming of sand and gravels behind large talus blocks or piles of rubble forming a framework that is subsequently "filled-in" by deposition of finer sands and muds. The sand-size and coarser material are derived from the wall and the margin of the platform and are dominated by Halimeda sands and coral rubble. The lobes of sediment are then rapidly lithified by pervasive submarine cementation. Repeated episodes of deposition and cementation result in the amalgamation of individual sediment packages that are linear in shape and discontinuous in both lateral and vertical dimensions along the slope. Because of the progressive infilling of the sieve-like internal structure of the lobes by fine sand and mud, the slope deposits are expected to have a considerably different internal fabric than those deposited by large-scale debris flows or turbidity currents.

Radiocarbon dating of skeletal components, utilizing accelerator mass spectrometer techniques to minimize the analytical error (Linick, et al., 1986), indicate that the cemented slope was an active depositional slope until approximately 10-11 ka. This suggests that the steep cemented slopes were actively forming while sea level was rising from the last lowstand of sea level (15-18 ka) and before the platform itself was flooded (6-8 ka). During this time, coarse sands and gravels derived from the wall were deposited primarily by grain flow and rock fall mechanisms on the steeply inclined slopes.

Another interesting and potentially significant feature observed along the Tongue of the Ocean slopes is the presence of rounded mounds that give the slope the appearance of a mogul field on an alpine ski slope. These moguls are found along the upper portions of the cemented foreslope (see slope profiles). They are nearly spherical at the top of the slope and gradually become more elliptical or elongate downslope with the long dimension oriented parallel to the slope. They are generally a meter or less in height and may be up to a few meters in diameter. Both dimensions decrease downslope. The surface of the moguls are typically covered by various encrusting and binding organisms.

Preliminary evaluation of these moguls suggests that they may have at least two possible origins. The first is that they may simply represent a "boulder field" of talus derived from above. Angular blocks derived from the wall could have been partially covered by prodigious amounts of sediment deposited on the slope. Progressive burial combined with surface colonization by encrusting organisms would have resulted in the rounded outline observed today.

Another possibility is that the moguls represent accretional features that formed by the sediment-trapping and binding of a community of turf-like organisms present on the surface of the slope. Subsequent cementation might lead to progressive formation of a hard, rounded, dome-like deposit similar to the observed moguls. Features similar to these have been described by Haddad et al. (1984) and James et al. (1988) from the Miocene in the Gulf of Suez, and from the Devonian of the Canning Basin, Australia (Playford et al., 1976). These features were interpreted by James (1988) and Playford (1976) to be deepwater "stromatolites" that formed along the foreslopes at depths approximately 50-100 meters below the level of the reef-crest. Continuing work on the moguls found in the Tongue of the Ocean should provide further insight into the evolution of these features.

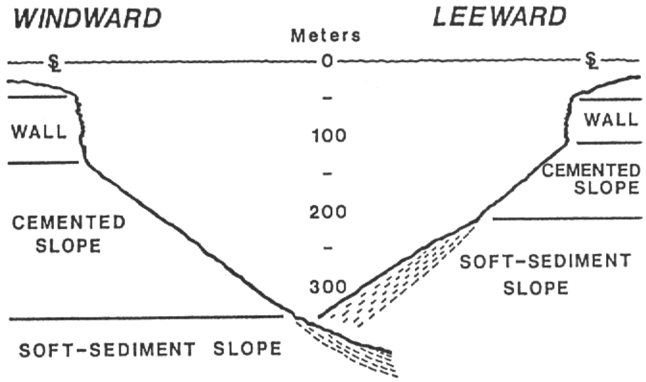


Figure 4. Schematic diagram showing variations in the slope profile related to windward or leeward positioning. Note that on leeward margins, the depth at which the soft-sediment onlaps the cemented slope is over 100m shallower than on windward margins and that the base of the wall appears to have been buried. Both results are presumably due to higher sedimentation rates along leeward margins.

WINDWARD VS. LEEWARD MARGINS

Our observations in the Tongue of the Ocean indicate that there are distinctive patterns of sediment accumulation related to the windward and leeward positioning of the margins (Figure 4). The most striking feature is the variable thickness in the wedge of unconsolidated, fine-grained sediment onlapping the cemented slope (see Figure 5). Leeward transects show a significantly higher upper limit of soft sediment onlap (about -215m) than the windward margin (about -320m), presumably as a result of greater amounts of fine-grained sediment being carried off the open leeward platform. Further north, where the leeward margin is partially sheltered by the Exuma chain, less fine-grained sediment accumulates (top at -275m). The depth to the base of the near-vertical wall also reflects variations due to windward versus leeward orientation. Figure 6 illustrates how the base of the wall is at a depth of 135-145m along the windward margins while it is considerably shallower on the leeward side. We believe that higher sedimentation rates along the leeward margins have resulted in the burial of the base of the wall along that side. This hypothesis is supported by the fact that in localized areas along the leeward margin, where there has apparently been some sheltering from sedimentation, the near-vertical wall extends down to depths equivalent to those found along the windward margin. These observations support the concept of rapid lateral growth on leeward margins and suggest that variations in sheltering effects may strongly influence carbonate platform growth.

ACKNOWLEDGEMENTS

This project has been funded as part of NOAA's National Undersea Research Program (SU-2-0887 and SU-2-0888 to RNG). Radiocarbon dating was performed by Tim Jull at the University of Arizona. We would like to acknowledge the valuable assistance provided by the captain and crew of the R/V Powell, and by the DELTA's support team, especially pilots Rich Slater and Doug Privitt. We are also indebted to our ship-board colleagues (Alton Brown, Paul Crevello, John Dunham, Gregor Eberli, Steve Murray, Harry Roberts, Art Saller, Stan Schumm, Peter Swart, and

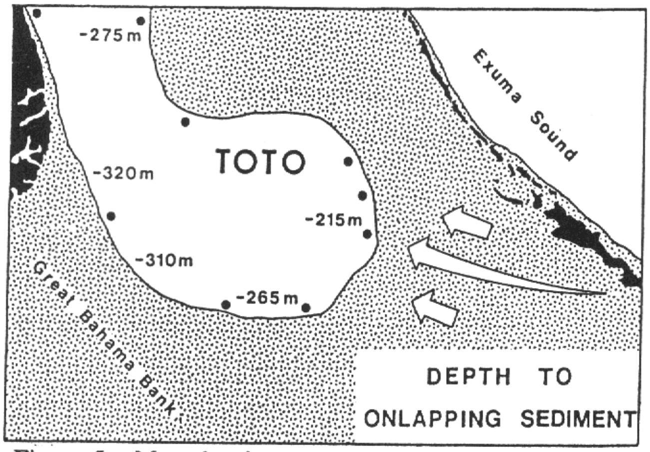


Figure 5. Map showing average depth to onlapping soft-sediment slope around TOTO. Depths determined from an analysis of all dives. Arrows indicate predominant winds (ESE). Note that on open leeward margins the soft-sediment has onlapped over 100m higher than on windward margins.

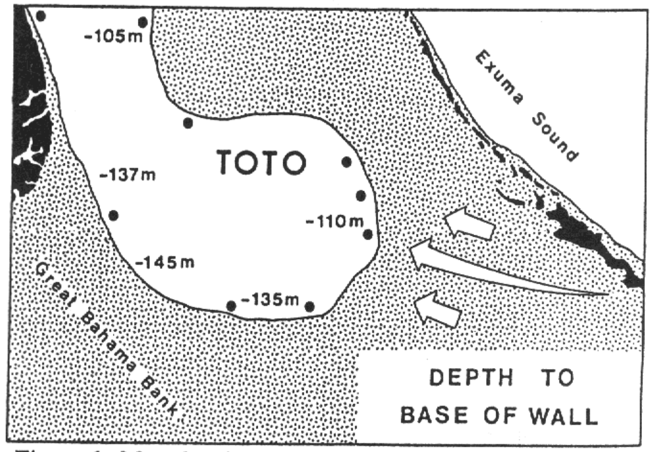


Figure 6. Map showing average depth to base of wall around the TOTO. Depths determined from an analysis of all dives. Arrows indicate the predominant winds (ESE). Note that the base of the wall has apparently been covered by greater amounts of sedimentation along the leeward margin.

Stuart Williams). Comments and suggestions by D. K. Larue improved the manuscript. A contribution from the Comparative Sedimentology Laboratory, Rosenstiel School of Marine and Atmospheric Science, University of Miami.

REFERENCES CITED

Bosellini, A., 1984, Progradation geometries of carbonate platforms: examples from the Triassic of the Dolomites, northern Italy: Sedimentology, vol. 31, p.1-24.

Cook, H. E., and H. T. Mullins, 1983, Basin Margin, in Scholle, P. A., Bebout, D. G., and C. H. Moore (eds.), Carbonate Depositional Environments: AAPG Memoir 33, p. 539-619.

Enos, P.. and C. H. Moore, 1983, Fore-reef Slope, in Scholle, P. A., Bebout, D. G., and C. H. Moore (eds.), Carbonate Depositional Environments: AAPG Memoir 33, p. 507-539.

Haddad, A., Aissaoui, M. D., and M. A. Soliman, 1984, Mixed carbonate-siliciclastic sedimentation on a Miocene fault-block, Gulf of Suez: Sedimentary Geology, vol. 37, p. 182-202.

Harris, M. T., 1988, Margin and foreslope deposits of the Latemar Carbonate Buildup (Middle Triassic), The Dolomites, Northern Italy: Ph.D. dissertation, Johns Hopkins University, 473 p.

James, N. P., and R. N. Ginsburg, 1979, The seaward margin of Belize barrier and atoll reefs: Int'l. Assoc. Sed., Special Publication no. 3, 191 p.

James, N. P., Coniglio, M., Aissaoui, D. M., and B. H. Purser, 1988, Facies and geologic history of an exposed Miocene rift-margin carbonate platform: Gulf of Suez, Egypt: AAPG Bulletin, vol. 72, p. 555-572.

Linick, T. W., Jull, A. J. T., Toolin, L. J., and D. J. Donahue, 1986, Operation of the NSF-Arizona Accelerator Facility for Radioisotope Analysis and results from selected collaborative research projects: Radiocarbon, vol. 28, p. 522-533.

Moore, C. H., Graham, E. A., and L. S. Land, 1976, Sediment transport and dispersal across the deep fore-reef and island slope (-55m to -305m), Discovery Bay, Jamaica: Journal Sed. Pet., vol. 46, p. 174-187.

Palmer, M., 1979, Holocene facies geometry of the leeward bank margin of Tongue of the Ocean: unpubl. M. S. Thesis, Univ. Miami, FL, 199 p.

Playford, P. E., Cockbain, A. E., Druce, E. C., and J. L. Wray, 1976, Devonian stromatolites from the Canning Basin, Western Australia, in M. R. Walter (ed.), Stromatolites: Elsevier, Amsterdam, p. 543-564.

Playford, P. E., 1980, Devonian "Great Barrier Reef" of Canning Basin, Western Australia: AAPG Bulletin, vol. 64, p. 814-840.

Playford, P. E., Hurley, N. F., Kerans, C., and M. F. Middleton, 1989, Reefal platform development, Devonian of the Canning Basin, Western Australia: SEPM Spec. Publ., no. 44, p. 187-202.

Rich, J. L., 1951, Three critical environments of deposition, and criteria for recognition of rocks deposited in each of them: GSA Bulletin, vol. 62, p. 1-20.

Sarg, J. F., 1988, Carbonate sequence stratigraphy, in Sea-Level Changes - An Integrated Approach: SEPM Spec. Publ., no. 42, p. 155-181.

Ward, R. F., Kendall, C. G. St. C., and P. M. Harris, 1986, Upper Permian (Guadalupian) facies and their association with hydrocarbons - Permian Basin, West Texas and New Mexico: AAPG Bulletin, vol. 70, p. 239-262.

Yurewicz, D. A., 1977, Origin of the massive facies of the Lower and Middle Capitan Limestone (Permian), Guadalupe Mountains, New Mexico and West Texas: SEPM (Permian Basin Section) Guidebook, no. 77-16, p. 45-92.