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REEFS AND BANKS OF THE NORTHWESTERN GULF OF MEXICO: THEIR GEOLOGICAL, BIOLOGICAL, AND PHYSICAL DYNAMICS

EXECUTIVE SUMMARY

Northern Gulf of Mexico Topographic Features Synthesis
Contract No. AA851-CT1-55

Submitted to the
U.S. Department of the Interior
Minerals Management Service
Outer Continental Shelf Office
New Orleans, Louisiana

Technical Report No. 83-1-T

Research Conducted Through
the Texas A&M Research Foundation

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CONTRIBUTORS

Program Manager
William J. Merrell, Jr.

Assistant Program Manager
Sylvia C. Herrig

Principal Investigators
Texas A&M University
Department of Oceanography

Richard Rezak
Geological

Research Staff

Patricia Brown
Jeffrey L. Payne
David Risch
Kyung-Sik Woo

Thomas J. Bright
Biological

Research Staff

Scott L. Baggett
Christopher L. Combs
Allison Craig
George Dennis
Steve Gittings
George Kraemer
Gregory Minnery
Richard H. Titgen

David W. McGrail
Sedimentological & Physical

Research Staff

Michael R. Carnes
Thomas M. Cecil
Lawrence Goldberg
Fern B. Halper
Jeffrey W. Hawkins
Doyle Horne

Editor

Rose Norman

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11. For editorial management, Rose Norman, Research Associate, Department of Oceanography, Texas A&M University.

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PREFACE

This is a summary of the final report "Reefs and Banks of the Gulf of Mexico: Their Geological, Biological, and Physical Dynamics." The final report is a synthesis of data collected between the fall of 1974 and the summer of 1981. The report is divided into three parts: 1) the regional setting, 2) the geology, hydrology, and biology of the East and West Flower Garden Banks, and 3) a categorization of the banks based upon the model of the Flower Garden Banks. In Chapter 3 of this summary report we describe certain banks as representative of the various recognized categories.

CHAPTER 1

REGIONAL SETTING

The Gulf of Mexico is a small ocean basin that originated approximately 160 million years ago (late Jurassic time) due to the rifting of the North American, African, and South American plates. (For those unfamiliar with the geologic time scale, one is presented in Appendix A.) The shallow, primordial Gulf has gradually evolved into its present configuration, being enlarged due to continued spreading, deepened due to subsidence, and being slowly filled by sedimentation. The spreading phase ended during the Cretaceous Period (approximately 80 to 100 million years ago). Sedimentation and subsidence will continue as long as streams flow into the Gulf from the continent and lime-secreting organisms continue to thrive in areas of low stream outflow.

The Western Gulf, from the Mississippi Delta to the Campeche Canyon on the west side of the Yucatan Shelf, illustrates very clearly the influence of deltaic sedimentation on the continental shelf of the Gulf. The Mississippi River, because of its great drainage area, has been the major contributor of deltaic sediments throughout Cenozoic time, and as a consequence has built an extremely large coastal plain - continental shelf complex in the northwestern Gulf of Mexico. The narrowing of the coastal plain (continental shelf complex southward into Mexico) is due to the limited drainage areas of the streams flowing into that part of the Gulf.

The shelves of Mexico, Texas, Louisiana, Mississippi, and Alabama are all floored with terrigenous sediment containing varying amounts of silt and clay (Figure 1.1). They also receive fresh water input that alters the nearshore salinity gradients. The presence of silt and clay, and other observations, suggest that nearshore waters are likely to be turbid top-to-bottom inside of the 10 m isobath and that the shelf will have a nepheloid layer that may reach 35 m or more in thickness.

The West Florida Shelf and the Yucatan Shelf are broad, shallow areas that are composed primarily of carbonate sediments produced by lime-secreting organisms. Neither suffers appreciable salinity variations. These areas of little or no continental sediment influx are underlain by thousands of metres of shallow-water carbonate sediments, indicating that accumulation of carbonate skeletons on the seafloor in these areas has kept pace with subsidence for many tens of millions of years.

The final structural complication in the northwestern Gulf is the formation of salt diapirs on the Outer Continental Shelf and

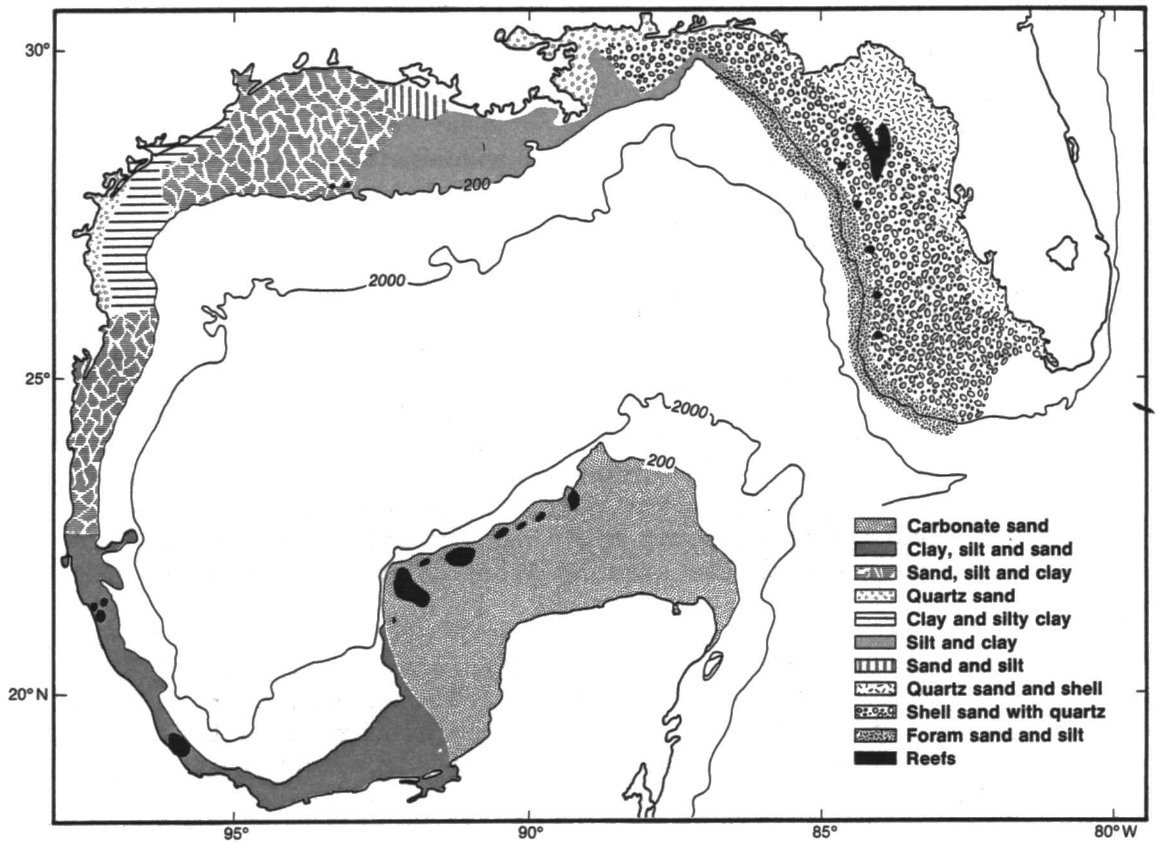

Figure 1.1 Sediment distribution, Gulf of Mexico Outer Continental Shelf.

continental slope. It is on these structures that most of the banks and reefs discussed in this report occur.

In the winter, cold fronts in the northwestern Gulf create deep mixed layers. Shoreward of where these mixed layers intersect the bottom, the temperature of the water may become very low because of the limited heat capacity of the water. As each front comes through, it extracts more heat so that coastal waters off Texas may drop to 10 or 12°C. Offshore of the intersection of the mixed layer with the bottom, water temperatures remain relatively high because of the large heat reservoir of the thick lens of water. At the shelf edge of Texas, the water at a depth of about 50 m remains warmer than 17.5°C all year and above 18°C most of the year.

Figure 1.2 summarizes the near surface circulation patterns and relative turbidity on the shelves.

With respect to the biotic communities of the Gulf, it has been demonstrated that Caribbean populations can be carried north and east along the Outer Continental Shelf off Mexico, Texas, and Louisiana in an anticyclonic circulation pattern. There has been no better demonstration of this than the IXTOC oil spill. Similar communities could be delivered to the Florida shelf by eddies that spin off the Loop Current and propagate to the north over the outer shelf.

The inflow of warm tropical water from the Caribbean, carrying larvae from West Indian reef ecosystems, is of overwhelming importance in determining the nature of the Gulf of Mexico benthos. The resultant planktonic "ambience" of tropical forms provides a broad potential for adult community structure, which is selectively expressed at various locations on the continental shelf.

Primarily, community structure depends on structural and sedimentological characteristics of the substratum, river outflow, and seasonal and regional variations in water temperature, salinity, and turbidity. In the northern Gulf, which is in many ways a differentially stressed ecotone for tropical biota, the influence of coastal marine and climatic environments is particularly important in determining the degree of expression of tropical benthic communities. Thus, assessment of marine biogeographical relationships in the Gulf and adjacent regions requires that one have some view of the distribution of and general relationship between major hard-bottom communities from the shore to at least the continental shelf edge.

The latitudinal boundary between tropical and warm temperate varies considerably within the Gulf of Mexico. The impact of temperate climatic conditions on community structure is certainly evident on the coast and inner shelf of the northern Gulf of Mexico. Even there, however, the basically temperate estuarine and nearshore assemblages are accompanied by tropical ecosystem components in

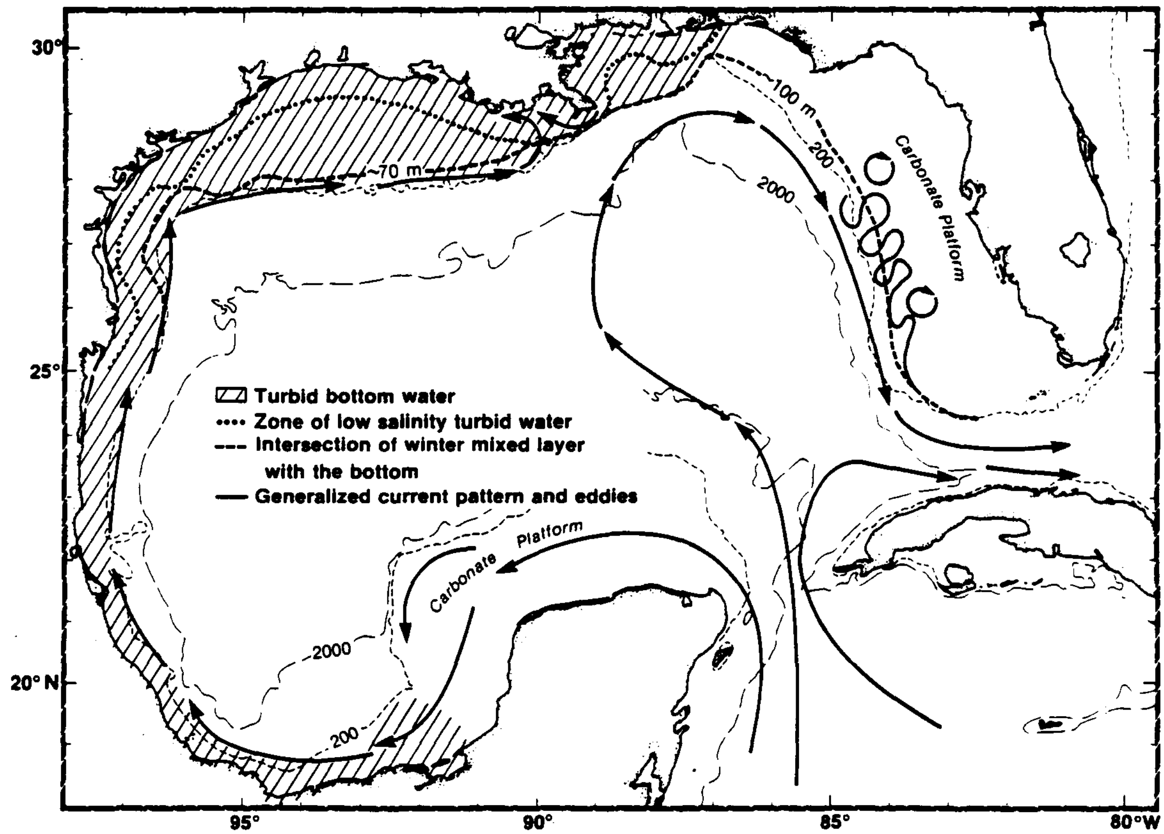

Figure 1.2 Map of Gulf of Mexico summarizing the primary near-surface circulation patterns which may be responsible for carrying biotic communities into the Gulf and from there either anticyclonically around the western Gulf or to the Florida shelf via the Loop Current and spin-off eddies. Diagonal pattern indicates regions of appreciable turbidity in the water column. Dotted line delineates seaward margin of near-shore, low-salinity turbid water. The dashed line near the Outer Continental Shelf indicates depths where the winter mixed layer intersects the bottom.

significant abundance. Progressing offshore, the benthic biota become increasingly tropical in nature so that the general impression is of a more-or-less crescent shaped coastal and nearshore zone in the northern Gulf wherein there is an incomplete transition from tropical offshore to basically warm temperature coastal biota. Biotic community type and distribution on the mid and outer shelves may be determined more by substratum type and bathymetry than by latitude.

Whatever the regional biogeographic relationships may be, it is certain that biotic communities occupying the Outer Continental Shelf hard-banks in the northwestern Gulf of Mexico are of tropical origin. However, depending on their distance from shore, these communities are living either barely within acceptable ecological tolerance levels for thriving tropical reef assemblages (Flower Gardens and other shelf-edge banks) or below such limits (Sonnier, Stetson, and the South Texas fishing banks). The studies described in the following chapters add significantly to our knowledge of the benthic communities on these banks and certain ecological processes essential to regional reef construction and maintenance.

CHAPTER 2

THE FLOWER GARDEN BANKS

The Flower Garden Banks are located near the shelf edge, approximately 107 NM due south of Sabine Pass (Figure 2.1). The East Flower Garden Bank is at 27°54'32"N latitude and 93°36'W longitude in Lease Blocks A-366, A-367, A-374, A-375, A-388, and A-389 of the High Island Area (Figure 2.2). The bank is pear-shaped and covers an area of about 67 km^2. Slopes are steep on the east and south sides of the bank, with gentle slopes on the west and north sides (Figure 2.2). The shallowest depth on the bank is about 20 m in the northeastern part of Lease Block A-388. The surrounding water depths are about 100 m to the west and north and about 120 m on the east and south sides. An elongate depression in the north-central part of Lease Block A-389 has a depth of 136 m. Total relief on the bank is about 116 m.

The West Flower Garden Bank is 12 km west of the East Flower Garden at latitude 27°52'27"N, longitude 93°48'47"W (Figure 2.1) in Lease Blocks A-383-385, A-397-399, and A-410 of the High Island Area, South Addition, and Lease Block GB-134 of the Garden Banks Area. It is a much larger bank, covering about 137 km^2. The bank is oval-shaped and oriented in a northeast-southwest direction (Figure 2.3). The crest of the bank lies at a depth of approximately 20 m. Surrounding depths vary from 100 m to the north, to 150 m to the south. Total relief on the bank is approximately 130 m.

The East and West Flower Garden Banks are bathymetric prominences caused by salt diapirs. Bedrock outcrops on the seafloor at the crests of these prominences, caused by fracturing of the rocks overlying the salt diapir (Figure 2.4) served as substrates for the initial growth of reef-building organisms. Because the conditions of water depth, temperature, salinity, and water clarity were favorable, a complex of reef communities developed (Figure 2.5) and drastically changed the nature of the bottom sediments in the area of the banks.

The normal sediments on the open shelf surrounding the banks are sands and muds that have been eroded from the North American continent and mechanically transported to the Gulf of Mexico by streams such as the Mississippi, Trinity, Sabine, and Brazos Rivers. The banks rise from surrounding shelf depths of from 100 to 180 m to crests as shallow as 20 m. The normal shelf sands and muds do not occur at depths shallower than 75 to 80 m. The sediments above the 75 m level are all coarse, skeletal sands and gravels and rocky, limestone structures built by corals and other lime-secreting, reef-dwelling organisms. The loose sediments around the reef reflect the depth zonation of the biological communities that are

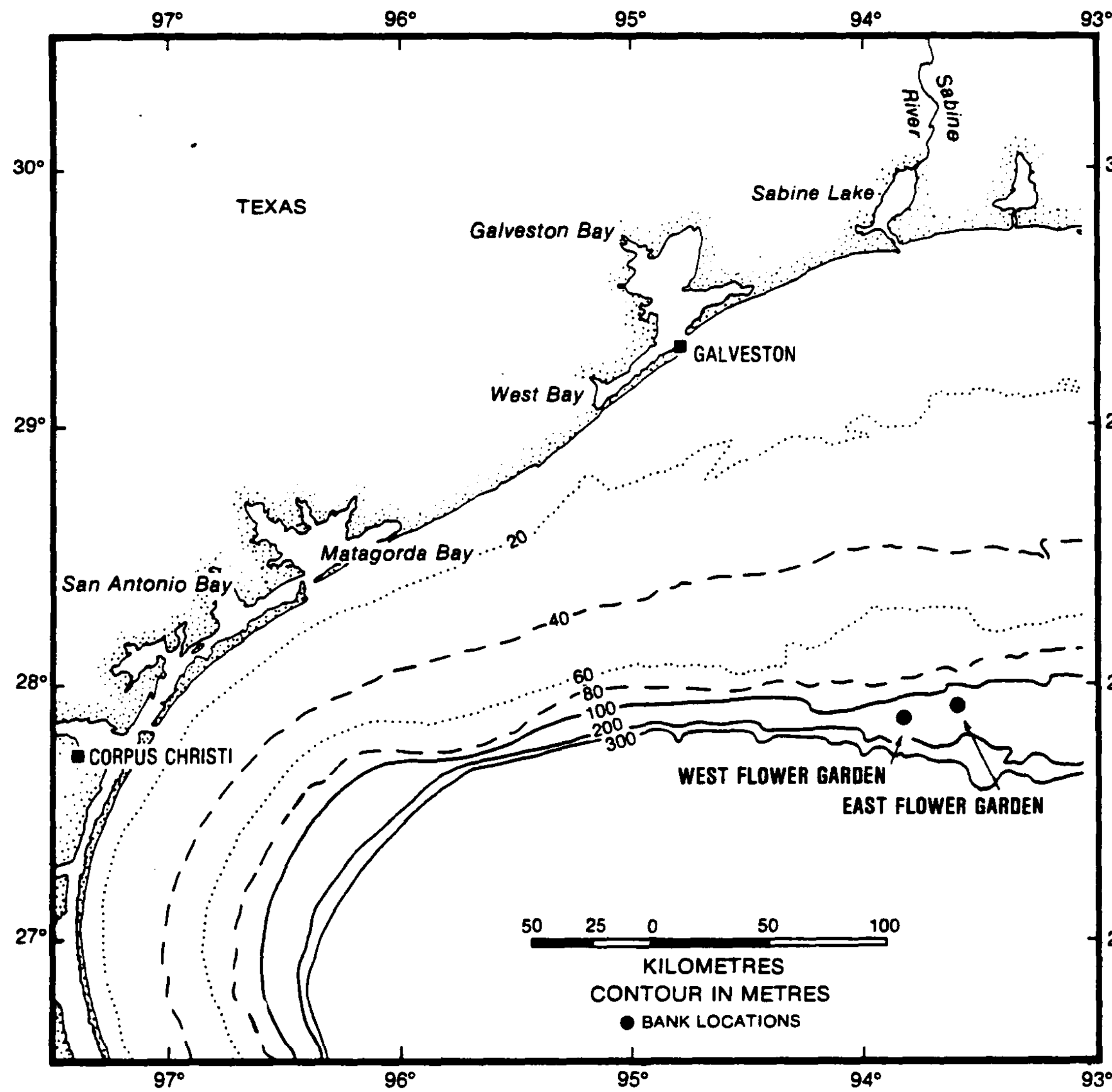

Figure 2.1 Location map of Flower Garden Banks, northwestern Gulf of Mexico.

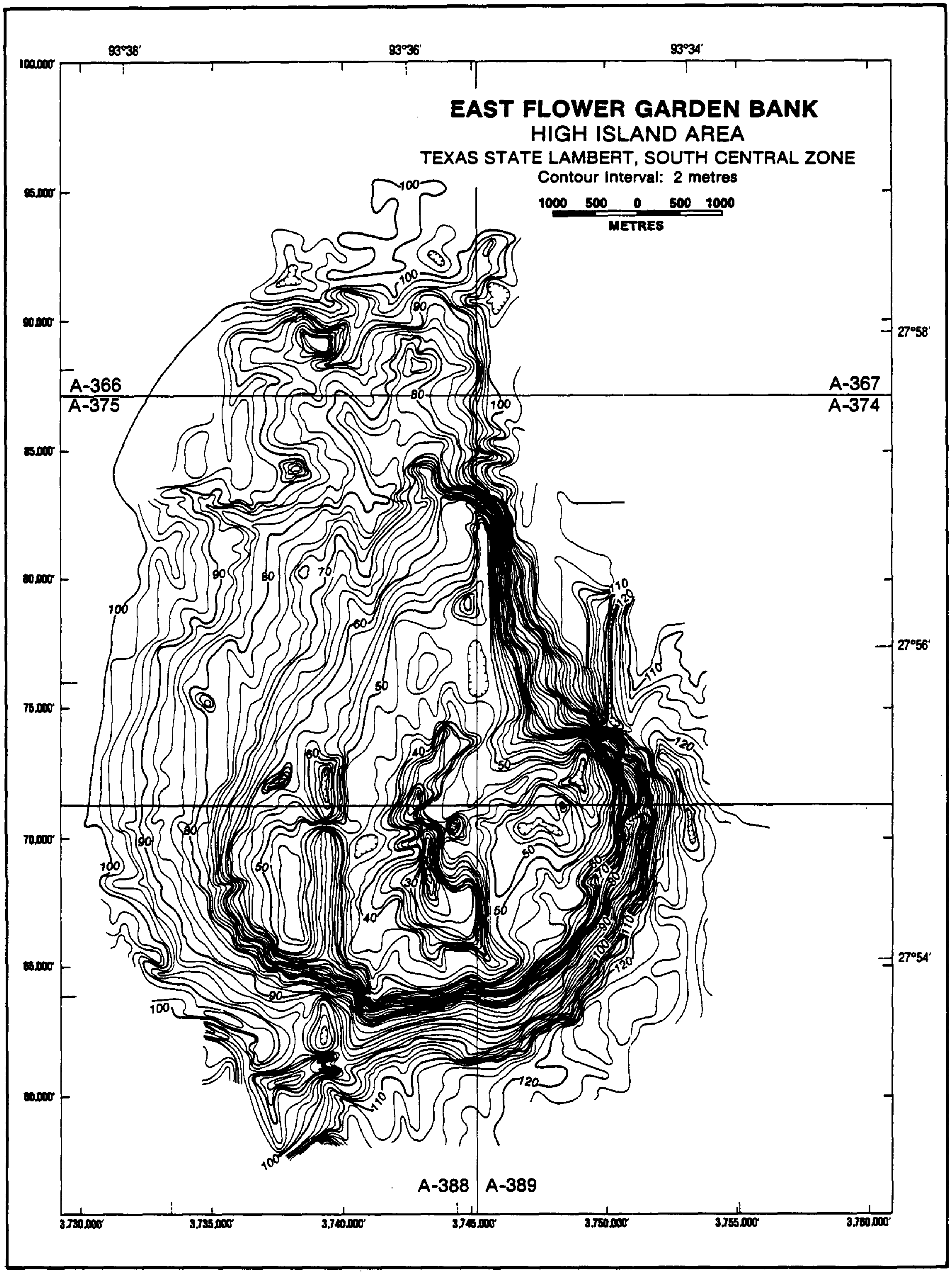

Figure 2.2 East Flower Garden Bank bathymetry.

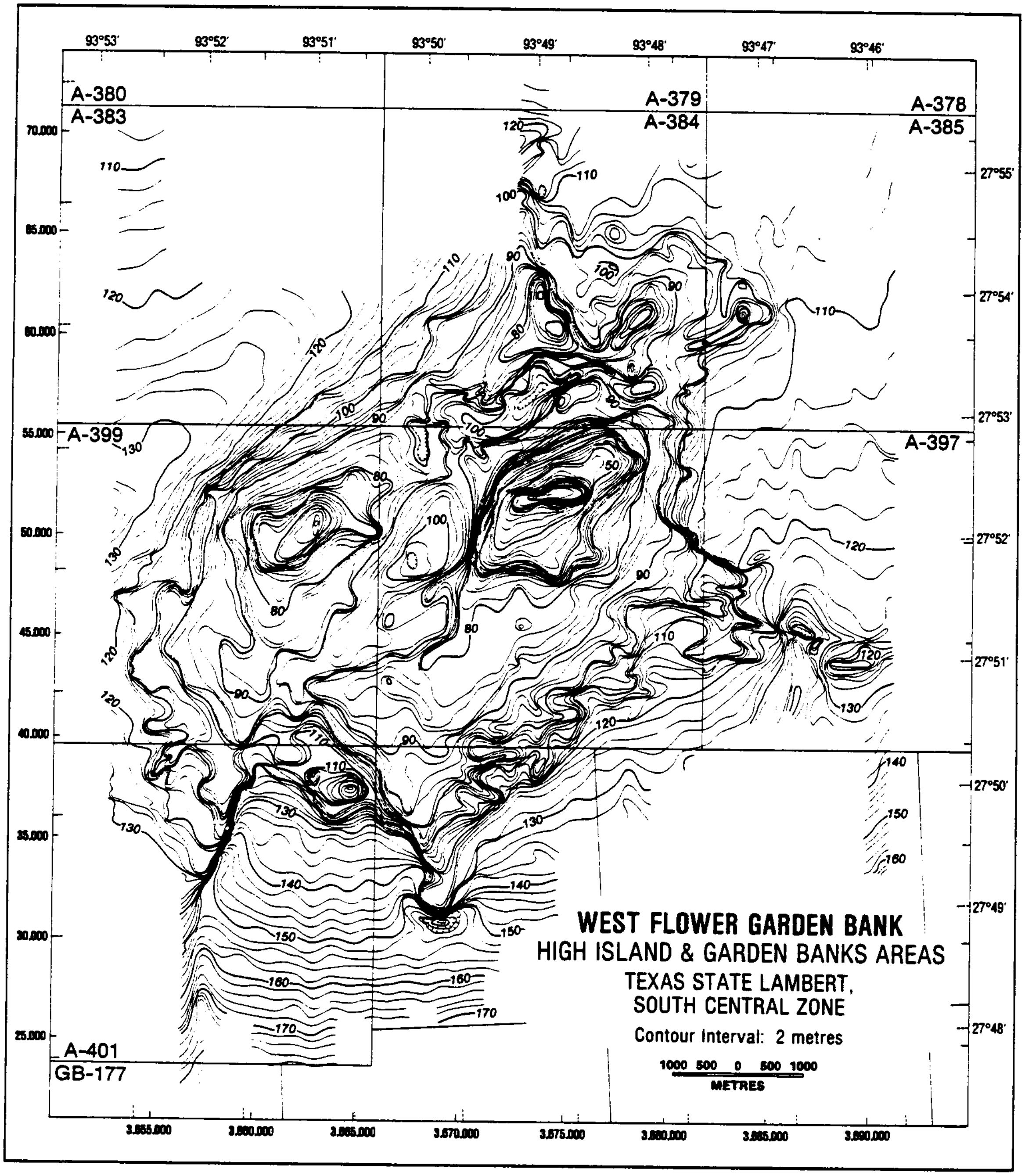

Figure 2.3 West Flower Garden Bank bathymetry.

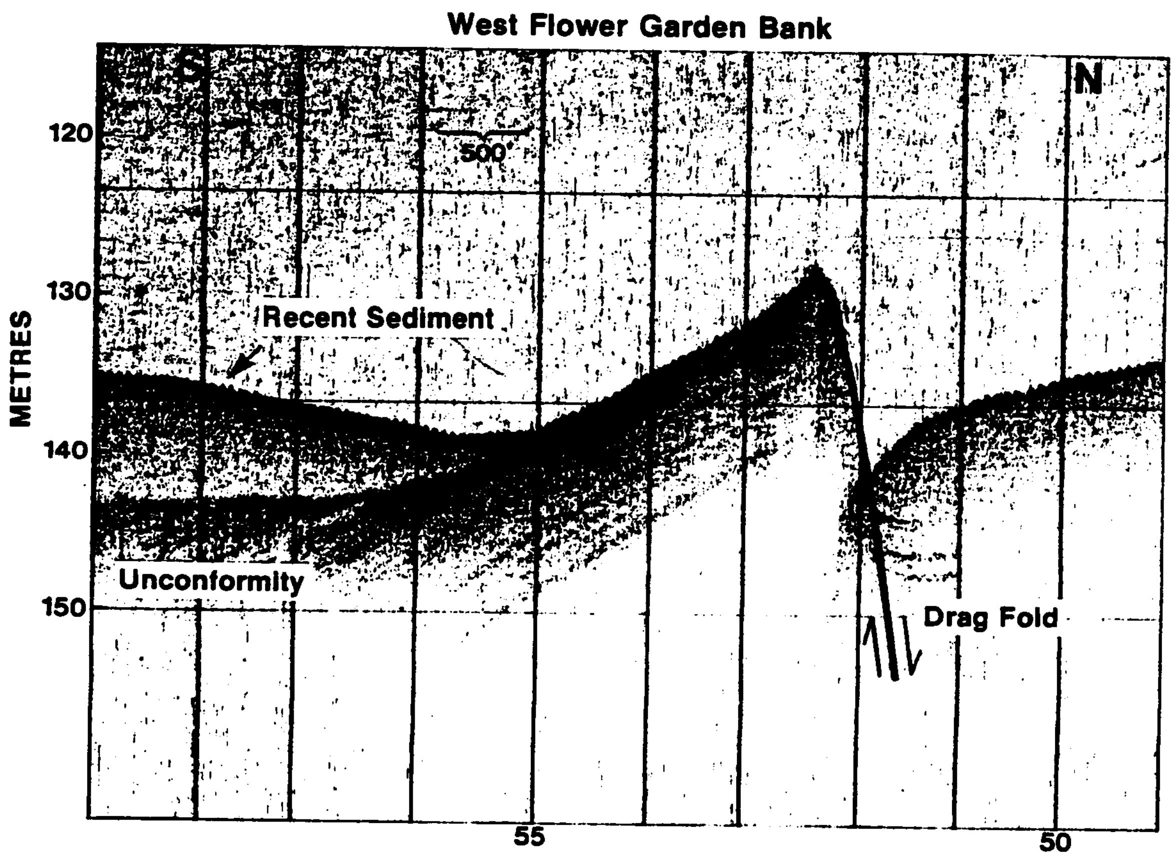

Figure 2.4 A 3.5 kHz north-south sub-bottom profile across the western part of the West Flower Garden Bank (Lease Block A-397).

West Flower Garden Bank

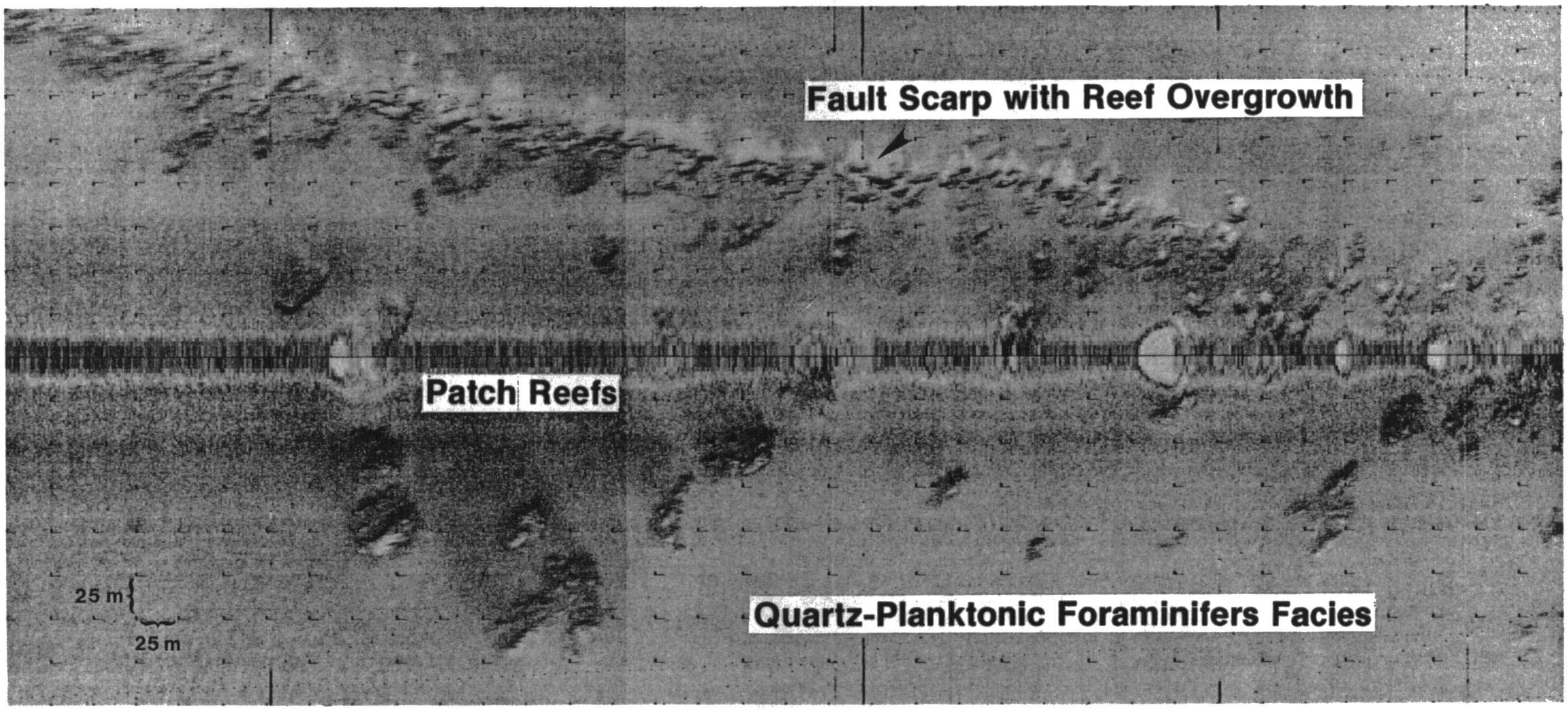

Figure 2.5 Side-Scan sonar record showing fault scarp with reef overgrowth in the northern part of the West Flower Garden Bank (Lease Block A-384). Water depth is about 105 m.

present on the two banks. However, the distribution of sediment types does not coincide with the boundaries between biotic communities due mainly to the downslope movement of sediment by the force of gravity (Table 2.1).

The downslope movement of sediment produced on the banks, together with the absence of land-derived muds in the bottom sediments above a depth of 75 m and the major biological boundary at approximately 88 m, substantiate the conclusion from water and sediment dynamics that the currents flow around the banks rather than up and over them. The nepheloid layer rarely rises to depths of 75 m.

The presence of a series of brine seeps and a brine lake has been documented, indicating the removal by dissolution of prodigious amounts of solid salt from the crest of the salt diapir. The removal of large volumes of solid salt from the shallow sub-bottom beneath the crests of the reefs creates hazardous seafloor instability in those areas.

The reefs at the crests of the East and West Flower Garden Banks are able to exist there because the banks are bathed in warm, clear, saline waters all year round. The depth of surrounding waters is great enough so that modest stratification exists year round and the heat capacity of this thick water column keeps temperatures at the level of the bank above 19°C even during cold frontal passages in the winter. The great distance from shore assures that the surface waters remain relatively free of light-attenuating sediment. Relatively high velocity currents and oscillation from surface gravity waves maintain active circulation over the corals.

The depth of coral reef penetration on the bank may well be correlated with light attenuation, and to some minor extent temperature. At 50 m depth temperatures may drop below 19°C for very brief periods.

Throughout the Algal Nodule Zone current velocities remain high because of orographic effects. This produces large bedforms in the nodules as they are transported over the surface of the bank. The benthonic forams, Amphistegina, are winnowed from this zone and swept downslope by gravity.

Currents on the bank surface remain elevated above those away from the bank but are attenuated toward the base of the bank. Deposition of silt and clay on the banks is restricted to depths greater than about 80 m because of two factors. Above this level, the combination of current acceleration by orographic effects plus trapping of tidal and inertial oscillations keep the shear stresses on the bottom sufficiently high to preclude deposition. Also, the bottom boundary layers separated from the seafloor to the northwest

Table 2.1 Relationship Between Sediment Facies and Biological Zones at the East Flower Garden Bank

SEDIMENT FACIES	DEPTH (m)	BIOLOGICAL ZONE	DEPTH (m)
1. Coral Reef	15-50	1. *Montastrea*-*Diploria*-*Porites*	15-36
a. Living Reef (massive limestone)	15-45		
b. Coral Debris (coarse sand and gravel)	25-50	2. *Madracis*	28-46
		3. *Stephanocoenia*	36-52
2. *Gypsina*-*Lithothamnium* (coarse gravel and massive limestone)	50-75	4. Algal-Sponge	46-88
3. *Amphistegina* Sand (medium to coarse sand, muddy at depths greater than 85 m)	75-90	5. Transition	88-89
4. Quartz-Planktonic Forminifers (sandy mud)	90+	6. Nepheloid	89
5. Molluscan Hash (muddy sand)	90+		

do not contain enough fine sediment at this level to contribute significant amounts of fine sediment for deposition.

The Flower Garden Banks (northwestern Gulf of Mexico), Florida Middle Ground (northeastern Gulf of Mexico), and Bermuda (western Atlantic) represent separate biogeographic extremes in the northward distribution of tropical Atlantic coral reefs and hard bottom communities dominated by corals. Coral diversity is considerably less in these northern reefal communities than on reefs in the Caribbean, south Florida, Bahamas, and the southern Gulf of Mexico.

In terms of species composition and dominance of stony corals, the Flower Garden reefs resemble the Bermuda reefs more than they do the Florida Middle Ground. The Flower Garden reefs seem most closely linked biologically to reefs in the southern Gulf of Mexico. They probably are the northernmost elements of an arc of reefal communities of common origin extending from the Campeche Bank to Veracruz, Tuxpan, and the Texas-Louisiana Outer Continental Shelf in the western Gulf.

Due to exceptional water clarity and near tropical water temperatures year round, population levels of corals and coralline algae at the Flower Garden reefs are high, and compare favorably with populations on Caribbean reefs. Montastrea annularis is the most abundant (dominant) coral above 36 m depth at the Flower Garden reefs. Stephanocoenia michelinii and Millepora alcicornis are dominant on deeper reefs (36 to 52 m). Coralline algae are overwhelmingly dominant between 50 and 85 m, forming nodules, crusts, and reefal structures.

Accretionary growth of corals at the Flower Garden reefs is as rapid as in south Florida and the Caribbean. Encrusting growth rates of M. annularis are similar at the East and West Flower Garden and Jamaican reefs.

The northerly location of the Flower Garden reefs has resulted in reduced coral diversity, but not reduced abundances or growth rates. Some examples of the reef biota are illustrated in Figures 2.6 to 2.9, and 2.10 to 2.13.

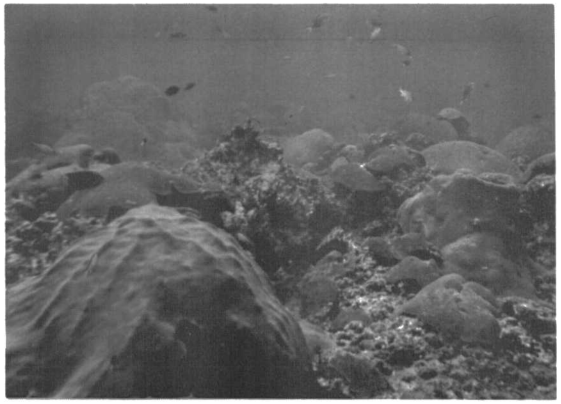

Figure 2.6 Typical Flower Gardens coral reef top (21 m depth).

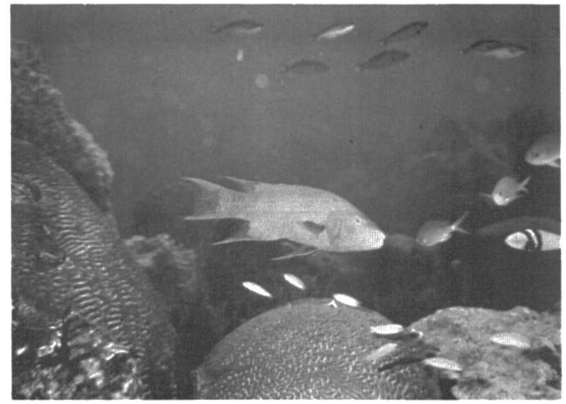

Figure 2.7 Brain corals and reef fishes (*Chromis* sp.; *Bodianus rufus*, Spanish hogfish; *Thalassoma bifasciatum*, Bluehead) at 20 m depth on the West Flower Garden.

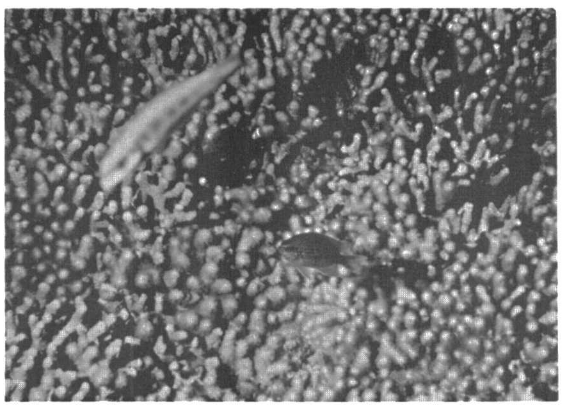

Figure 2.8 *Madracis mirabilis*, dominant coral of *Madracis* zone (28 m depth, East Flower Garden).

Figure 2.9 Leafy algae zone (28 m depth, East Flower Garden).

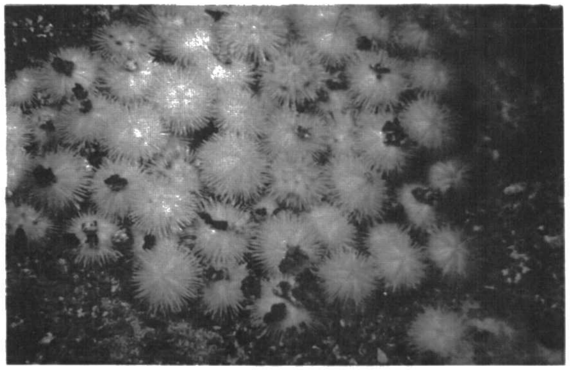

Figure 2.10 Aggregation of white urchins, *Pseudoboletia maculata*, at 59 m depth on bottom covered with very small algal nodules (rhodoliths). Note the nodules displayed on spines of urchins.

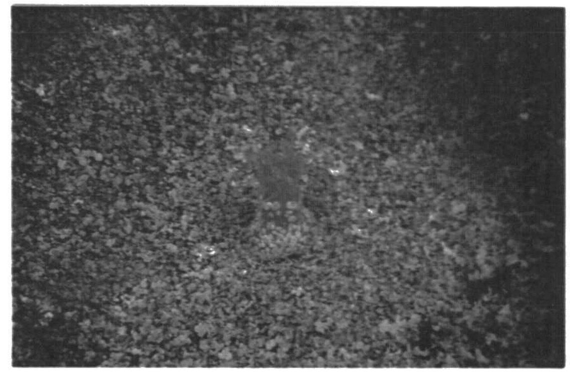

Figure 2.11 Patch of living *Halimeda* sp. at about 55 m depth, East Flower Garden. Large organism in the center is an anemone.

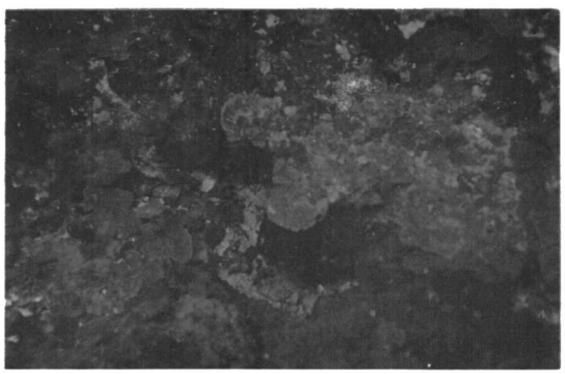

Figure 2.12 Crusts of coralline algae on hard substratum of "partly drowned reef" at the East Flower Garden (60 m depth).

Figure 2.13 Hard sponges attached to carbonate rock coated with veneer of sediment. This is representative of drowned reefs (105 m, Diaphus Bank).

CHAPTER 3

CLASSIFICATION AND CHARACTERIZATION OF BANKS

Submarine banks may be classified in a variety of ways both geologically and biologically. We have settled on a classification based upon the general location on the shelf (i.e., midshelf or outer shelf) and the nature of the geological structure expressed in them. From this very general beginning we may then look at details of the geology and biology of the banks in order to further characterize them and to develop groupings of banks with similar attributes. The relationship of the geology, biology, and hydrology of the banks will be developed in this chapter, with the ultimate aim of providing a basis for predicting the geological and biological environments on less studied banks from limited amounts of remotely sensed data.

SYSTEM OF CLASSIFICATION

Geological categorization is based upon structural expression; that is, did the bank or reef develop on relatively undisturbed strata, like the banks off South Texas, or did it grow on a diapiric structure, like the banks off East Texas and Louisiana? A further subdivision may be made on the basis of the nature of the structure underlying the bank. Is the structure that which we normally associate with salt diapirs or is the structure inherited from early Jurassic and Triassic tectonic features? The nature of the substrate is also involved in the categorization. Is the substrate made up of bedded Mesozoic and/or Cenozoic sandstones, siltstones, or claystones? Or is the substrate a carbonate cap (reef) that totally conceals the original bedrock substrate? Based on these considerations, the geological classification of the banks identifies two categories: midshelf bedrock banks, and outer shelf bedrock banks with carbonate reef caps.

The most appropriate means of categorizing the banks biologically involves recognition of a number of distinct benthic biotic zones characteristic of hard banks in the northwestern Gulf of Mexico, with an indication of the banks on which each zone occurs, and the depth range of each zone on each bank. Seven characteristic benthic biotic zones have been identified. These are classified within four general categories depending on degree of reef-building activity and primary production as follows:

A. Zones of Major Reef-Building Activity and Primary Production.

I. *Diploria-Montastrea-Porites* Zone: A zone consisting of living, high-diversity coral reefs. Hermatypic corals dominant. Coralline algae abundant. Leafy algae limited.

II. *Madracis* Zone and Leafy Algae Zone: The *Madracis* Zone is dominated by the small branching coral *Madracis mirabilis*, which produces large amounts of carbonate sediment. In places, large (possibly ephemeral) populations of leafy algae dominate the *Madracis* gravel substratum (Leafy Algae Zone).

III. *Stephanocoenia-Millepora* Zone: A zone consisting of living, low diversity coral reefs. Hermatypic corals dominant. Coralline algae abundant. Leafy algae limited.

IV. Algal-Sponge Zone: A zone dominated by crustose coralline algae actively producing large quantities of carbonate substratum, including algal nodules. The zone extends downward, past the depth at which algal nodules diminish in abundance, to the greatest depth at which coralline algal crusts are known to cover a substantial percentage of the hard substratum. This is the largest of the reef-building zones in terms of area of sea bottom. Leafy algae are very abundant.

B. Zone of Minor Reef-Building Activity.

V. *Millepora*-Sponge Zone: A zone where crusts of the hydrozoan coral *Millepora* share the tops of siltstone, claystone, or sandstone outcrops with sponges and other epifauna. Isolated scleractinian coral heads may be present, but rare. Coralline algae are rare.

C. Transitional Zones Wherein Reef-Building Activity May Range from Minor to Negligible.

VI. Antipatharian Zone: Limited crusts of coralline algae and several species of coral exist within a zone typified by sizeable populations of antipatharians. Banks supporting Algal-Sponge Zones (A, IV above) generally possess something comparable to an Antipatharian Zone as a "transition" between the Algal-Sponge Zone and the deeper, turbid-water, Nepheloid Zone of the lower bank.

D. Zone of No Reef-Building Activity.

VII. Nepheloid Zone: A zone wherein high turbidity, sedimentation, resuspension of sediments, and resedimentation dominate. Rocks and drowned reefs here

> are generally covered with veneers of fine sediment. Epifauna are depauperate and variable; deep-water octocorals and solitary stony corals are often conspicuous. This zone occurs in some form on lower parts of all banks below the depths of the Antipatharian or Transitional Zones.

This scheme does not represent a final word on benthic zonation on hard banks in the northwestern Gulf of Mexico. The supposed "Antipatharian Zone" and "Nepheloid Zone" are particularly problematic and may not be valid designations in the biological sense. Each surely represents several biotic assemblages of superficial similarity which could all ultimately be given separate zonal designations. No single bank off Texas-Louisiana possesses all of the zones indicated above, though the East and West Flower Garden Banks lack only the *Millepora*-Sponge Zone. The two Flower Garden Banks harbor the most diverse and thoroughly developed offshore hard-bottom epibenthic communities in the region. They differ from other shelf-edge carbonate banks primarily in the degree of development of coral reefs. High diversity coral reefs (*Diploria-Montastrea-Porites* Zone) are not present on any other northern Gulf banks. Lower diversity coral reefs (*Stephanocoenia-Millepora* Zone) are present at the Flower Gardens and also at two other shelf-edge banks, 18 Fathom and Bright.

The *Millepora*-Sponge Zone, occupying depths comparable to the *Diploria-Montastrea-Porites* Zone, is characteristic of the Tertiary bedrock substrata of the Texas-Louisiana midshelf banks. Interestingly, the zone is present on one shelf-edge carbonate bank (Geyer) but only on a bedrock prominence at the bank's crest.

Upper parts of the relict Pleistocene carbonate reefs of the South Texas midshelf banks and certain midshelf carbonate banks off North Texas and Louisiana are occupied by benthic assemblages comparable to those of the supposed *Antipatharian* Zone found at somewhat greater depths on the north Texas-Louisiana shelf-edge carbonate banks.

Thus, the basic geological categories of northwestern Gulf Outer Continental Shelf banks are also broadly distinguishable from one another in terms of benthic community structure. The biotic differences between bank types are probably explicable in terms of lateral and depth-related variations in substratum type, water temperature, turbidity, and sedimentation.

SOUTH TEXAS RELICT CARBONATE SHELF REEFS

Geology

A line drawn from Matagorda Bay to the shelf break (Figure 3.1) divides the Texas continental shelf into an area of drowned reefs on a relict carbonate shelf and an area of banks situated on salt diapirs.

There is no doubt that the banks on the South Texas shelf are drowned coralgal reefs. Rock dredging by the U.S. Geological Survey (Berryhill et al., 1976) and Texas A&M University (Bright and Rezak, 1976) recovered coralline material from Southern Bank and samples of dead coral from Dream Bank. Radiocarbon (C^{14}) dating yielded ages of 18,000 and 10,580 years B.P., respectively. These banks are dead reefs that were living close to a Late Pleistocene to Early Holocene shoreline.

NORTH TEXAS-LOUISIANA REEFS AND BANKS ON DIAPIRIC STRUCTURES

Midshelf Banks

Midshelf banks are defined as banks rising from depths of 80 m or less and having a relief of from about 15 m to about 50 m. Banks on the North Texas-Louisiana shelf that fall into this category are Stetson, Claypile, Coffee Lump, Sonnier, and Fishnet. These banks are similar to each other in that they are all associated with salt diapirs and are outcrops of relatively bare, bedded Tertiary limestones, sandstones, claystones, and siltstones.

Shelf-Edge Carbonate Banks and Reefs

The shelf-edge carbonate banks and reefs are located on complex diapiric structures. Although all of the shelf-edge banks have well developed carbonate caps, there are local areas of bare bedded rocks that have been exposed by recent faulting.

Structural Geology

Complexity and variety of structural style in the banks are due to a number of factors, the most important of which are: 1) the

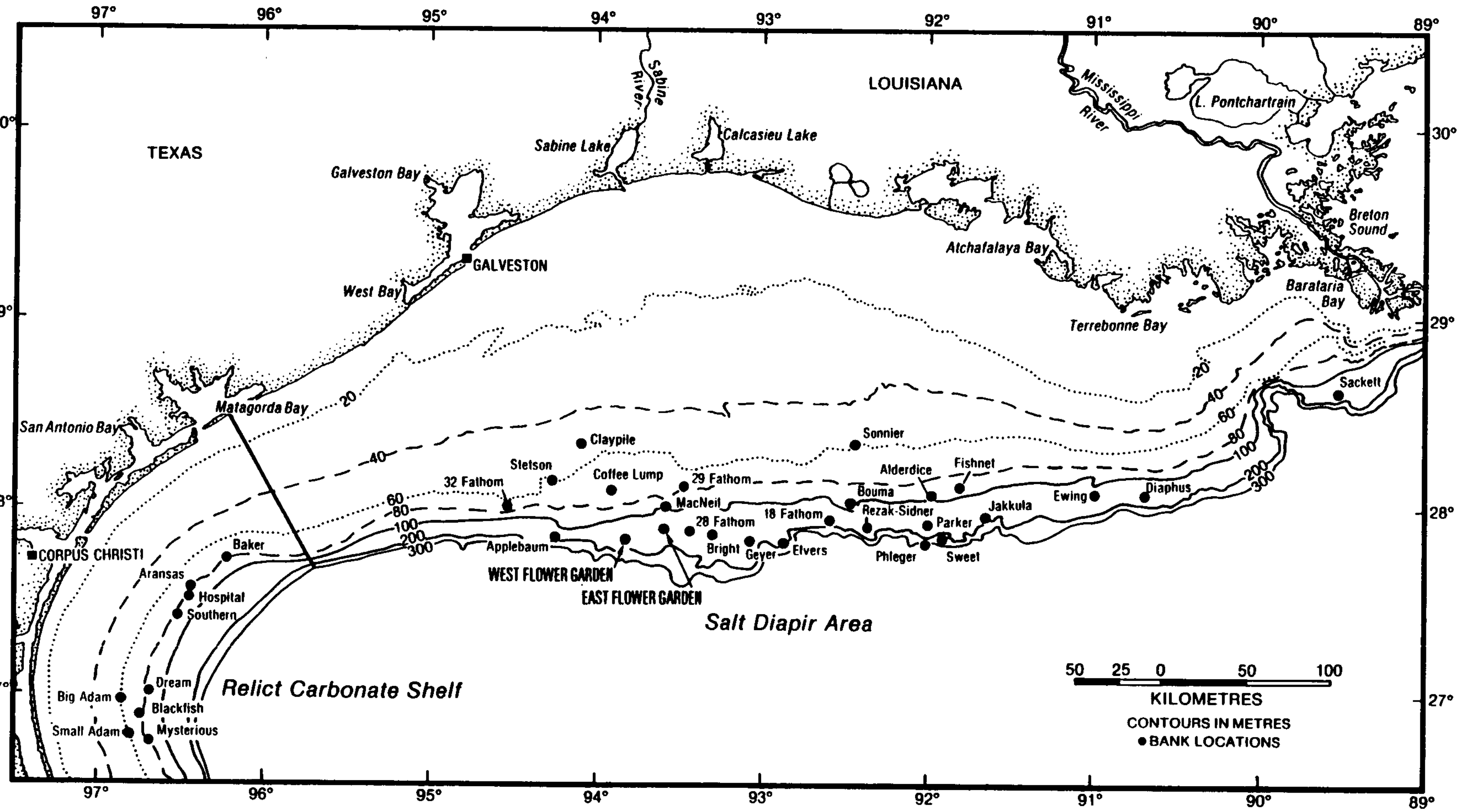

Figure 3.1 Location map of banks discussed in text. Note boundary between relict carbonate shelf and salt diapir area.

regional stress field; 2) the shape of the dome (circular or elliptical); and 3) structures inherited from Late Triassic to Early Jurassic tectonics.

The influences of outline shape and regional strain on salt dome fault patterns have been amply demonstrated by Withjack and Scheiner (1982), using both experimental and analytical models. They found that circular domes in the absence of regional stresses developed radial fault patterns such as those observed on some of the banks studied. With regional extension, most normal faults on the crests of circular domes trend in a direction perpendicular to the direction of regional extension. Diaphus Bank is a good example of this kind of fracture pattern. Diaphus lies close to the shelf edge. The major fault on the bank parallels the shelf edge.

With elliptical domes not involved with external stresses, the pattern of normal faults roughly parallels the long axis of the ellipse, but the faults splay outwards towards the ends of the long axis. With regional extension the normal faults trend perpendicular to the regional extension direction.

Unfortunately, few domes are perfectly circular or elliptical. The shapes of domes may be strongly controlled by pre-existing regional structures. The strongest evidence for the control of shape by pre-existing structures is Rezak-Sidner Bank. The structure of that bank is a rectangular block bounded by normal faults on three sides. The east-facing fault scarp of the bank has a displacement of at least 130 m. Salt domes, by definition, are roughly circular in outline and the overlying beds dip in all directions away from a point. Therefore, according to the definition of a salt dome, Rezak-Sidner Bank is not a salt dome.

If it is not a salt dome, then what is it? The only tectonic processes known to be active on the Outer Continental Shelf are salt diapirism and gravity faulting. Salt diapirs, as described above, should be circular or elliptical in plan view. Gravity faults are linear features that parallel the shelf break. Rezak-Sidner Bank is neither of these. The major fault at Rezak-Sidner Bank trends north-south and is approximately perpendicular to the shelf break. Trippett and Berryhill (1982) show Rezak-Sidner Bank to be a part of a northwest-southeast trending series of banks formed by a ridge of salt at depth. Many of the banks on the shelf break and the upper slope on this map (Trippett and Berryhill, 1982) appear to be parts of complex salt ridges with arcuate patterns. We have demonstrated (Rezak, et al., 1983) that the East Flower Garden is located at the intersection of two salt ridges, and that the non-reflective area at the West Flower Garden Bank is linear rather than circular. Geyer and Elvers Banks (Rezak and Bright, 1981a) are also situated on arcuate bathymetric prominences. Their non-reflective cores are also linear rather than circular. The linearity of these cores must be due to the presence of pre-intrusion zones of weakness along which the salt was intruded. These zones of weakness might be joints or fault systems inherited from pre-salt tectonic features. Many of the banks on the upper slope and outer shelf are complicated due to regional extension. Parallel normal faulting, oriented at right angles to the regional extension direction, is common on the East Flower Garden, West Flower Garden, and Geyer Banks. At the East Flower Garden the faulting does not parallel the crests of the intersecting salt ridges but is nearly parallel to the shelf break. At the West Flower Garden and Geyer Banks the faulting is more complex. Some faults parallel the shelf break and some parallel the salt ridge crest.

Consequently, the patterns of faulting will vary depending upon the developmental history of a salt diapir. Those diapirs that are not associated with pre-injection tectonic features will be circular or elliptical in plan view. Those that are associated with pre-injection tectonic features will assume the pattern of those features. These two forms are extreme end members in a spectrum of structural styles that lies between them. These styles are controlled by the history of changes in the regional stress field at a given location on the shelf or slope.

ENVIRONMENTAL CONTROLS

Based on the nature, distribution and degree of development of their epibenthic communities, hard-banks on the Texas-Louisiana Outer Continental Shelf can be divided into five environmental groups as follows:

1. South Texas midshelf relict Pleistocene carbonate reefs bearing turbidity tolerant Antipatharian Zones and Nepheloid Zones (surrounding depths of 60 to 80 m; crests 56 to 70 m).

2. North Texas-Louisiana midshelf Tertiary outcrop banks bearing clear water, *Millepora*-Sponge Zones and turbid water-tolerant Nepheloid Zones (surrounding depths of 50 to 62 m; crests 18 to 40 m).

3. North Texas-Louisiana midshelf banks bearing turbidity tolerant assemblages approximating the Antipatharian Zone (surrounding depths of 65 to 78 m; crests 52 to 66 m).

4. North Texas-Louisiana shelf-edge carbonate banks bearing clear-water coral reefs and Algal Sponge Zones, transitional assemblages approximating the Antipatharian Zone, and Nepheloid Zones (surrounding depths of 84 to 200 m; crests 15 to 75 m).

5. Eastern Louisiana shelf-edge carbonate banks bearing poorly developed elements of the Algal Sponge Zone, transitional

Antipatharian Zone assemblages, and Nepheloid Zones (surrounding depths of 100 to 110 m; crests 67 to 73 m).

The clear-water biotic zones on these banks (Millepora-Sponge Zone, several coral reef zones, and Algal-Sponge Zone) are distinctly tropical in faunal and floral content. Biota of the Antipatharian and related transitional zones are largely composed of tropical species apparently more tolerant of turbidity. Environmental factors which can be correlated with and probably control regional patterns of community structure, distribution, abundance, and zonation of tropical epibenthos in the northwestern Gulf are: distance from shore, regional patterns of substratum type, bottom depth, bank relief, water temperature, salinity, river runoff, turbidity, sedimentation, currents, and seasonal variation in the last six of these.

Conditions at the shelf edge near and beyond the 80 m depth contour on the broad North Texas-Louisiana shelf west of about 91° longitude are favorable for development of tropical reef communities. Current patterns are such that shelf-edge waters come primarily from the southwest, and are oceanic, with little admixture of neritic water from the Texas-Louisiana shelf (Figure 1.2). These currents carry larvae, spores, and juveniles from the Gulf of Campeche, Yucatan shelf, and the Caribbean.

There is a strong tendency for coastal water masses, highly influenced by outflow from the Mississippi and other rivers in Louisiana and North Texas, to be held onshore and shunted west most of the year (particularly during February to May periods of peak runoff) by the general shelf circulation pattern. As a result, turbidity in the shelf-edge waters is usually nil, and salinity averages 36 ppt. Where high runoff combines with seasonal disruption of the typical counterclockwise current regime on the shelf (such as may occur in late spring or early summer), lower salinities may occur in shelf-edge waters; however, the lowest surface salinity we have ever measured at the Flower Gardens was 32 ppt, and this was accompanied by 34 ppt at 25 m depth.

For most of the year, near-surface water temperatures throughout the Gulf are tropical to sub-tropical (27 to 30°C). However, near shore in the northern Gulf, temperatures become warm-temperate from December through March. During the coldest months (January to February) temperatures grade from as low as 10°C in the estuaries to 18°C on the outer shelf edge.

Onshore-offshore seasonal movements of the 18° and 16°C surface isotherms probably have very significant influences on distribution of tropical reef biota in the northwestern Gulf. The minimum seasonal temperature limit for vigorous growth of coral reefs is considered to be 18°C. The lower limit, 16°C, is stressful for most reef-building corals. Though reef-building coralline algae and other biotic elements of the tropical reef ecosystem may tolerate somewhat lower temperatures, 16°C is probably near the bottom of their optimal range.

In the northwestern Gulf, the 18°C winter surface isotherm can be expected to occur somewhere between the locations of the 30 and 80 m depth contours, projected upward. The 16°C isotherm occurs between the 20 and 40 m depth contours. The surface isothermal layer during winter extends 50 to 75 m downward, with temperatures only 1 to 3°C less at 100 m. Thus, above 50 m depth off North Texas and Louisiana, and seaward of the general 80 m bottom depth contour, salinities are high and temperatures range annually from approximately 18 to 30°C (Figure 3.2). Where suitable hard substratum exists in the absence of chronically turbid water, conditions on this part of the shelf are favorable for the growth of tropical reef communities dominated by corals or coralline algae, or both. The degree of light penetration into clear surface waters, and the antagonistic effects of turbidity in bottom nepheloid layers are almost certainly the factors controlling depth ranges for these communities on the various shelf-edge banks. High turbidity decreases light penetration and is therefore inimical to the development of coral and algal reef communities. Sedimentation associated with high turbidity results in smothering of encrusting epibenthos by veneers of silt and clay. In the northwestern Gulf, due to the enormous sediment load entering it from the rivers, turbidity and sedimentation are major factors limiting development of tropical reef assemblages. It is speculated that reef development at Sackett Bank (Algal-Sponge Zone) is seriously attenuated, due in part to increased turbidity in surface waters from admixed Mississippi River outflow. This influence, accompanied by somewhat reduced salinities, diminishes westward but may extend as far as Diaphus Bank (91°W) during periods of particularly high runoff.

Mid-Shelf banks (Mysterious to Fishnet) arise from surrounding depths of 60 to 80 m. Their tops, which support Antipatharian Zone type assemblages between 56 and 73 m, exist within a depth range which on shelf-edge banks (Flower Gardens to Elvers) is occupied by diverse, clear-water Algal Sponge Zones. The lack of Algal-Sponge Zones on the midshelf banks, and the occurrence instead of antipatharian assemblages which are typically found in deeper water at the shelf edge is probably due largely to high turbidity.

The effects of bottom nepheloid layers and associated sedimentation are certainly more pronounced on the midshelf banks than at the shelf-edge banks. We speculate that most or all of the midshelf banks are frequently totally covered by the nepheloid layer, especially during severe wave conditions. At the Flower Garden Banks, a substantial nepheloid layer has not been observed shallower than about 80 m, and usually the water is fairly clear even at that depth. Fine, terrestrial sediments are not found on shelf-edge carbonate banks above the lower limit of their Algal-Sponge Zones. The midshelf banks, however, are generally

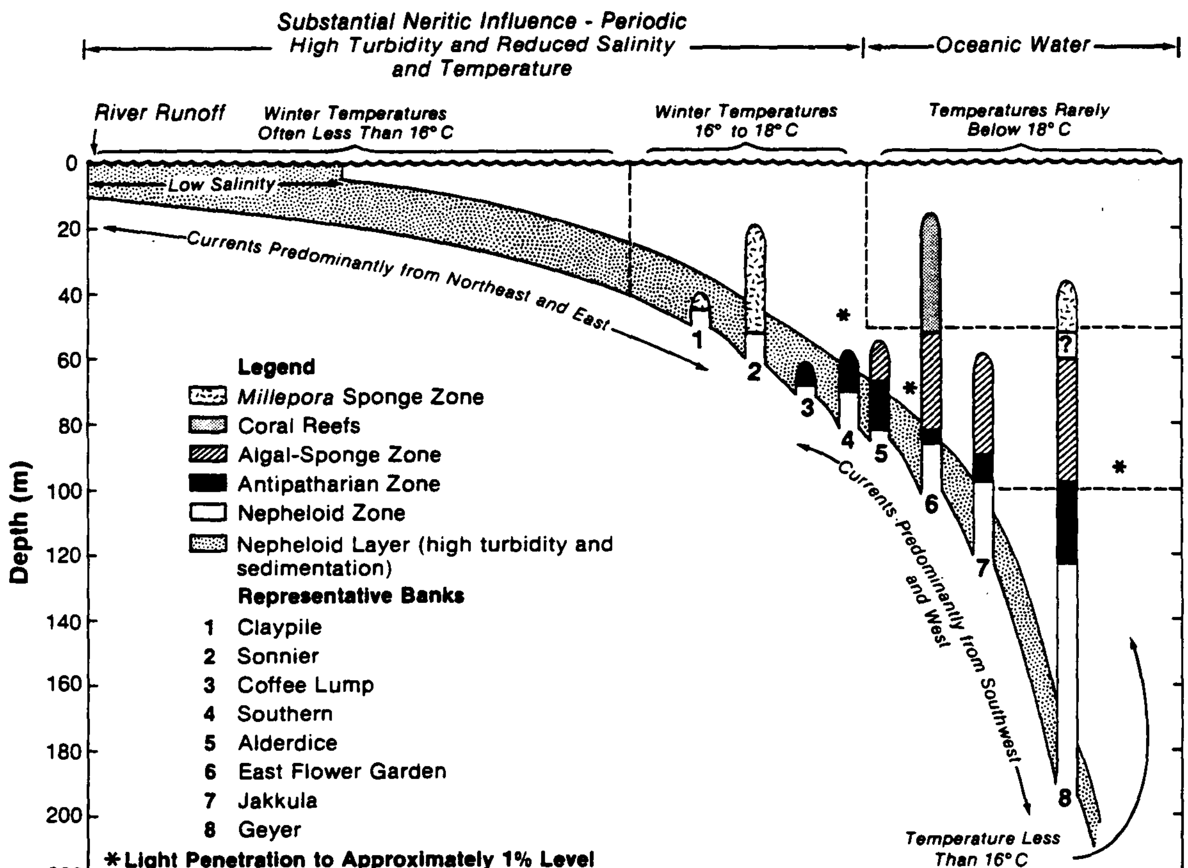

Figure 3.2 Comparison of biotic zones to temperature, salinity, turbidity, and light differences at selected banks.

coated with thin to thick layers of fine sediment, presumably derived from nepheloid layers.

Relief above the surrounding bottom is of considerable importance in alleviating the negative impacts of bottom nepheloid layers and attendant sedimentation on the development of epibenthos. An Algal-Sponge Zone probably will not become established on banks which have less than about 15 m relief above a mud bottom due to the impact of nepheloid layers. At Alderdice Bank, the Algal-Sponge Zone extends downward to only 67 m, which is 17 m above the surrounding mud. Farther offshore, at the East Flower Garden, the Algal-Sponge Zone extends downward to 82 m, about 18 m above the surrounding soft bottom. In even deeper water where surrounding depths are over 180 m (Geyer and Elvers Banks), the vertical extent of the Algal-Sponge Zone is not limited by bottom nepheloid layers because of the high relief. Here, the zone extends down to over 95 m depth.

Thus, on the shelf-edge banks, there is a gradual increase in the maximum depth of expression of coralline algae-dominated communities with increasing surrounding depth (Figures 3.2 and 3.3). A similar trend is apparent for the Antipatharian Zones on these banks (Figure 3.2). These observations imply that the bottom nepheloid layers are of great importance as ecological limiting factors on the lower 15 to 20 m of the banks.

Thus, the deeper clear-water reefal communities (Algal-Sponge Zones) are excluded from the midshelf carbonate banks by winter low temperatures, high turbidity, reduced light, and sedimentation. They are limited in downward extent on some of the shelf-edge banks by the effects of nepheloid layers. In their place is a less diverse and less abundant "Antipatharian Zone" assemblage made up of epibenthic forms which, though basically tropical in origin, are tolerant of the stresses imposed.

Hard substratum exists within suitable depths for coral reef development in the form of midshelf claystone-siltstone banks arising from surrounding depths of 52 m and extending upward to 18 m (Sonnier Bank) and 20 m (Stetson). The Millepora-Sponge Zones of these banks are undoubtedly subject to seasonal temperatures somewhat less than the 18°C minimum for vigorous reef growth, but probably not much less than 16°C.

The crests of Stetson and Sonnier Banks may, however, be fairly well isolated from the effects of bottom nepheloid layers due to their relief (40 to 42 m) above the surrounding mud bottom. The other midshelf claystone-siltstone bank, Claypile, with only 10 m relief, is certainly often covered by the nepheloid layer. Consequently, the abundance of dominant epibenthos is least at Claypile (lowest relief) and greatest at Sonnier (highest relief).

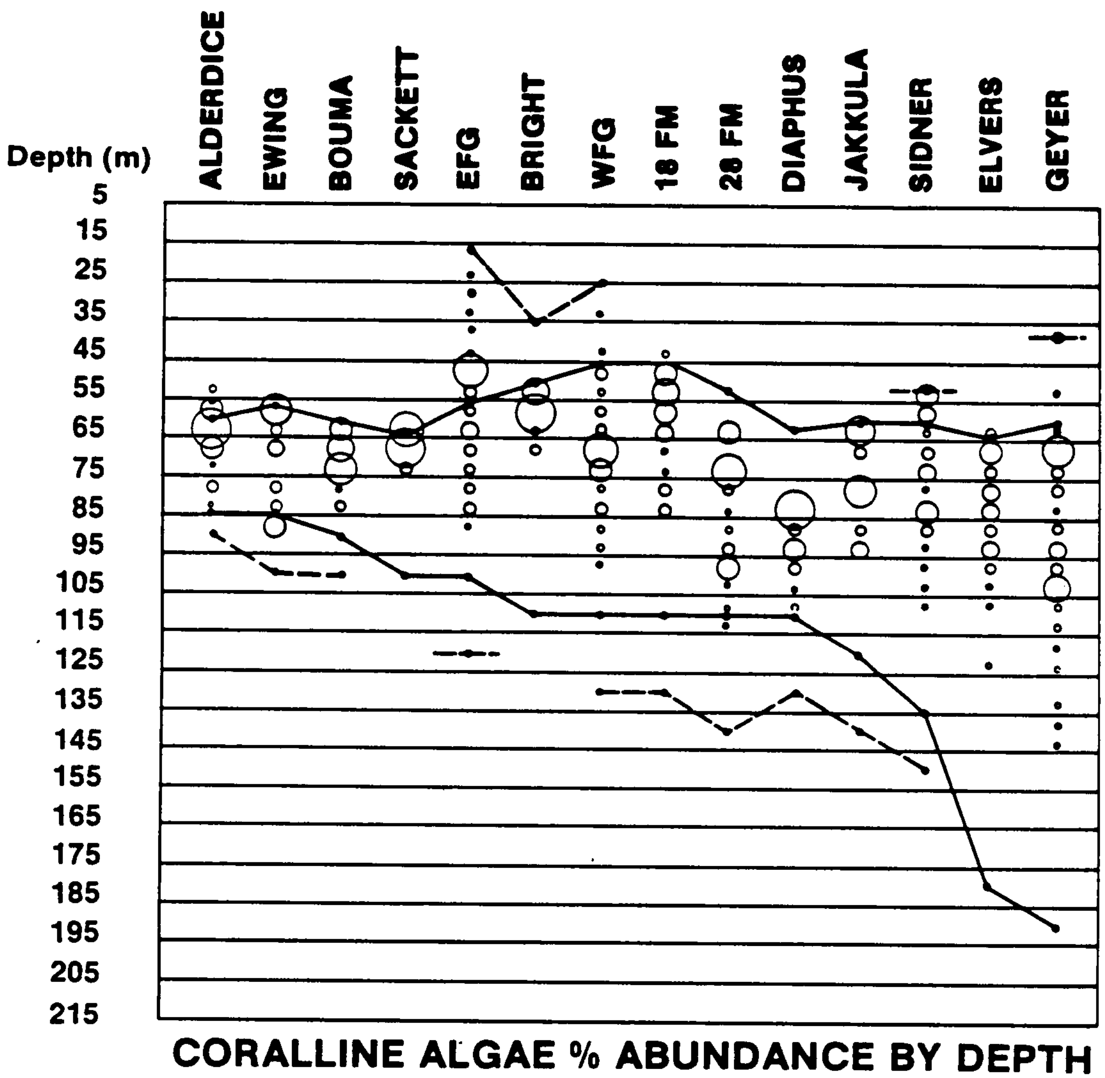

Figure 3.3 Coralline algae relative abundance by depth on shelf-edge OCS carbonate banks in the northwestern Gulf. Sizes of circles represent percentage abundance of coralline algae at various depths within banks only (total area of all circles within one bank equals 100% of the coralline algae population for that bank). Bank to bank variation in abundance is not represented.

Diagonal solid lines between 45 and 65 m depth represent the crest depths of the major carbonate platforms at the various banks. Dashed lines or presence of circle centers above the solid line, represent crest depths of reefs or pinnacles. Diagonal solid lines below 85 m depth represent the general depth of the mud bottom surrounding the banks. Lower dashed lines indicate that parts of the surrounding bottom adjacent to the banks extend to the depths of the lines.

Speculation on environmental factors governing the development of the Millepora-Sponge Zone is complicated by the fact that the zone also occurs on shelf-edge bedrock outcrops, protruding from the crest of Geyer Bank between 37 and 52 m depth. The implication here is that development of this zone is dependent upon the presence of newly exposed bedrock outcrops, and vigorous development of the biota is favored by clear water and winter minimum temperatures above 16°C.

The question is why have tropical coral reefs not developed on the claystone-siltstone outcrops on Geyer Bank, which are exposed to the same oceanic conditions as are the coral reefs at the Flower Garden Banks? Hypothetically, the claystone, which is very soft and disintegrates readily upon exposure to water, may be unsuitable substratum for most reef-building corals. Indeed, the epifauna inhabiting the Millepora-Sponge Zone obviously "prefer" the thin beds of rock-hard siltstone which protrude from the softer but more extensive claystone on these outcrops. One can imagine a faunal succession on shelf-edge banks which results in: 1) recruitment of reproductively prolific hydrozoan corals (Millepora) to exposed, hard siltstone beds; 2) spreading of these to adjacent claystone to create a carbonate veneer over the outcrop; 3) partial mortality of Millepora and subsequent recruitment of anthozoan hermatypic corals on the carbonate skeletal crust; 4) crowding out of the hydrozoan corals by the more competitive anthozoans; resulting in 5) transformation to a tropical coral reef.

The distributions of major epibenthic biotic zones in relation to the environmental factors discussed above are summarized in Figure 3.2. Correlations exist between regional patterns of winter temperature, turbidity, and light penetration in shelf waters and distribution patterns of the recognized biotic zones on Outer Continental Shelf banks. Coral reefs are restricted to clear oceanic water where temperatures rarely drop below 18°C. Most of the other bank zones may experience lowest winter temperatures of around 16°C. Neritic seasonal variability in temperature and salinity is greatest along the coast and diminishes offshore to roughly the 80 to 85 m depth contour, beyond which more stable, oceanic conditions predominate. Neritic influences on the midshelf are greatest in the upper 10 m of the water column. Deep tropical reef zones dominated by coralline algae are restricted to the clear, oceanic, shelf-edge waters beyond the 85 m depth contour. Neritic influences extending to the edge of the narrow shelf off the Mississippi delta limit reefal development on nearby banks.

Chronic turbidity of bottom water (nepheloid layers) and associated sedimentation severely limit epibenthos on the lower 15 to 20 m of most banks. Vigorous reef development is restricted to those parts of banks well above the effects of nepheloid layers. Continual turbidity and sedimentation on low relief banks substantially reduces diversity and abundance of the assemblages present. Penetration of sunlight into the water decreases toward shore due to generally increasing turbidity. This, combined with the light blocking and smothering effects of bottom nepheloid layers and suspended sediment around the bases of the banks, tends to "displace" zones upward on the banks closer to shore.

BIBLIOGRAPHY

Berryhill, H.L., Jr., G.L. Shideler, C.W. Holmes, S.S. Barnes, G.W. Hill, E.A. Martin, and C.A. Pyle, 1976. Environmental Studies, South Texas Outer Continental Shelf, 1976. Prepared for the Bureau of Land Management, Contract AA550-MU6-24, NTIS Order No. PB-277-337/AS, 626 pp.

Bright, T.J. and R. Rezak, 1976. A Biological and Geological Reconnaissance of Selected Topographical Features on the Texas Continental Shelf. Final Report to U.S. Dept. of the Interior, Bureau of Land Management, Contract #08550-CT5-4, NTIS Order No. PB80-166036, 377 pp.

Rezak, R. and T.J. Bright, 1981a. Northern Gulf of Mexico Topographic Features Study. Final Report to U.S. Dept. of the Interior, Bureau of Land Management, Contract #AA551-CT8-35. Dept. of Oceanography, Texas A&M Univ., Tech. Rep. #81-2-T, 5 vols., 995 pp., NTIS Order Nos.: Vol. I, PB81-248650; Vol. II, PB81-248668; Vol. III, PB81-248676; Vol. IV, PB81-248684; Vol. V, PB81-248692.

Rezak, et al., 1983. Reefs and Banks on the Northwestern Gulf of Mexico: Their Geological, Biological, and Physical Dynamics. Final Report to the U.S. Dept. of the Interior, Bureau of Land Management, Contract #AA851-CT1-55. Dept. of Oceanography, Texas A&M Univ., Tech. Rep. #83-1-T, 502 pp.

Trippett, A.R. and Berryhill, H., 1982. Geology of the continental shelf edge and upper continental slope off wouthwest Louisiana. U.S. Dept. of the Inteior, Minerals Management Service. Open File Report #82-02, Sheet VI.

Withjack, M.O. and C. Scheiner, 1982. Fault patterns associated with domes: An experimental and analytical study. AAPG Bull., 66, 302-216.

APPENDIX A

GEOLOGIC TIME SCALE

Era	Period	Age (10^6 yr)	Gulf of Mexico
CENOZOIC	QUATERNARY		Beginning of Recent time ~ 20,000 yrs. BP
	— 2 $\pm$ 1 —	0	Beginning of Pleistocene
	TERTIARY		
			Great influx of terrigenous sediment
	— 65 $\pm$ 2 —		
MESOZOIC			Rapid deepening of Gulf
	CRETACEOUS		
		100	Shallow-water carbonate deposition
	— 135 $\pm$ 5 —		
	JURASSIC		
			Salt deposition
	— 190 $\pm$ 5 —		Terrigenous sedimentation Block faulting
	TRIASSIC	200	
	— 225 $\pm$ 5 —		
PALEOZOIC	PERMIAN		
	— 270 $\pm$ 5 —		
	CARBONIFEROUS	300	
	— 340 $\pm$ 10 —		
	DEVONIAN		
	— 400 $\pm$ 10 —	400	
	SILURIAN		
	— 430 $\pm$ 10 —		
	ORDOVICIAN		
	— 500 (?) —	500	
	CAMBRIAN		
	— 600 (?) —	600	
PRECAMBRIAN	OLDEST ROCKS IN SOLAR SYSTEM	5000	

Time scale is not proportionally accurate in this diagram.

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.