GEOLOGIC DEVELOPMENT AND DEPOSITIONAL HISTORY OF THE FLORIDA MIDDLE GROUND: A MID-SHELF, TEMPERATE-ZONE REEF SYSTEM IN THE NORTHEASTERN GULF OF MEXICO

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ABSTRACT: The Florida Middle Ground (FMG), the northernmost living coral reef in the Gulf of Mexico, was investigated by high-resolution seismic-reflection methodology, surface-sediment analyses, and direct observation by submersible to identify controls and processes responsible for recent geologic development, and to determine how it relates to development of the surrounding west Florida continental margin, a non-reef-rimmed carbonate platform. Modern reef growth is developed on a foundation consisting of a dead reef that probably was formed during one or more sea-level highstands of the Quaternary. Initial reef growth probably was controlled by bathymetry and regional circulation patterns that served to recruit Caribbean fauna to the FMG.

Surface sediments are distributed in indistinct zones exhibiting a patchy distribution controlled by physical processes and the rugged bathymetry. Sediments throughout the FMG consist dominantly of molluscan shell hash derived from both the reef ridges and surrounding shelf environment. Barnacle fragments are the only major constituent found associated with reef ridges and not the surrounding shelf sediments. Barnacles probably are prevalent on the FMG because of the suitable sites for attachment provided by the dead-reef foundation. Thus, barnacles provide the only major sedimentological indicator of a transition from an open-shelf to reefal environment. The lack of a clear distinction between sediment types of the two environments may have implications for those investigating ancient carbonate environments.

Recent geologic development of the FMG parallels that of the west Florida margin. Driven by high-frequency sea-level fluctuations, similar carbonate sediments are produced in both settings during periods when the shelf surface is flooded. Thick surface sediments on the FMG, relative to the surrounding shelf, indicate reef ridges act to trap sediments much like shelf-edge reefs trap sediments on a reef-rimmed carbonate platform surface. Reef growth and sediment accumulation cannot keep pace with sea-level rise, which results in the drowning of FMG reefs along with the remainder of the west Florida carbonate margin.

INTRODUCTION

Modern reefs are commonly viewed in terms of lush tropical coral reefs typical of the Caribbean and equatorial Pacific regions. Research has shown that modern reefs, as well as those preserved in the ancient rock record, are not limited to shallow tropical waters, but occur in a variety of settings (James, 1983). Consequently, the inhabiting organisms responsible for maintaining reef growth are highly variable and, once incorporated into surrounding sediments, form deposits characteristic of each particular reefal environment.

The Florida Middle Ground (FMG), located on the outer west Florida continental margin (Fig. 1) at approximately 28°30'N latitude, has the distinction of being the northernmost living coral reef in the Gulf of Mexico (Jordan, 1952; Back, 1972; Cheney and Dyer, 1974). It covers over 700 km^2 of the midshelf and ranges from 25 to 40 m in depth (Fig. 2). The FMG is characterized by two north-northwest-trending parallel ridges over 30 km in length, separated by a broad, flat central valley as much as 7 km wide (Fig. 2). At the southern end of the central valley, several isolated knolls, pinnacles and small ridges rise (Fig. 2). The surrounding region is a drowned karst plain exhibiting a rolling topography of limestone with sinkholes and solution basins (Brooks, 1974). The FMG occurs at a break in regional gradient, which increases from a seaward slope of 0.01° from the east to 0.06° to the west (Hilde and others, 1981).

The FMG is situated in a complex area of mixing between the Caribbean-derived Loop Current, the West Florida Estuarine Gyre and Florida Bay Waters (Fig. 1). The water is generally clear, of constant salinity (36±0.5°/oo), and classified as north tropical in nature (Austin and Jones, 1974; Cheney and Dyer, 1974). Average annual bottom temperatures fluctuate between 16° and 20°C with the lowest values occurring in January and February and the highest in September and October.

The objectives of this study were to define the controls and processes responsible for the development of the FMG, to determine its relation to the development of the surrounding west Florida margin, and to compare it with other modern reef systems. Results will be useful for identifying similar "atypical" reef environments in both the modern and ancient sedimentary records.

METHODS

The data base for this project consisted of a combination of high-resolution seismic-reflection data, surface-sediment sample analyses and video data recorded from a manned submersible. Seismic data were collected with a 500 Joule EG&G Uniboom by Texas A&M University. Transects were oriented in an east-west direction normal to the strike of reef ridges. Surface-sediment samples were collected seasonally during each of four cruises from October 1978 to July 1979. The samples, obtained by divers, grab sampler and dredge hauls, were taken from four benchmark stations previously determined to represent a typical biological assemblage of the region. During November 1978, closely spaced samples were recovered along transects in the vicinity of three of these stations. A total of 178 samples was analyzed. Twenty-eight samples from transects across the Middle Ground, taken in 1973, were analyzed for sediment constituents. Textural and calcium-carbonate data from these samples were determined previously by Birdsall (1978) and are incorporated into the interpretation of results. The sample locations are shown in Figure 2. Direct observations were made and video data recorded on FMG reefs via submersible.

Seismic data were analyzed using sequence and facies analysis as described in Mitchum and others (1977).

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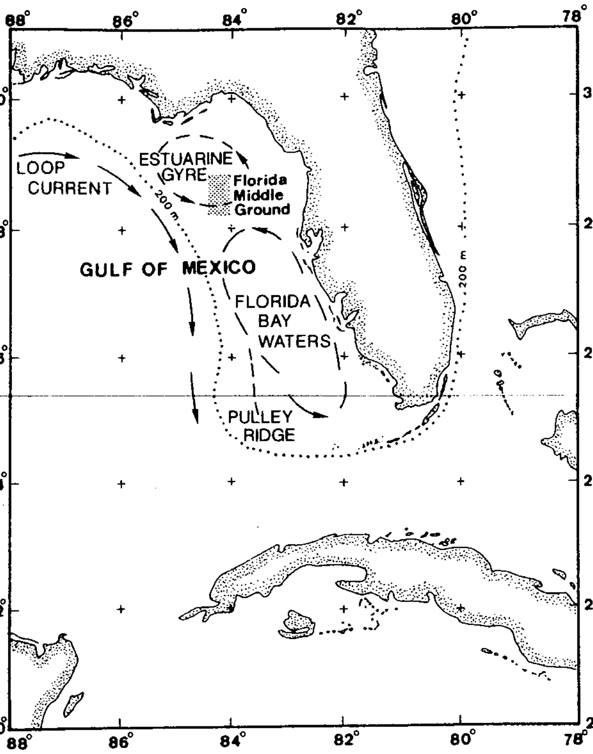


FIG. 1.—Location map showing the Florida Middle Ground on the west Florida shelf. Also shown are the current systems influencing the study area, and the Pulley Ridge biohermal complex on the southern shelf.

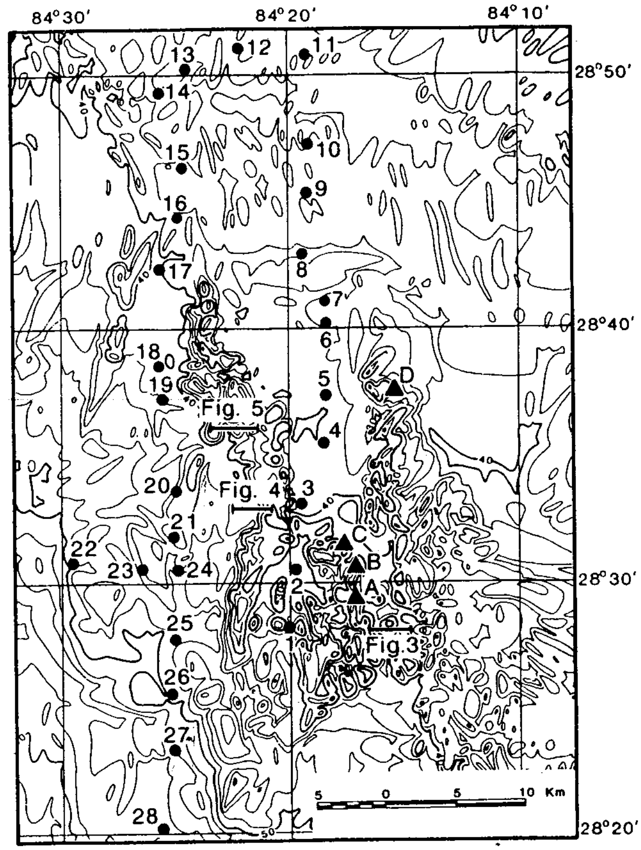


FIG. 2.—Bathymetric map of the Florida Middle Ground showing sampling sites and locations of seismic profiles shown in Figures 3–5. Contour interval 2 m. ● denotes surface-sample transect sites occupied by Birdsall (1978). ▲ denotes Benchmark sites, A = 491, B = 481, C = 151, D = 247.

Surface-sediment samples were analyzed for texture, calcium-carbonate content, constituent composition and mineralogical composition. Grain size was determined for all samples by the seive and pipette method (Folk, 1965). Calcium-carbonate content was determined by acid leaching as described in Milliman (1974). Sediment constituent composition was determined by the whole-grain point-count method (Carver, 1971). For each sample, at least 100 particles were identified from each whole phi (ϕ) interval of the sand-size fraction. This method gives a 95 percent chance of finding any constituent type comprising at least 3 percent of the total sample (Dennison and Hay, 1967), which obviates bias that may occur due to size differences. Sediment constituent composition was normalized to 100 percent for each sample. An acetate impression of the internal structure was made on 10 selected samples according to the technique described by Milliman (1974) to identify constituents too degraded for identification under reflected light. Each sample was analyzed and constituents identified by transmitted light. Surface texture of individual sediment grains was identified for 10 representative samples. At least 100 grains from each sample were selected by the point-count method (Carver, 1971) and described as "fresh," "dull," or "worn," according to criteria described in Wanless (1977). "Fresh" refers to grains showing no weathering at all, but exhibiting detailed surface features. "Worn" refers to grains that have essentially lost all of their surface features, but may be identifiable by shape. "Worn" grains commonly exhibit a rough, pitted and/or bored surface. The term "dull" refers to grains that have lost little material to the weathering process, but have lost their gloss, are discolored, or otherwise altered from their "fresh" appearance.

The mineralogical composition of 10 samples selected from different environments was determined by X-ray diffraction techniques (Grim, 1968; Carver, 1971). Amino-acid racemization dates were determined for selected samples. Both a complete assemblage and a monospecific molluscan assemblage were dated from each of nine samples. The complete assemblage was used to gain a general idea of the age of the sediment constituents collectively. Monospecific molluscan material was used to obtain a more specific age for the mollusc fraction, which is by far the dominant fraction in FMG surface sediments.

RESULTS AND DISCUSSION

Seismic Data

As a result of the high reflectivity of FMG carbonate-rich sediments, penetration of the signal beneath the sea floor was greatly inhibited. On the average, approximately 20 ms (two-way time) or less of penetration yielded useful data. Three distinct seismic sequences are present, each bounded by an unconformable surface (Figs. 3–5).

The bottom sequence, termed sequence I, is characterized by a very irregular, highly reflective surface (Figs. 3–5). This unit represents the acoustic basement in the study area. Surface irregularities are shown by discontinuous, truncated and occasional hyperbolic reflectors, though often their identification is inhibited by signal noise. This surface is interpreted to represent a karst surface, the irregular nature resulting from dissolution of the underlying carbonate rock during one or more periods of lowered sea level. Sequence I may correspond to the Miocene (?) karst surface underlying the south Florida outer shelf and cropping out on the upper slope along the southwest corner of the platform. Holmes (1985) reports that this surface is covered by a thin veneer of sediment on the shelf and, like sequence I underlying the FMG, abruptly increases in slope from the relatively flat (0.07° seaward dip) inner shelf to a gently sloping (0.2° seaward gradient) outer shelf.

The middle sequence, sequence II (Figs. 3–5), is bounded on top by a flat-lying surface and on the bottom by the irregular surface of sequence I. Sequence II is less than 5 to 10 ms thick. Seismic facies are dominantly reflection free. Where internal reflectors are present, they are generally parallel to subparallel and discontinuous. Once again, signal noise inhibits the identification of seismic facies. The extremely flat surface and lack of internal reflectors suggest that this sequence formed by uniform deposition independent of underlying bottom relief, possibly representing the Holocene, or earlier, transgressive sand sheet. Based upon the broader data base, Hilde and others (1981) report that this sequence downlaps and eventually pinches out against the surface of sequence I along a north-northwest-south-southeast line through the study area. Hence, sequence II does not appear to exist landward of the study area.

Sequence III (Figs. 3–5) is bounded by the sea floor at the top and the relatively flat surface of sequence II at the base. It is from less than 5 to 10 ms thick with thickest deposits occurring along the flanks of ridges (Figs. 3–5) and as lenses in the plain between ridges (Fig. 3). As with sequence II, seismic facies are dominantly reflection free, and where present, internal reflectors are parallel to sub-

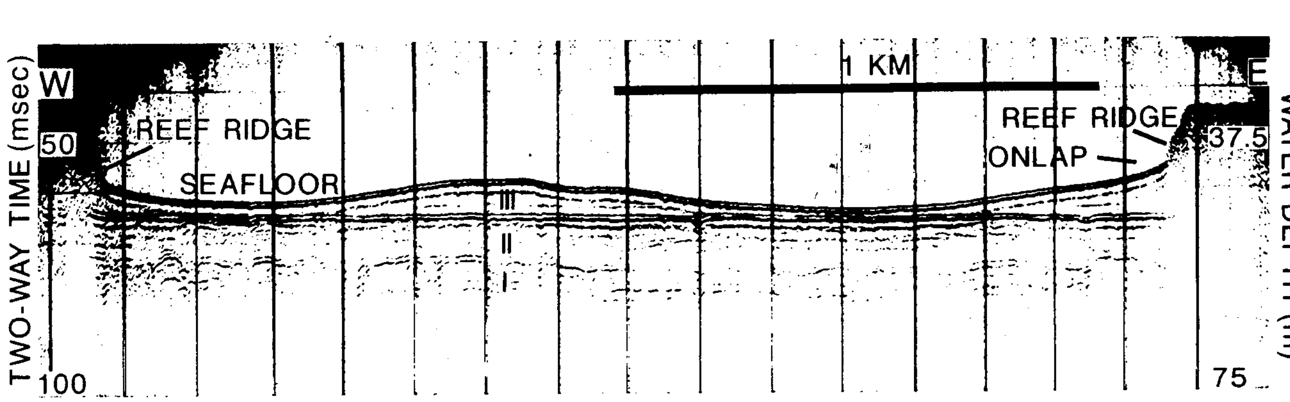


FIG. 3.—Seismic profile showing two reef ridges separated by a broad plain (see Fig. 2 for location). Note the presence of three sequences (I, II and III) bounded by unconformities, and onlapping of the surface unit against ridges as well as the thickening of the unit in the center.

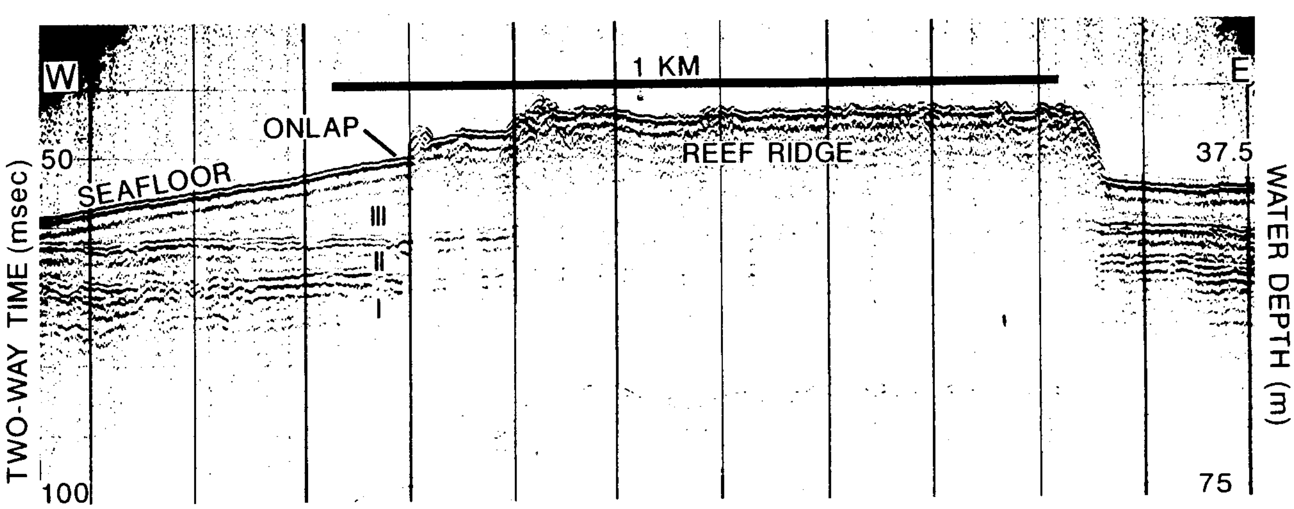


FIG. 4.—Seismic profile showing sequences I, II and III, and the reef ridge with onlapping sediments (see Fig. 2 for location).

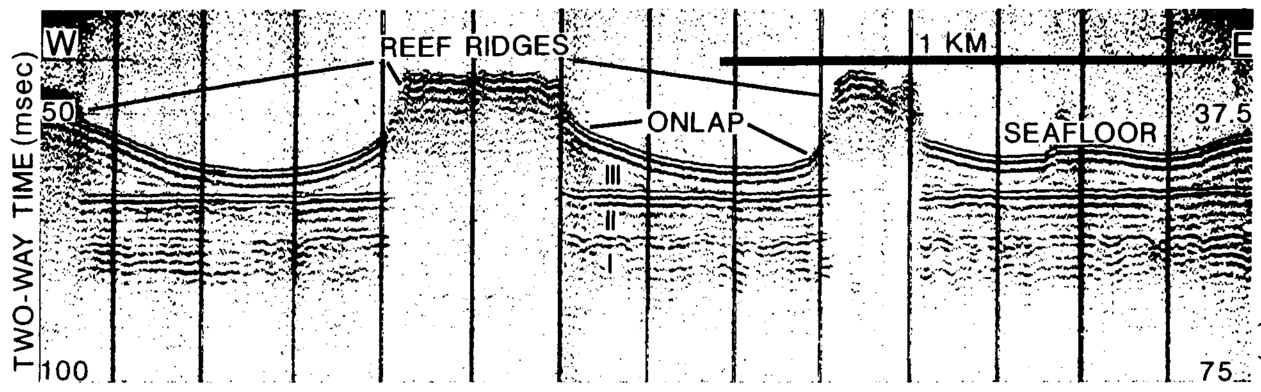


FIG. 5.—Seismic profile showing sequences I, II and III, and reef ridges with onlapping sediments (see Fig. 2 for location).

parallel and discontinuous. Reflectors appear to lap out against FMG reef ridges, forming sediment wedges more than 7 ms thick (Fig. 3). Sediments of sequence I are interpreted to have been deposited as sheet drape. The thick wedges of sediments along ridge flanks suggest that sediments are either derived from the ridges and shed off along the flanks, or that physical processes are transporting sediments and depositing them against the ridges. The presence of thick sediment lenses, some in excess of 5 ms, in the broad, flat plains (Fig. 3) indicates that sediments are being "ponded" between reef ridges.

Reef ridges (Figs. 3–5) are acoustically transparent features with highly reflective surfaces. Ridges are tens to hundreds of meters wide and rise from 5 to 15 ms above the surrounding sea floor. Ridges do not appear to be accumulating an appreciable sediment cover.

Sediments

Results of sedimentological analyses are discussed in terms of both areal distribution patterns and temporal changes, on a seasonal basis, of parameters including texture, major sediment constituents, calcium-carbonate content and age dating of selected samples.

Textural distribution patterns are shown in Figures 6 and 7. Sediment distribution is patchy on both a regional scale throughout the FMG as shown by Figure 6, and locally as shown by the closely spaced samples along transects at benchmark stations (Fig. 7). Mean grain sizes of transect samples range from −0.9 ϕ (very coarse sand) on a ridge crest in the vicinity of BM-481 (Figs. 2 and 7), to 3.4 ϕ (very fine sand) on the open shelf immediately northwest of the westernmost ridge (Fig. 6).

Coarsest grained sediments are found on ridge crests with mean sizes consistently in the very coarse (−1 to 0 ϕ) to coarse (0–1 ϕ) sand range (Fig. 7). Immediately adjacent to ridge crests and in bathymetric depressions within ridges, mean sizes decrease to dominantly fine sand (2–3 ϕ; Fig. 7). With few exceptions, sediments in the central plain and on the shelf adjacent to the ridges have mean sizes from fine (2–3 ϕ) to very fine (3–4 ϕ) sand (Fig. 6). The fining of sediments away from the ridge crests suggests either that the ridge crests are the origin for coarse-grained sediments or that fine-grained sediments are being winnowed from the ridge crests, leaving only the coarser grained sediments behind. The occurrence of finer grained sediments in bathymetric depressions within ridges (Fig. 7) supports the contention that fines are being winnowed from exposed portions of ridge crests and suggests that the rugged bathymetry associated with the FMG may be a major control on sediment distribution. The few instances of relatively coarse mean

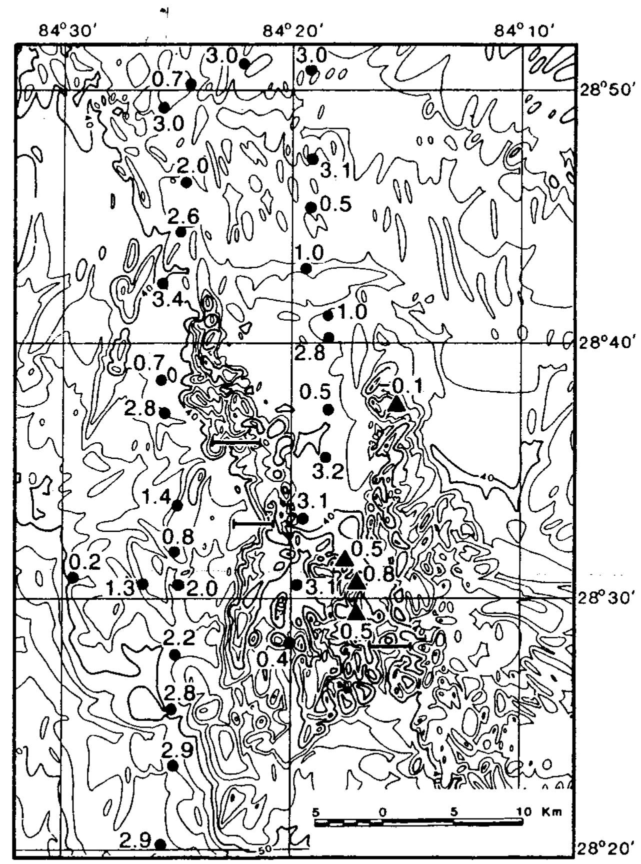


FIG. 6.—Bathymetric map of the FMG showing a general decrease in mean grain size away from the reef ridges. Values expressed as mean phi (ϕ).

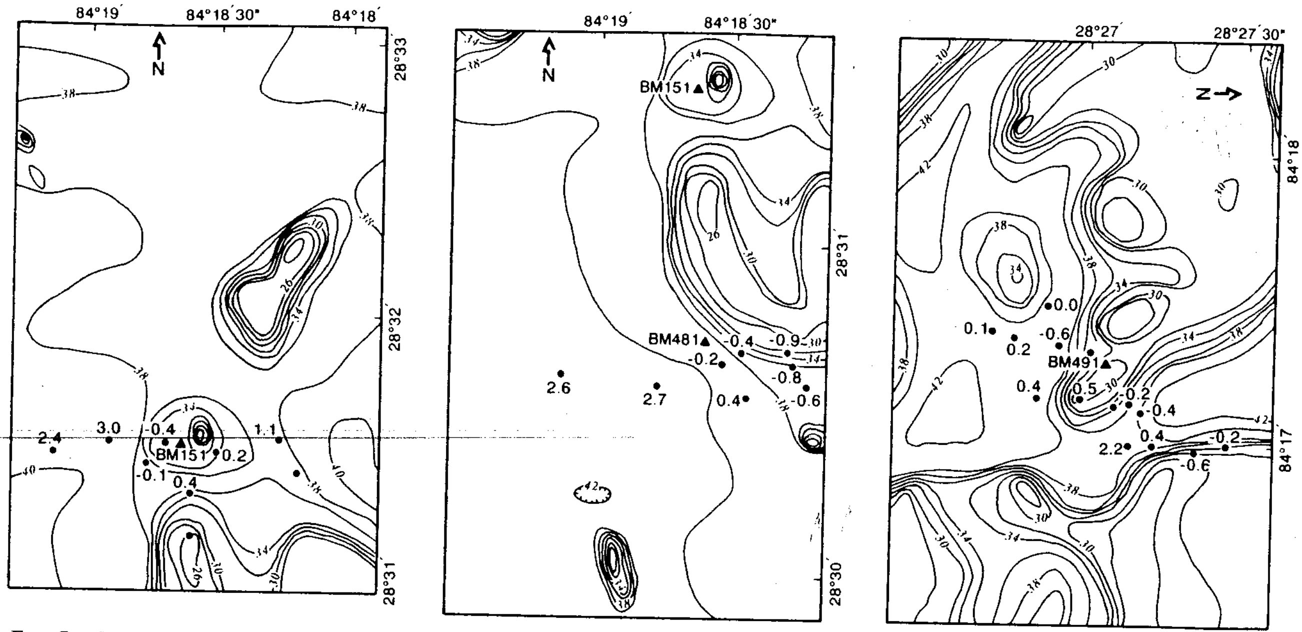


FIG. 7.—Bathymetric maps of the vicinity of Benchmark stations 151, 481 and 491, on reef ridges showing a general decrease in mean grain size abruptly away from ridge crests and in bathymetric depressions within ridges. Values expressed as mean phi (ϕ).

grain sizes on the central plain and shelf sediments adjacent to ridges may reflect localized *in-situ* production of relatively coarse-grained biogenic calcium carbonate.

The mean grain size of sediments collected from benchmark stations on ridge crests shows a tendency toward coarsening from October 1978 to June 1979 (Fig. 8). Mean sizes for the October 1978 sampling period range from 0.3 ϕ (coarse sand) to 1.4 ϕ (medium sand). Mean sizes for the two stations (151 and 247) sampled during January 1979 were both −0.6 ϕ (very coarse sand). Mean sizes for the June 1979 sampling period ranged from −1.0 ϕ (granule/very coarse sand) to 0.3 ϕ (coarse sand). This tendancy toward coarsening may be a result of progressively greater winnowing by bottom currents between October 1978 and June 1979, or alternatively, a greater input of production of coarser grained sediments within this time period. The latter possibility is doubtful because coarse-grained sediments consist dominantly of biogenic calcium carbonate, and an increase in the biogenic production of calcium carbonate of sufficient magnitude to produce the observed trends is unlikely. We suggest that this progressive tendancy toward coarser mean grain sizes is a result of greater winnowing. It is probably more a result of a gradual increase in bottom-current activity, or a series of high-energy events (such as winter-cold fronts), rather than one single event because of the incremental increases from October 1978 to January 1979 and then again from January 1979 to June 1979 at stations 151 and 247.

The distribution of calcium carbonate in sediments is similar to that of mean grain size in that it is quite patchy (Figs. 9 and 10). Values for the closely spaced samples collected along transects in the vicinity of each bench mark range from 78 to 99 percent calcium carbonate (Fig. 10). Highest values, most greater than 90 percent, are found on the shallow-ridge crests, whereas lower values (70–90 percent) are found in deeper areas adjacent to ridge crests and bathymetric depressions within ridges (Fig. 10). Lowest percentages are found farthest from the reef ridges with values as low as 18 percent $CaCO_3$ reported for the northernmost sample in the study area (Fig. 9). The non-calcium-carbonate component consists dominantly of fine-grained quartz sand. The apparent decrease in calcium-carbonate content away from the reef ridges suggests that biogenic calcium-carbonate production is greatest on reef-ridge crests. Alternatively, this tendancy may be explained by the lack of input of quartz sand on ridge crests. The occurrence of fine quartz sand in shelf samples, especially north of the reef ridges, may simply mask the calcium-carbonate content. The lack of quartz sand on ridge crests could be an artifact of winnowing of finer grained sediments, as mentioned previously.

Mean percentages of calcium-carbonate content for samples collected at different periods throughout the year show no appreciable change (Fig. 8). Values are all greater than 90 percent $CaCO_3$, ranging from 91 to 99 percent. This suggests that, although sediments on reef crests may be winnowed at a greater rate during certain times of the year, as indicated by the sediment textural distribution, the relative input of calcium-carbonate material to the sediment remains consistent and is independent of the winnowing process.

Constituent composition of FMG sediments (Fig. 11) is dominated by molluscs with an average of 36 percent; followed by barnacles at 8 percent; benthic foraminifera, annelid tubes and bryozoa at 3 to 4 percent; and the coralline alga *Goniolithon* spp. at 2 percent. Planktonic foraminifera, Station 151

```
        10/78
   Grain Size
   mean = 0.3ϕ

   Percent Carbonate
   mean = 98.2
75%-

                       x
50%-                   x
                       x
                       x
25%-x                  x
    x        x         x
    x   x    x         x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

```
        01/79
   Grain Size
   mean = -0.6ϕ

   Percent Carbonate
   mean = 91.3

                       x
    x                  x
    x                  x
    x                  x
    x   x        x     x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

```
        06/79
   Grain Size
   mean = -1.0ϕ

   Percent Carbonate
   mean = 94.1

    x
    x                  x
    x                  x
    x   x        x  x  x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

Station 247

```
        10/78
   Grain Size
   mean = 1.2ϕ

   Percent Carbonate
   mean = 98.7
75%-

                       x
50%-                   x
    x                  x
    x                  x
25%-x                  x
    x   x              x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

```
        01/79
   Grain Size
   mean = -0.6ϕ

   Percent Carbonate
   mean = 91.3

                       x
    x                  x
    x                  x
    x   x              x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

```
        06/79
   Grain Size
   mean = -1.0ϕ

   Percent Carbonate
   mean = 95.3

    x                  x
    x                  x
    x                  x
    x   x              x
    x   x        x     x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

Station 481

```
        10/78
   Grain Size
   mean = 1.4ϕ

   Percent Carbonate
   mean = 98.7
75%-

                       x
50%-                   x
    x                  x
    x                  x
25%-x                  x
    x   x              x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

```
        06/79
   Grain Size
   mean = -0.3ϕ

   Percent Carbonate
   mean = 93.0
75%-


50%-
    x
    x                  x
25%-x   x              x
    x   x        x  x  x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

Station 491

```
        10/78
   Grain Size
   mean = 0.9ϕ

   Percent Carbonate
   mean = 98.8
75%-

                       x
50%-                   x
                       x
    x                  x
25%-x                  x
    x   x              x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

```
        06/79
   Grain Size
   mean = 0.1ϕ

   Percent Carbonate
   mean = 96.2
75%-


50%-
    x
    x                  x
25%-x                  x
    x   x        x  x  x
    x   x   x    x  x  x
    ---------------------
    1   2   3   4   5   6
   Sediment Constituents
```

1 = mollusc, 2 = barnacle, 3 = benthic foraminifera, 4 = annelid, 5 = bryozoa, 6 = other

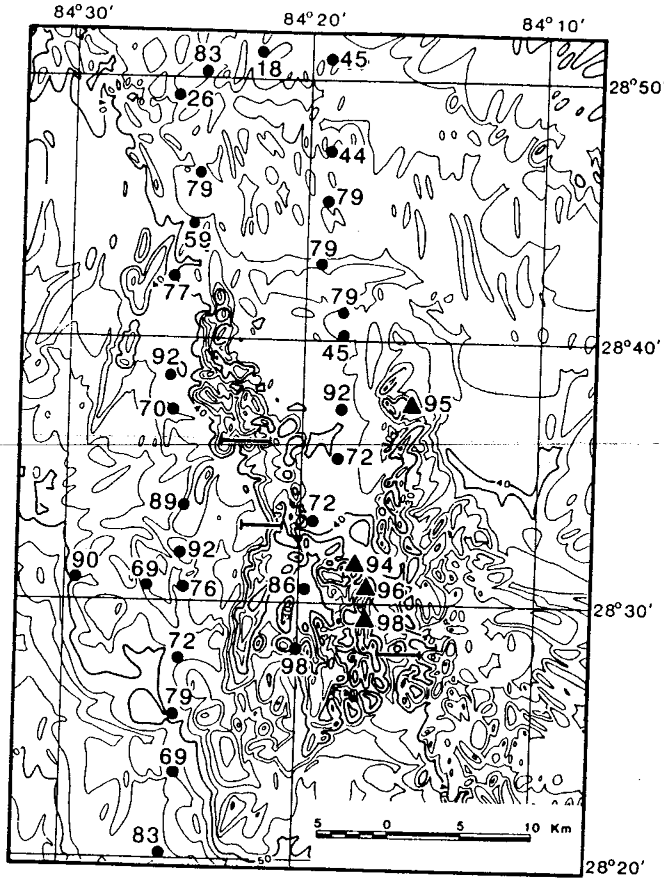


FIG. 9.—Bathymetric map of the FMG showing a general decrease in calcium-carbonate content away from the reef ridges. Values are expressed as the percentage of sediments consisting of calcium carbonate.

echinoids, octacorals, schleractinians, ostracods, arthropods, sponge spicules, complex skeletal particles (molluscs encrusted with bryozoa or annelid tubes), rock fragments, pelletoids, aggregates, and quartz were identified in trace amounts. Typically, quartz is present only in trace quantities; however, some samples, especially those collected north of the reef ridges, are dominated by quartz. This is supported by the percent $CaCO_3$ data (Fig. 9), as the insoluable residue consists almost entirely of fine quartz sand.

The abnormally high percentage of grains unidentifiable under reflected light (38 percent as shown in Fig. 11) can be attributed to the method of identification and/or the degraded condition of the grains. Because grains were analyzed from each whole phi (ϕ) interval, the grains in the finer fractions (2–3 ϕ and 3–4 ϕ) often consisted of fragments too small to identify. When these fine fractions constituted a large portion of the sediment sample, the entire sample would have a large unidentifiable fraction. Additionally, the quality of individual grains often was found to be quite poor. Such poor condition could be a reflection of age, or rapid degradation by physical, chemical or biological processes. Results of acetate-peel analyses indicate that the composition of grains unidentifiable under reflected light is essentially the same as for the identifiable fraction, with the exception of a slight increase in *Goniolithon* spp. grains. An increase in *Goniolithon* spp. probably reflects the error associated with identifying *Goniolithon* spp. because of the lack of distinguishing external morphological characteristics, especially when in such a degraded condition as observed here.

Areal distributions of the three most abundant constituents, namely molluscs, barnacles and benthic foraminifera, are shown in Figures 12 and 13. Mollusc fragments comprise from 7 to 55 percent of FMG sediments. They are by far the dominate carbonate constituent present. With few exceptions, molluscs comprise from 30 and 50 percent of the sediment collected along transects in the vicinity of benchmark stations (Fig. 13). Lower values are generally confined to samples collected in deeper areas away from or between ridge crests, or from protected areas within ridges created by the rugged bathymetry. Percentages of sediments consisting of mollusc fragments in the central plain and on the shelf immediately surrounding the FMG ridges is not appreciably different from those of samples from on the ridges (Fig. 12). In fact, the two highest percentages (53 and 55 percent) were reported for sediments collected on the shelf immediately west of the westernmost ridge. Lowest values, ranging from 7 to 39 percent, were found for sediments north of the ridges (Fig. 12), and are interpreted to be a reflection of the high percentage of fine-grained quartz sands (Fig. 9).

Molluscan content for benchmark stations varies little between October 1978 and June 1979 (Fig. 8). Values range from approximately 30 to 50 percent, which is consistent with transect samples collected from ridge crests. No evidence of seasonal variability exists.

Barnacle fragments average approximately 8 percent of FMG ridge-crest sediments, second only to molluscs (Fig. 11), but are highly variable from station to station (Figs. 14 and 15). Barnacles range from 0 to 13 percent of closely spaced samples collected along benchmark transects (Fig. 15). Highest values, commonly greater than 5 percent, often are found on shallow-ridge crests, whereas lowest values, generally no more than a few percent, are found on deeper areas away from ridge crests (Fig. 15), or in bathymetric depressions within ridges.

Lowest concentrations of barnacles occur in the central plain, as well as north and southwest of the ridges, where only trace amounts were found (Fig. 14). The distribution is quite patchy however, as values from 5 to 10 percent are reported for samples collected at considerable distances away from ridge crests (Fig. 14).

Barnacle fragments show no appreciable change in percentage from October 1978 to June 1979 (Fig. 8). Values

FIG. 8.—Mean grain size, calcium-carbonate content and relative percentages of sediment constituents for Benchmark stations 151, 247, 481 and 491 during different sampling periods.

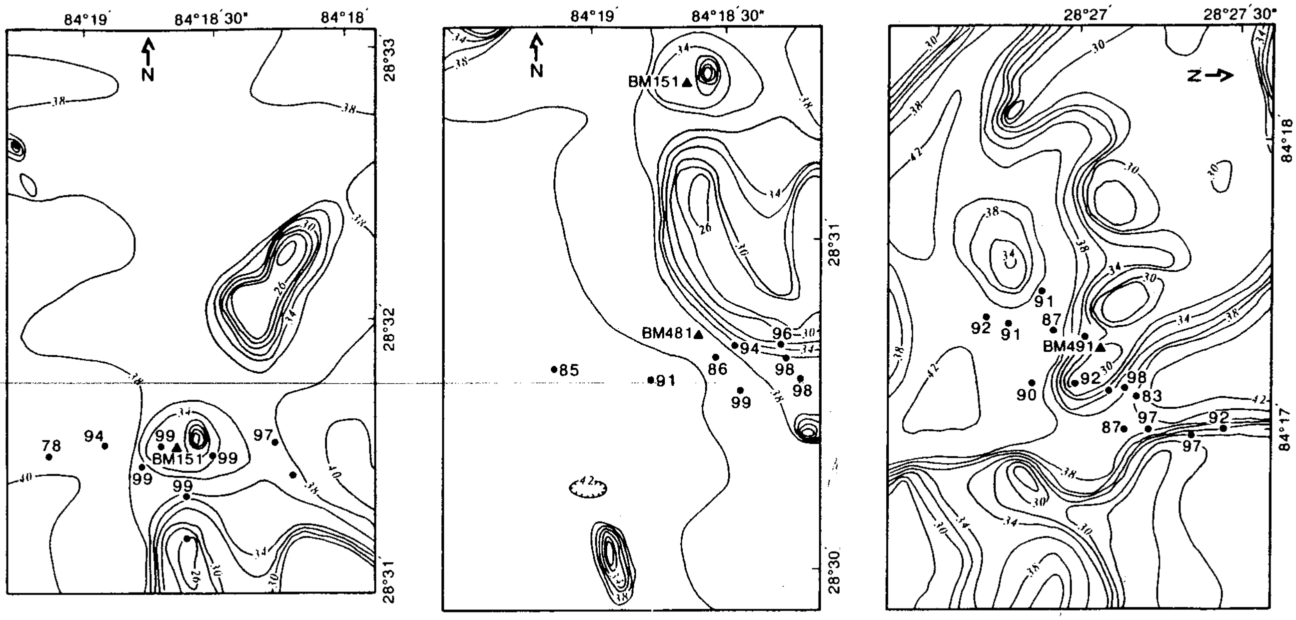


FIG. 10.—Bathymetric maps of the vicinity of Benchmark stations 151, 481 and 491, on reef ridges showing a general decrease in calcium-carbonate content abruptly away from ridge crests and in bathymetric depressions within ridges. Values are expressed as the percentage of sediment consisting of calcium carbonate.

range between 5 and 15 percent, which is consistent with transect sample values reported for ridge crests.

Benthic foraminifera average approximately 4 percent of FMG sediments (Fig. 11) but range from 0 to 15 percent of the sample (Figs. 16 and 17). Values for samples along benchmark transects are quite variable, with a weak tendancy to increase in deeper samples away from ridge crests (Fig. 17). Both highest (15 percent) and lowest (0 percent) values were recorded for these closely spaced benchmark transect samples (Fig. 17), illustrating the patchy areal distribution.

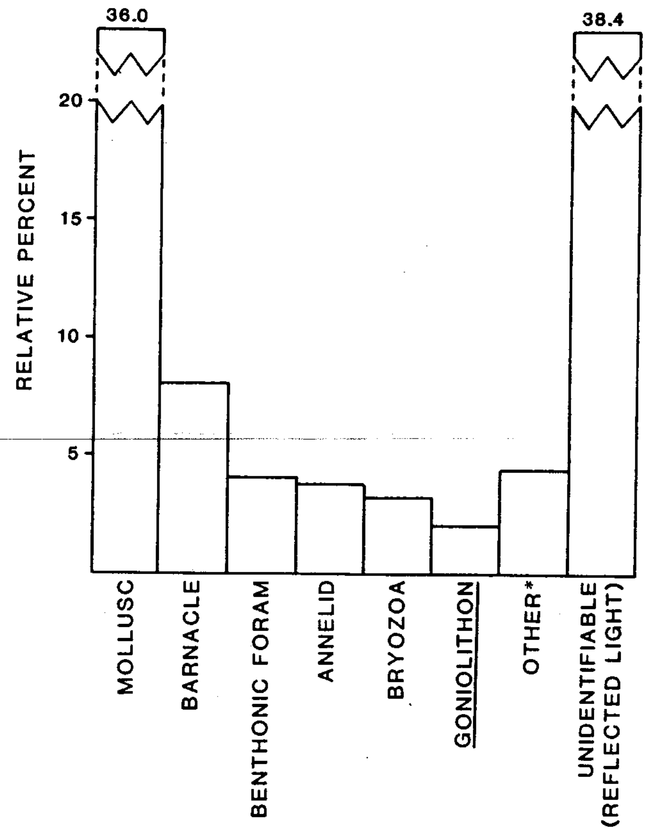
Samples collected on and near reef ridges including the central plain contain consistently less than 10 percent benthic foraminifera, with most less than 7 percent. Samples collected away from reef ridges, with the exception of the northernmost quartz-rich samples, have somewhat higher values, some of which exceed 10 percent (Fig. 16).

Benthic foraminifera percentages show no evidence of variability from October 1978 to June 1979 (Fig. 8). Values are consistently in the 5 percent or less range for all sampling periods.

In general, distribution patterns of the three most abundant carbonate constituents reflect their origin, physical dispersion and bathymetry. The dominance of mollusc fragments throughout the study area indicates that molluscs are a common organism to both reefal and shelf environments. The lower percentages reported for sediments collected in bathymetric depressions within ridge crests probably reflects dilution by finer grained carbonate-producing organisms. Mollusc fragments are more common in the coarse-grained fraction. Consequently, in exposed areas such as ridge crests, winnowing of finer grained material results in an increase in the percentage of molluscan debris. The low percentages of molluscan material in the northernmost samples probably reflects dilution by the large quantities of fine-grained quartz sands.

The distribution of barnacle fragments is similar to that of molluscs in that percentages are highest on ridge crests. It differs from that of molluscs, however, in that lowest percentages are reported for samples collected farthest from reef ridges, suggesting an association of barnacles with reef ridges. Like molluscs, barnacles are more common in the coarser size fractions, which may explain why percentages are much greater on shallow, exposed portions of ridge crests than in deeper, more protected areas within ridges. The distribution of benthic foraminifera is patchy, but generally opposite that of barnacles. Because benthic foraminifera occupy the finer size fractions, their distribution is more heavily influenced by low to moderate-energy processes relative to what is required to distribute coarser grained material, hence the patchy distribution, especially when considering the rugged bathymetry. Their apparent increase in shelf samples may reflect winnowing from ridge tops, or alternatively, may be an indication that benthic foraminifera are not associated exclusively with reef ridges.

Surface-texture analysis indicates that, on average 76 percent of the grains are "worn," 20 percent are "dull" and 4 percent are "fresh." Figure 18 illustrates examples of each category as well as a typical constituent assemblage. The general deteriorated condition probably is responsible for the large number of grains unidentifiable under reflected light (Fig. 11), and may be indicative of intense weathering or old age. Amino-acid racemization ages range from 3,700±1,500 yrs to 7,500±2,500 yrs. Youngest sediments



* INCLUDES: PLANKTONIC FORAMINIFERA, ECHINOIDS, OCTOCORALS, SCLERACTINIANS, OSTRACODS, CRABS, SPONGE SPICULES, COMPLEX SKELETAL (MOLLUSCS ENCRUSTED WITH BRYOZOA OR ANNELIDS), ROCK FRAGMENTS, PELLETOIDS, AGGREGATES, & QUARTZ.

FIG. 11.—Constituent composition of FMG sediments.

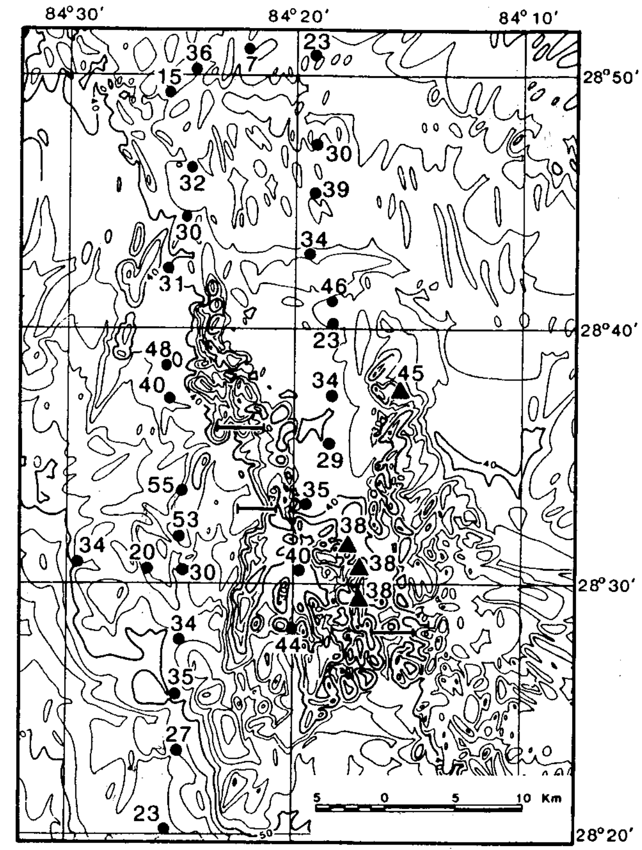


FIG. 12.—Bathymetric map of the FMG showing the distribution of mollusc shells in sediments. Values expressed as the relative percentage of sediment consisting of mollusc shells or fragments.

are found on the ridge crests, whereas oldest sediments are found on the central-plain and open-shelf environments.

Clay minerals constitute less than 5 percent of FMG sediments and, therefore, are relatively unimportant from a volumetric standpoint. The only clay mineral detected was hydrobiotite, a member of the illite group, and most common in temperate to subtropic regions (Grim, 1968). Blackened grains were found to be common in samples collected away from reef ridges, especially in the northernmost portion of the study area. Mineralogically, the blackened grains consist almost entirely of calcium carbonate. Their blackened appearance is the result of postdepositional processes occurring in the open-shelf but not reefal environment.

Video Data

Direct observations from submersible and video tape reviews reveal a variety of characteristics associated with FMG reef ridges, ridge flanks and the central plain/open shelf. The reef top exhibits rugged bathymetry covered extensively by *Millepora* sp. Less than 50 percent is covered by sediments, the remainder consisting of exposed reefal material. Sediment covering on ridges is confined principally to bathymetric depressions and sheltered, low-energy areas. Sediments consist dominantly of coarse sand, gravel and reef rubble.

Reef flanks consist, for the most part, of large blocks of reefal material appearing to be calving from reef margins. Blocks average approximately 1 m on a side, but reach more than 3 m in some cases. Reef flanks are occupied by living assemblages dominated by coralline algae, *Millepora* sp., and sponges. Surface sediments drape over calved reef blocks and biologic assemblages. Sediments consist of coarse sand and rubble rich in *Madracis* sp. fragments and appear to be transported from the ridge tops, where they are deposited as a drape over associated ridge flanks.

The central plain separating the two reef ridges and the surrounding open shelf exhibits similar characteristics. Sand waves and ripples exist in a variety of orientations. Some are characterized by dark, finer grained material in their troughs, whereas others were reported to be covered by various types of algae. Sediments consist of a fine sand to silty sand and appear to be heavily bioturbated.

In all environments of the FMG, sand waves and ripples

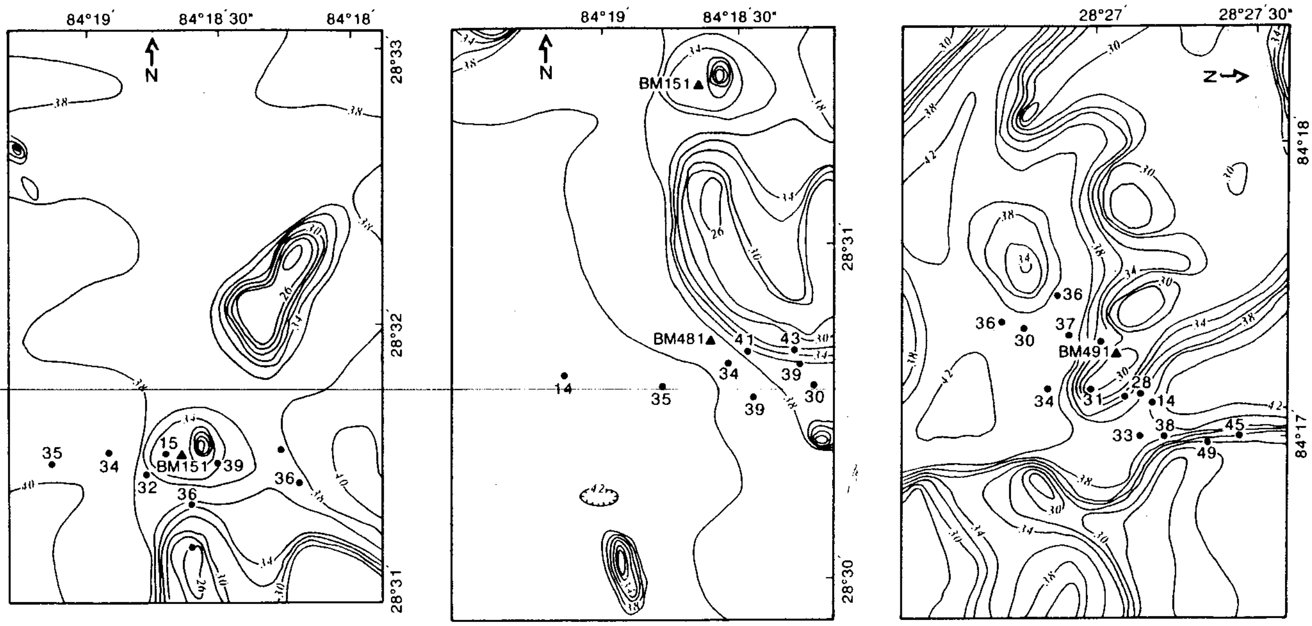


FIG. 13.—Bathymetric maps of the vicinity of Benchmark stations 151, 481 and 491, on reef ridges showing the distribution of mollusc shells in sediments. Values expressed as the relative percentage of sediment consisting of mollusc shells or fragments.

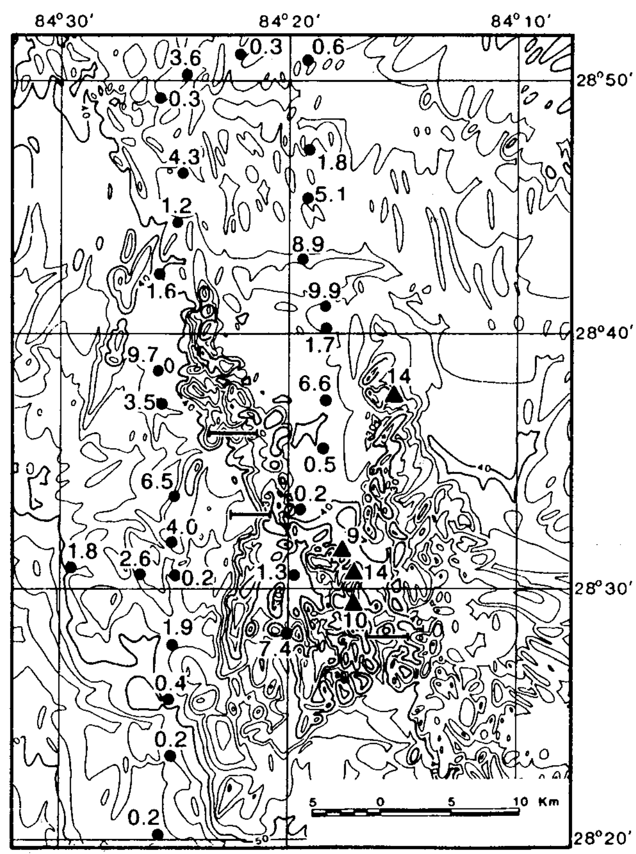


FIG. 14.—Bathymetric map of the FMG showing a general decrease in barnacle fragments away from the reef ridges. Values expressed as the relative percentage of sediment consisting of barnacle fragments.

were noted having north, northeast and northwest orientations. Bottom currents were measured directly flowing from north to south. Current velocity was not measured. Observations of a variety of bedforms suggest a complex physical environment consisting of omni-directional flow of variable velocities.

Geologic Development

Modern reef growth is limited to the tops of the highest ridge crests, built upon a dead-reef foundation. This dead-reef foundation may have formed during one or more of the sea-level highstands of the Pleistocene, or to some extent, during the early Holocene transgression. Bloom (1974) suggests that modern reef complexes commonly form as thin veneers on Pleistocene reefal buildups. These reefal buildups are not planed off during subaerial exposure, because their high permeability permits water to be easily transmitted through the framework. Controlling factors responsible for initiating original reef growth are not clearly understood. Growth may have been initiated by the break in bottom gradient between the relatively flat-lying shelf to the east and the gently seaward-dipping surface to the west. This explanation would be consistent with that postulated for the Pulley Ridge central-shelf biohermal complex discovered on the south Florida shelf. Pulley Ridge (Fig. 1), which is from 70 to 90 m deep, corresponds to a slight but rather abrupt break in slope of the underlying Miocene(?) surface interpreted to represent post-Miocene, westward tilting of the west Florida platform (Holmes, 1981).

Original growth also may have developed preferentially on an underlying karst surface, as suggested by Price (1954). The irregular surface of sequence I is interpreted to represent a karst surface that developed by dissolution of the

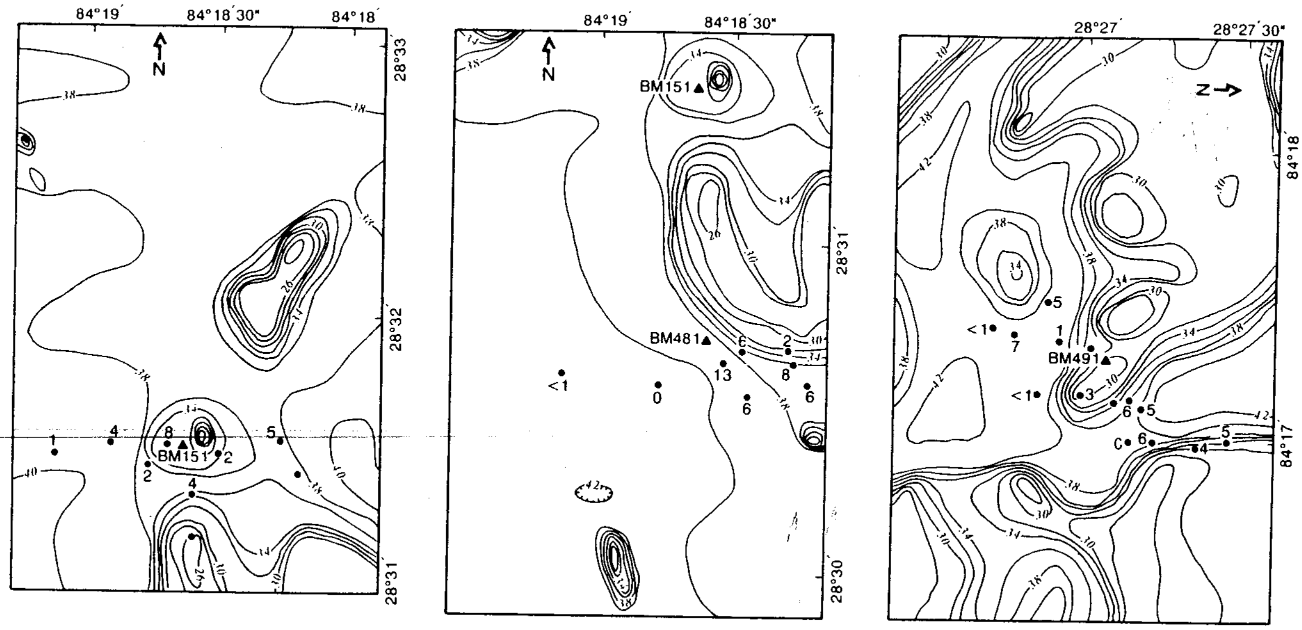


FIG. 15.—Bathymetric maps of the vicinity of Benchmark stations 151, 481 and 491, on reef ridges showing a general decrease in barnacle fragments abruptly away from ridge crests and in bathymetric depressions within ridges. Values expressed as the relative percentage of sediment consisting of barnacle fragments.

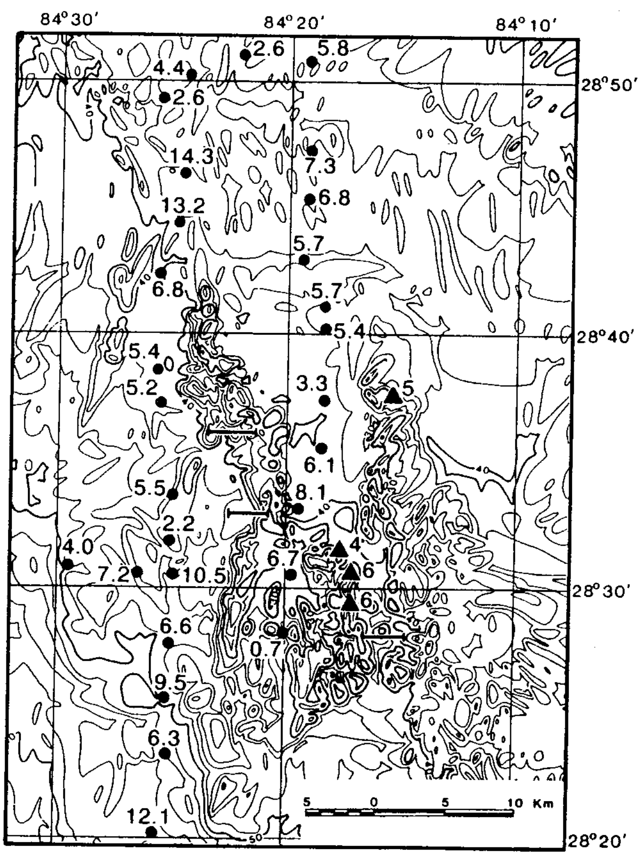


FIG. 16.—Bathymetric map of the FMG showing a general increase in benthic foraminifera away from the reef ridges. Values expressed as the relative percentage of sediment consisting of benthic foraminifera.

underlying limestone during one or more sea-level lowstands when the area was subaerially exposed. Reef growth may have developed during an ensuing sea-level rise, on a bathymetric high or slight break in gradient created by karstification. Modern reefal development on karst surfaces is thought to be common, with different stages of karstification often resulting in a specific reef type (Purdy, 1974). It also has been suggested that FMG ridges occupy what were once the banks of a river that was active during a period of lower sea level (Jordan, 1952). During the subsequent sea-level rise, these river banks may have created a bathymetric high optimum for reefal development. Hence, paleodrainage patterns also may have controlled the parallel-ridge configuration of the FMG.

Initial development as well as continued maintenance of FMG reefs also may have been controlled to a large extent by regional circulation patterns. The FMG occupies a junction between three major water masses; the Gulf Loop Current, the west Florida Estuarine Gyre and Florida Bay Waters (Fig. 1). It has been suggested (MAFLA, 1975) that Caribbean reefal organisms become entrained in the Loop Current, which transports them to the junction of these water masses where they settle out to form part of the biologic community. Consequently, this biologic recruitment may regularly provide species that would not normally be able to reproduce, given the relatively low water temperatures (MAFLA, 1975), thereby continuously "stocking" the FMG with Caribbean reefal fauna.

It is likely that Loop Current recruitment occurs to some extent at present, and perhaps, in conjunction with bathymetry, may have controlled initial FMG reef development. Considering the midshelf setting and the volume of reef growth, we feel the most reasonable interpretation is that

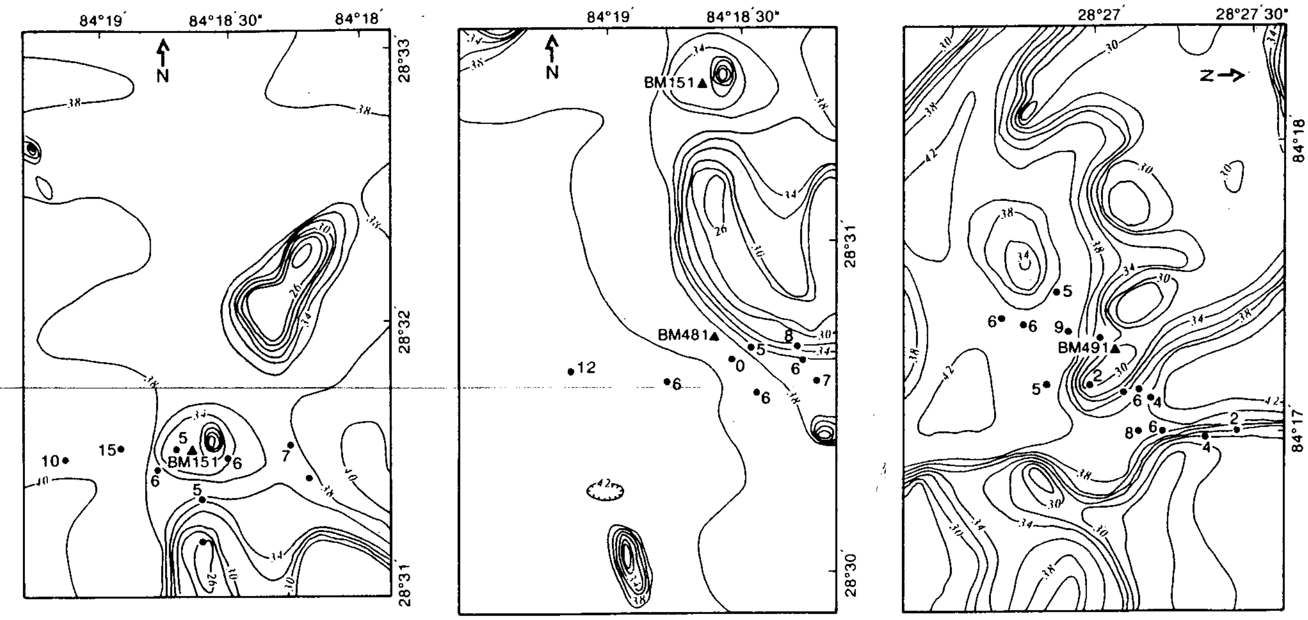


FIG. 17.—Bathymetric maps of the vicinity of Benchmark stations 151, 481 and 491 on reef ridges showing a general increase in benthic foraminifera abruptly away from ridge crests and in bathymetric depressions within ridges. Values expressed as the relative percentage of sediment consisting of benthic foraminifera.

original reef development occurred during one of the Pleistocene sea-level highstands and not during the early Holocene transgression, and that primary bathymetric controls were the karst surface of sequence I and the slight but abrupt seaward increase in slope of the same surface. The break in slope and karst surface of sequence I could have offered a suitable site for reef development, even in a midshelf setting. If initial development occurred during the early Holocene, up to 12 m of vertical growth would have had to develop on the smooth, flat surface of sequence II since being flooded, which is unlikely. Initial reef development on the banks of an ancient river is also unlikely, because there is no evidence of extensive channeling in the subsurface as would be expected if a river of this scale were to have occupied the region.

Modern sediments on the FMG have originated from two sources, the reef ridges and surrounding shelf. Shelf sediments consist of biogenic carbonates, principally a molluscan shell hash, and relatively fine-grained quartz sands. Reef-derived sediments consist of biogenic carbonates similar to those produced on the adjacent shelf. They are produced by biogenic processes on reef ridges and by destruction of the reef framework. "Calving" of large blocks and reef rubble commonly observed on reef flanks may be a consequence of erosion by bottom currents, undermining by biologic organisms, or a combination of the two. Despite the reef destruction, very few lithoclasts were identified as surface-sediment components, suggesting that either these blocks are not eventually broken down to sand-size grains, or that they are broken down to their individual components, making their lithoclastic origin unrecognizable. Another possibility is that sediment contribution directly by biogenic-carbonate production occurs at much faster rate than reef breakdown. We believe this unlikely due to the large quantity of blocks and rubble observed on reef flanks.

Components of reef-derived sediments are similar to the carbonate fraction of those surrounding the FMG, with the exception of barnacles. Barnacles, a major component of FMG reef-derived sediments, are rare in associated shelf sediments. We suggest that barnacles are common on the FMG because of the optimum sites for attachment provided by exposed reefal material. Barnacles probably attach to the lower, "dead" portions of the reef, the same structure that provides the foundation for modern reef growth. This attachment may actually be a form of bioerosion that aids in the destruction of reef ridges. Hence, the barnacle component of reef-derived sediments provides a sedimentological indicator of the transition from an open-shelf to reefal environment.

Sediments on and surrounding FMG reef ridges are not zoned with respect to reef environments, but are well distributed, controlled by physical processes, and bathymetry. Patchy sediment-distribution patterns suggest that biogenic-carbonate sediments produced on ridge crests are winnowed, where exposed, leaving relatively coarse carbonate sands. The relatively thin sediment cover observed on ridges indicates this winnowing process to be quite active. Currents exceeding 100 cm/s have been observed along ridge crests (Back, 1972). Sediments entrained in the current probably are transported to ridge flanks and the nearby shelf/central valley where they mix with shelf-derived sediments. Finer grained ridge-crest sediments in bathymetric depressions, or otherwise sheltered from currents, are not winnowed but continue to accumulate. Ridge-crest sediments

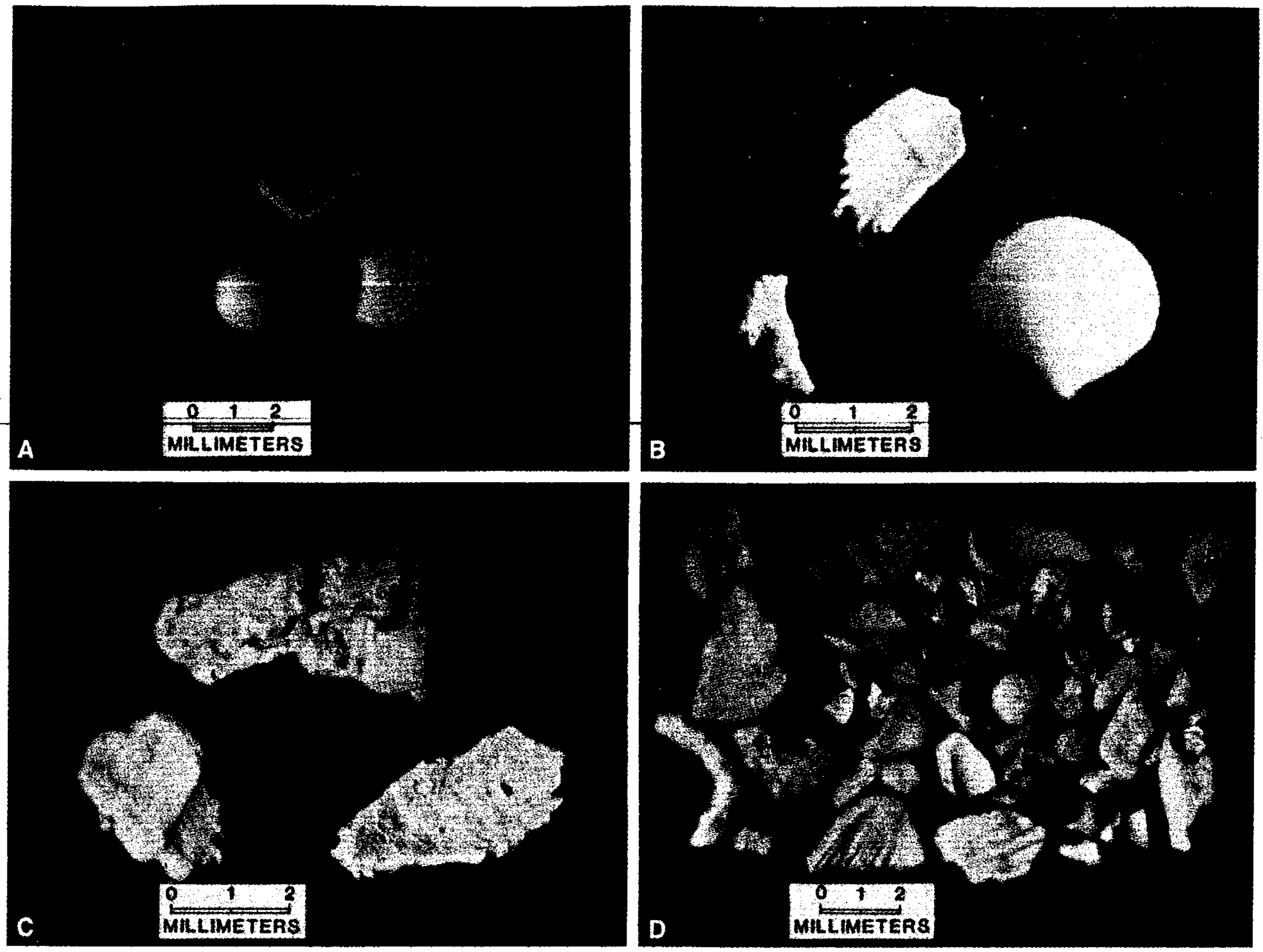


FIG. 18.—Photographs of FMG sediments showing fresh (A), dull (B) and worn (C) constituents, as well as a typical sediment assemblage (D).

deposited on ridge flanks are probably those too coarse to be transported in suspension by currents. They are transported off the ridge margin, where they form a sediment drape covering eroded reef-flank blocks and rubble. Shelf-derived sediments "onlapping" onto reef flanks by bottom currents may augment reef-derived input. This has been suggested by Hilde and others (1981), based upon an apparent asymmetry of reef-flanking sediments indicating unidirectional flow. These asymmetric patterns were not apparent here; furthermore, input from both ridge crests and the adjacent shelf, two opposing directions, would require periods of bidirectional flow. Multiple orientations of bedforms on ridge crests and the shelf/central valley show that this is quite possible.

The central valley between reef ridges functions as a sediment sink (Brooks, and others, 1980). Fine-grained sediments winnowed from reef ridges remain in suspension and are transported to these areas where they mix with shelf-derived sediments. Reef ridges act to shelter these areas from physical processes that are responsible for continuously redistributing sediments on open portions of the shelf (Neurauter, 1980; Logue, 1990). The result is the continued accumulation of a mixture of sediments derived from reef ridges and the adjacent shelf, producing deposits in excess of 5 m thick compared to the thin veneer (<1–3 m) for the surrounding shelf (Doyle and Sparkes, 1980).

Development of the FMG is consistent with that of the west Florida margin as a whole. Numerous investigations have shown that recent development of the west Florida margin is driven by high-frequency sea-level fluctuations, biogenic-carbonate production and physical processes (Doyle and Sparkes, 1980; Neurauter, 1980; Holmes, 1981; Doyle and Holmes, 1985; Holmes, 1985; Mullins, and others, 1987; Mullins and others, 1988; Brooks and Holmes, 1989, 1990; Logue, 1990). During sea-level transgressions and highstands when the shelf is flooded, shallow-water carbonate sediments are produced and deposited on the shelf surface. Sediments are redistributed periodically by a variety of physical processes including storm-generated currents, tidal currents and landward intrusion of the Loop Current (Neu-

TABLE 1.—MAJOR SEDIMENT CONTRIBUTORS FROM VARIOUS AREAS

Skeletal Fragments (%)	Florida Middle Ground[1]	Florida Reef Tract[2]	Alacran Reef[2]	Andros, Bahamas[2]	Abaco, Bahamas[2]	Ragged Islands[2]	Hogsty Reef[2]	Courtown Cays[2]	Albuquerque Cays[2]	Roncader Bank[2]	Serrana Bank[2]	West Florida Shelf Surrounding Florida Middle Ground[3]
Coral	2	20	26	24	27	12	27	35	30	25	33	Tr
Molluscs	30	12	7	6	11	18	22	10	9	15	5	47
Foraminifera	3	6	8	12	11	13	5	3	2	3	3	10
Coralline Algae	1	10	11	33	10	—	19	21	21	24	24	Tr
Halimeda	Tr	30	40	17	16	39	2	28	32	17	17	Tr
Misc. Skeletal	—	7	1	6	5	—	1	—	1	1	1	15
Barnacle	8	?	?	?	?	?	?	?	?	?	?	Tr

[1]This study
[2]Milliman (1974)
[3]Brooks, G. R. (unpublished data)

rauter, 1980). Storm-generated currents probably have the most profound effect on sediment distribution. These currents can be generated by hurricanes, tropical storms and winter-cold fronts that average every 5 to 10 days during the winter (Niiler, 1976). In addition to being redistributed throughout the shelf, sediments may be transported offshelf where they settle onto the slope and eventually are transported to the slope base by gravity flows (Doyle and Holmes, 1985; Mullins and others, 1987; Brooks and Holmes, 1989, 1990). Bathymetry plays a role in this process as offshelf transport is facilitated by the lack of a continuous shelf-edge reef rim. Offshelf transport may be one factor responsible for the occurrence of such a thin sediment veneer (less than 3 m) overlying the Miocene (?) limestone surface on the shelf. Another factor may be the relatively slow production of mollusc-rich carbonate sediments in this setting compared to the more prolific production of coral- and algal-rich sediments common to lower latitude carbonate platforms.

As a consequence of the relatively slow accumulation of carbonate sediments on the shelf surface during sea-level highstands, erosion of these sediments is more complete during lowstands. Hence, with the exception of modern sediments, no appreciable accumulations (from a volumetric standpoint) are present overlying the Miocene (?) surface.

The FMG is likewise controlled by sea level, with carbonate-sediment production occurring during sea-level highstands when the surface is flooded. Physical processes are important for distributing sediment, but bathymetry is important on the FMG more for trapping sediments, rather than aiding in their export, as described for the non-reef-rimmed, shelf-slope break. Hence, FMG reefs act to impound sediments much like a shelf-edge reef functions to impound sediments on the platform surface. In this instance, however, accumulation is insufficient to keep pace with rising sea level. The FMG therefore, like the remainder of the west Florida shelf, is slowly being drowned.

In comparison to what are considered "typical" modern reef systems, the FMG is unique. Its midshelf, high-latitude setting and preponderance of non-reefal sediments, which lack zonation, show that in terms of carbonate-sediment production and accumulation, the FMG is more like an open-shelf than coral reef environment. Table 1 compares the dominant FMG sediment components with those of other reef systems and the surrounding west Florida shelf. FMG sediments are unlike those of most reef systems and with the exception of barnacle fragments, virtually indistinguishable from surrounding shelf carbonate sediments. This subtle difference in sediment type has implications for the interpretation of ancient open-shelf versus reefal environments. Based solely upon sedimentology, the two environments may be virtually indistinguishable.

SUMMARY AND CONCLUSIONS

Modern reef growth on the Florida Middle Ground is controlled by bathymetry, in that the foundation is a dead reef that originally developed during one or more of the Pleistocene sea-level highstands. Controls on original reef growth are not fully understood but are probably a combination of bathymetry and circulation patterns that supplied the FMG with Caribbean reefal fauna. This recruitment may be occurring at present, thereby acting to continually "stock" the FMG with Caribbean fauna. Sediments on the FMG are derived from two sources, the reef ridges and surrounding shelf environment. Sediments, dominantly a molluscan shell hash, are virtually indistinguishable between the two sources with the exception of barnacle fragments in reef-ridge sediments. Barnacles are common reefal constituents probably because of the suitable sites for attachment provided by the dead-reef foundation. Barnacles, therefore, provide the principle sedimentological indicator of a transition from shelf to reefal environment. Sediments are not zoned, as in many reefal settings, but have a patchy distribution controlled by physical processes and the rugged bathymetry. A variety of types and orientations of bedforms indicates numerous, different, flow directions and velocities, probably driven by tides and storms. Geologic development of the FMG parallels that of the surrounding west Florida margin, driven principally by high-frequency sea-level fluctuations. FMG reef ridges act to trap sediments much in the same manner as shelf-edge reef systems, but sediment accumulation and reef growth cannot keep pace with sea-level rise. The result is that the FMG is being drowned along with the remaining west Florida continental margin.

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