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Front Cover: Lee-side exposure of a fossil parabolic dune viewed from the Grahams Harbour side (west) of North Point, San Salvador, Bahamas. These Holocene carbonate eolianites have been assigned to the North Point Member of the Rice Bay Formation (Carew and Mylroie, 1995). The eolian cross-stratification dips below present sea level, proving that late Holocene sea-level rise is real. Top of the dune is about 7 meters above the sea surface. Photo by Al Curran.

Back Cover: Dr. Noel P. James of Queen's University, Kingston, Ontario, Canada, keynote speaker for this symposium. Noel is holding a carving of a tropical fish created by a local artist and presented to him at the end of the symposium. Photo by Al Curran.

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SEDIMENTARY FACIES OF WESTERN GREAT BAHAMA BANK: BANK-EDGE MARGIN TO SLOPE TRANSITION

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ABSTRACT

Petrographic analysis permits sediment characterization of bank top to slope environments of western Great Bahama Bank into three distinct facies (A,B,C). The bank top/bank edge facies (A) (<15m) closely resembles the *grapestone* facies defined 35 years ago for the bank top edge (Purdy, 1963b). It is mostly a non-skeletal facies. The coarse sand (46%) consists of aggregates and ooids, and largely the fine and very fine sand (78%) is non-skeletal pelletoids, usually with an oolitic coating. The deeper bank edge (20m-65m), analogous to the *coralgal* facies of Purdy (1963b), is a calcareous algal meadow zone (B1), flanked to the east by sparse shallow patch reefs and to the west by a rocky escarpment. Sediments in this zone contain fresh *Halimeda* plates, up to 60% of which are altered at greater depths (>80m). The rocky escarpment (B2) is an accreting step-like build-up of cemented *Halimeda* plates and bank top-derived non-skeletal sands. Seismic profiles show the accreting morphology to be biohermal-like structures. The lower slope (C) (>140m) is predominantly fine grained, consisting of pelletoids and aggregates as well as fragmented skeletal debris and fresh planktic (up to 30%) skeletal grains.

Rapid alteration characterizes the bank edge margin to slope transition. Dissolution and re-crystallization of aragonite into bladed and fibrous needles, pelloids and high Mg-calcite blocky crystals are evident in the utricles of *Halimeda* plates and in the void spaces of other skeletal grains in the sediment.

Though carbonate production is primarily considered an *in situ* process, dispersal and transport of the *'in situ'* carbonates by strong currents and steep gradients can co-mingle allogenic and authigenic sediments in a fashion similar to siliciclastic deposits. The ultimate sink for the sediments, their deposition, and cementation patterns in such environments therefore can reflect markedly different environments than those of formation.

INTRODUCTION

We attempt to characterize the sediment from the bank top margin to slope in western Great Bahama Bank in the tradition of Purdy (1963b)(Figure 1). Three distinct facies (A,B,C) are proposed (Figure 2). The bank top margin/bank edge facies (Facies A) at depth less than 15m, is mostly a non-skeletal facies composed of pelletoids, ooids, and composite aggregate grains. The majority of grains in this zone exhibit an oolitic coating, produced in a high energy precipitating environment (Bathurst, 1967, 1975). The very fine sand (63-125µm) component is comprised (45%) of rounded, shiny coated aragonitic pelletoids, containing from 0.94 to 0.97% Sr in aragonite. This figure is in

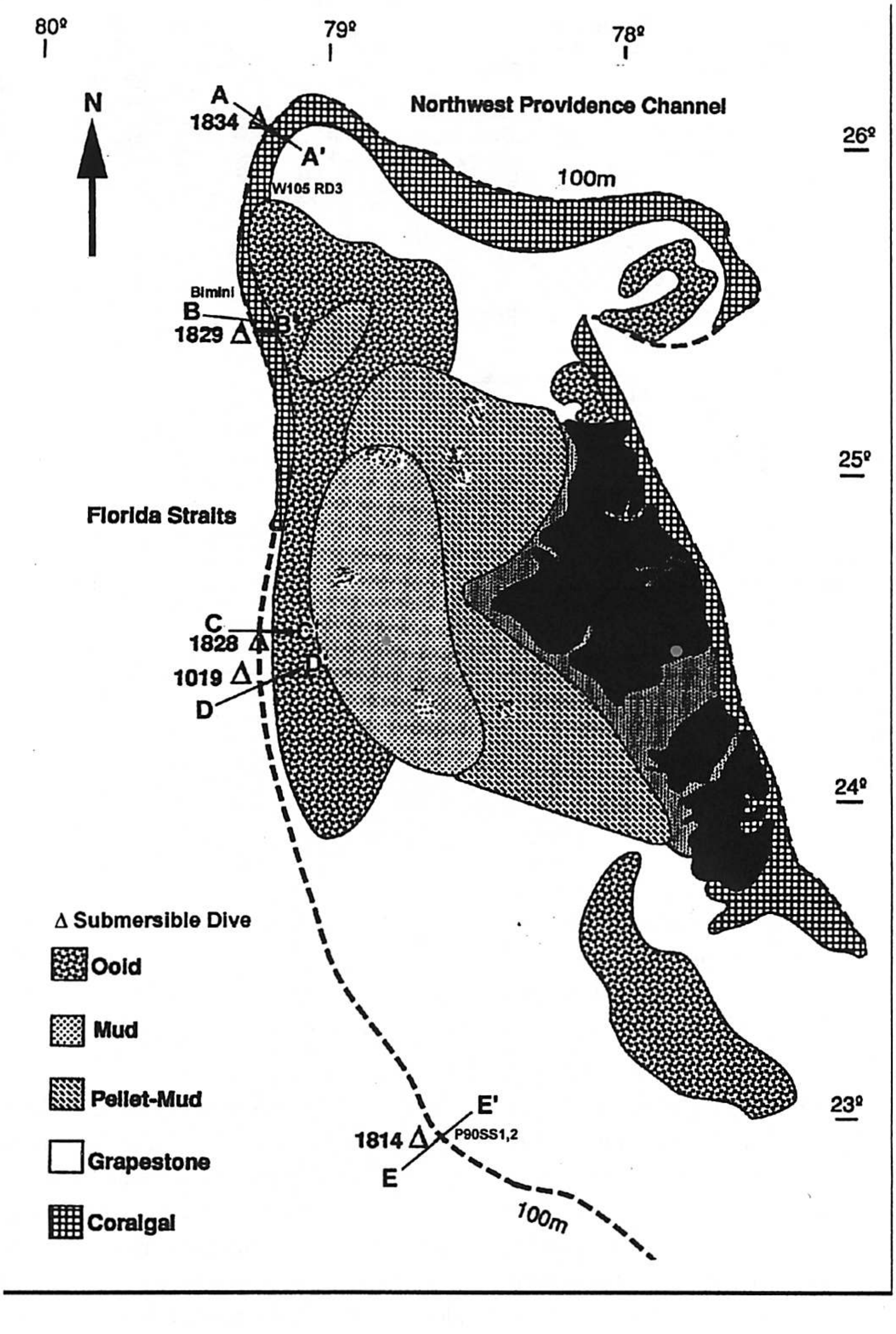


Figure 1. Location map Great Bahama Bank (GBB). Distribution of bank top facies is modified from Purdy (1963b). Some sample locations for this study are noted, in all 51 samples were used from along the bank margin. Bank top margin samples were collected from water depths <15m (average bank top depth, 5m), northern-most sample W105RD3 and southern-most sample P90SS1,2 are noted. Bank edge samples were collected from 15 to 65m, rocky escarpment samples from 65 to 150m and slope samples from >150m. Five perpendicular to the bank transacts from bank top to slope where analyzed (A-A', B-B', C-C', D-D' and E-E').

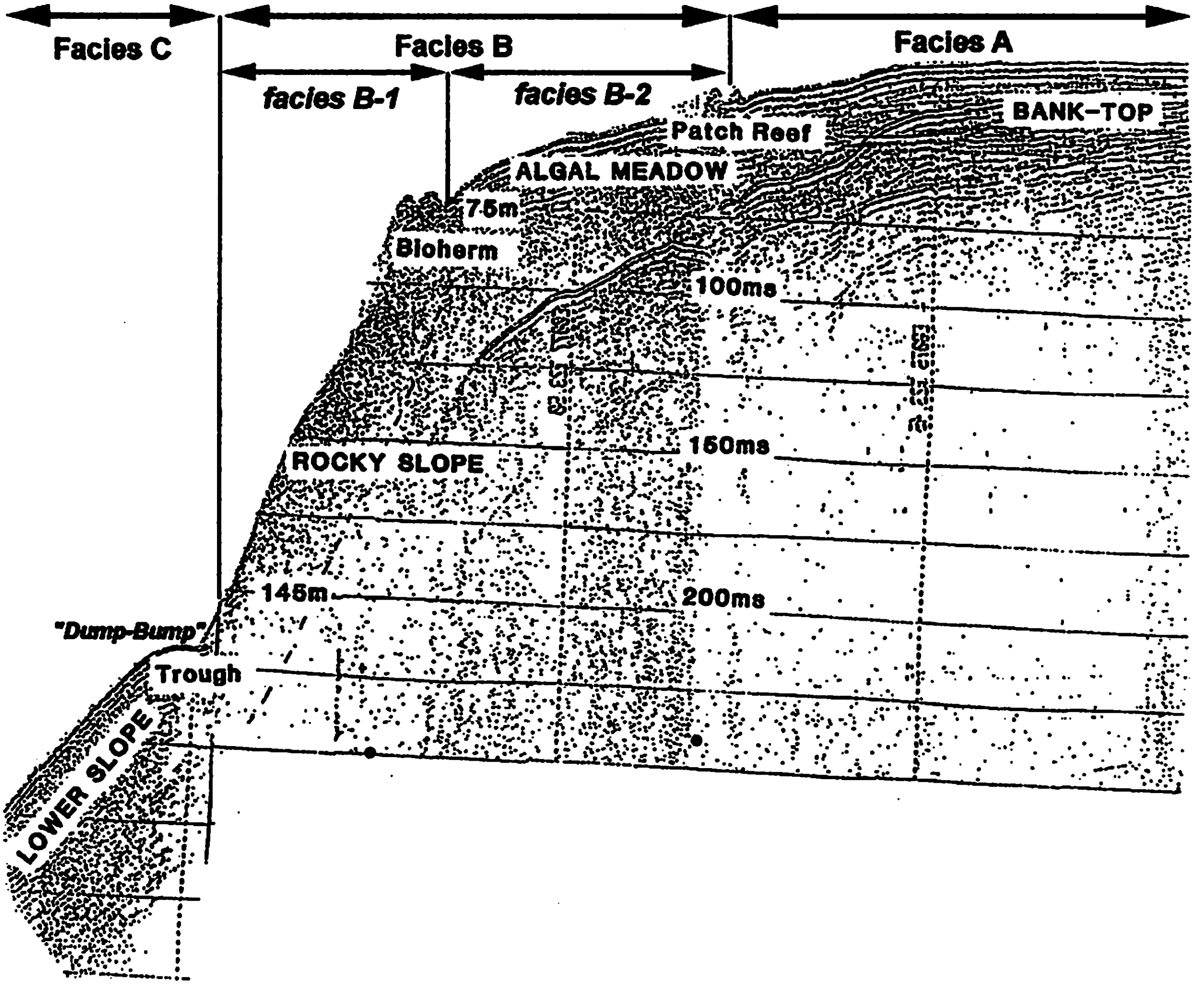


Figure 2. Representative seismic line across WGBB margin indicating the location of facies types: Facies A, bank-top margin; Facies B1, bank-edge algal meadow zone; Facies B2, rocky slope, and Facies C, lower slope. Visible features present include; bank-edge patch reefs, and 'bioherms'; parallel to slope 'trough' and 'dump bump' (after Wilber et al., 1990).

agreement with the reported values for ooids (cf. Kinsman and Holland, 1969; Milliman, 1974). The deeper bank edge (20m-65m) is the calcareous algal meadow zone (Freile et al., 1995) (Facies B1)(Figure 2). This zone is flanked to the east by a shallow sparse patch reefs area, and to the west (seaward) by the rocky escarpment. This zone is mainly composed of fresh *Halimeda* plates. The rocky escarpment (Facies B2) (Figure 2) is an accreting, step-like build-up of cemented *Halimeda* plates and bank top derived non-skeletal sands. The cemented accreting nature of this zone is observed in seismic lines as 'biohermal'-like structures at the platform break (.65m) (Figure 2). Coarse sand cascades from higher up and accumulates behind the lips of these ledges and undergoes cementation on the steps by either aragonite or Mg-calcite. The cementing medium is depth dependent. Aragonite pelloids and needle cement predominate in areas that are less than 100 meters deep, while Mg-calcite is the cementing medium at greater depths. These biohermal build-ups appear in several seismic lines. Their pinnacle-shaped, convex upward morphology would probably be identified as bioherms in the rock record (cf. Roberts et al., 1988). The lower slope (Facies C) (>140m) (Figure 2) is a predominantly (>75% of the sediment) fine-grained area composed primarily of pelletoids and aggregates, as well as fragmented skeletal debris and fresh planktic (up to 30%) skeletal grains.

A descriptive facies analysis based on point counts of at least 2 thin sections for each sample is discussed. A thin-section of the coarse-grained fraction (500-2000µm), a thin-section of the fine-grained fraction (125-500µm), and some other sections of grains in the 63-125µm size class are analyzed. The three facies- A,B,C, previously described, closely follow depth/location across the western side of Great Bahama Bank. Even though carbonate production is primarily considered an *in situ* process, that is to say authigenic/autochthonous; dispersal and transport of the '*in situ*' carbonates, by strong currents and hurricanes, can result in allochthonous deposits as observed in siliciclastic deposits. The ultimate sink for the sediments, as well as their deposition and cementation patterns, can be in areas of markedly different environments than those of formation. This is particularly the case for the fine-grained fraction (<63µm), but it is also important for facies classification of grains that have undergone alteration- cementation, re-crystallization and micritization.

In all five sources are recognized 1) fine grain suspension (limited to the clay and very fine silt fractions) 2) coarse silt and sand lateral transport 3) *in situ* production and accumulation 4) altered material 5) cements both internal (void infilling) and external (particle bonding). Together and separately they react to form the different facies observed.

Overall, the facies analysis utilizes 51 samples and 119 thin-sections along the western edge of GBB (Figure 1). In all 24 bank top margin samples (<15m); 7 bank edge samples (15-60m); 5 rocky slope samples (60-150m) and 15 slope samples (>150m), along five perpendicular to the bank transects from bank top to slope are analyzed.

There is a predictable relationship between grain size and particle origin. In carbonates coarser grains are not only the product of degradation as they are in terrigeneous clastics, but are also the product of aggregation through cementation, coating and growth (Milliman, 1974; Bathurst, 1975). Grain types like grapestones and composite grains, ooids and pelletoids are examples of aggregation (Illings, 1954; Purdy, 1963a). Alteration of grains also plays an important role in carbonate facies. The extensive re-crystallization, micritization, borings and infilling that is present in shallow tropical marine waters give carbonate facies diagenetic importance when classifying constituents (Bathurst, 1966; Milliman, 1966; Shinn, 1969; Reid et al., 1990; Freile et al., 1992; Freile,1996; Perry, 1998; Reid and Macintyre, 1998).

Interrelationships exist between biochemical and inorganic processes, as well as between grain sizes. Aggregation and disaggregation or breakdown are of great importance in a classification scheme. Purdy (1963b, p.494) attempted to illustrate these interrelationships, however his diagram is difficult to follow. To understand the origin and genesis of carbonate particles is as important as knowing the sedimentary environments where they are produced. The origin and genesis of carbonate particles directly reflects the sedimentary environment that produces them. There are limited environments of production of specific carbonate grains and subsequent alteration of these grains is just as important.

RESULTS

Non-Skeletal Components

Non skeletal grains are those which are not derived from invertebrates, calcareous algae or micro-organisms. Four main types are recognized by Folk (1959): coated grains, peloids, aggregates, and clasts. Of these only coated grains, peloids and aggregates appear in abundance on western Great Bahama Bank (WGBB), though some clasts are visible in the rocky slope facies and in the adjacent trough sediments.

Coated Grains

Coated grains are varied in characteristics and are of a polygenetic origin. Since their means of formation are unclear, and similar grains can form in widely different environments, they are of limited paleoenvironmental use (Tucker and Wright, 1990). The WGBB margin only exhibits two types of coated grains: those that are mostly inorganically precipitated (ooids) and surficially coated pelletoids (Bathurst, 1967). It is likely, however, that an organic catalyst (algal film or organic cell) is responsible for the coatings observed on ooids and some pelletoids (Robbins and Blackwelder, 1992; Folk, 1993).

All ooids on the shoals of WGBB are aragonitic in composition and contain very high Sr in the aragonite values (0.95-1.12%; analysis herein, and in Kinsman and Holland, 1969; Milliman, 1974; Loreau, 1982, Milliman et al., 1993). The aragonite needles are arranged tangentially around the nucleus, and in some 'micro-ooids' this arrangement is clearly observed.

Coatings on grains are due to agitated conditions in shallow waters (where CO_2 is liberated) and where periodic resuspension of the grains after a period of burial are requisite conditions (Bucher, 1918; Black, 1933; Twenhofel, 1928; Monaghan and Lytle, 1956; Deelman, 1978; Tucker and Wright, 1990). On occasion, low energy conditions have been known to precipitate oolitic coatings as well (Bathurst, 1967).

Ooids predominate throughout the fine to medium size sand fraction (125-500µm), but are generally a major component of the 250µm fraction. In some areas along the bank margin (i.e. Sample P90 SS 8), the coated pellets or ooids exceed 90% of the 125-500µm size class. They are readily identifiable under a binocular microscope by their ovoid shape and pearly luster or in thin-section by a characteristic nucleus (possibly a skeletal fragment) and a visible cement rind.

Pellets, Pelletoids and Lumps

The term pellet is strictly applied to a microcrystalline oval-shaped object of a fecal origin (Newell et al., 1951, 1959; Purdy, 1963a). Pelletoid is a term suggested by Milliman (1974), as equivalent to the term peloid (McKee and Gutschick, 1969); it is used here to characterize a sand-sized (100-500µm) microcrystalline oval-shaped lump of polygenetic origin. A fecal pellet can be identified by its regular elliptical outline and characteristic specks of dark organic matter representing presumably undigested nutrients. This is especially the case in thin-section. Similarly pelletoids can be readily identified if: 1) they contain a visible skeletal fragment and/or appear to be the product of micritization; 2) have an irregular outline or; 3) can be identified as a rounded skeletal grain, principally those that are altered *Halimeda* (Figure 3D). These grains however are not always so easily diagnosed. One distinction made here is that if no skeletal fragments are clearly visible and no clear identification as a composite grain can be made, then irregularly-shaped microcrystalline particles are always identified as lumps (Figure 3G).

Pellets, pelletoids and lumps are the most abundant constituents in the fine-sand fraction on the bank-top (Purdy's (1963b) *pellet-mud facies*), bank-top margin (cf. Newell et al., 1959; Purdy, 1963a,b; Queen, 1977) and slope. They are clearly a major constituent of the coarse-fraction of the bank-top margin as well.

Aggregate Grains

Aggregate grains are also known as grapestones (*sensu* Illings, 1954), composite-skeletal, and composite-non-skeletal grains. The characteristics they share in common are a cemented origin and more than one constituent particle (skeletal or pelletoid) is visible within the grain (Illings, 1954; Milliman, 1974; Bathurst, 1975; Deelman, 1978). They mostly belong in the coarse-sand fraction (>500µm).

Grapestones resemble closed clusters of grapes (Figure 3B,C,D). The 'grapes' are pelletoids or ooids which have been cemented together by cryptocrystalline, blocky or fibrous cements (Deelman, 1978) (Figure 3B,C). In SEM the meniscus type cement is clearly visible between the pellets or pelletoids. Blocky cement in grapestones is also very distinctive (Figure 3C). The formation of these aggregates are favored in areas of uneven water agitation and circulation as well as low sedimentation rates (Winland and Matthews, 1974).

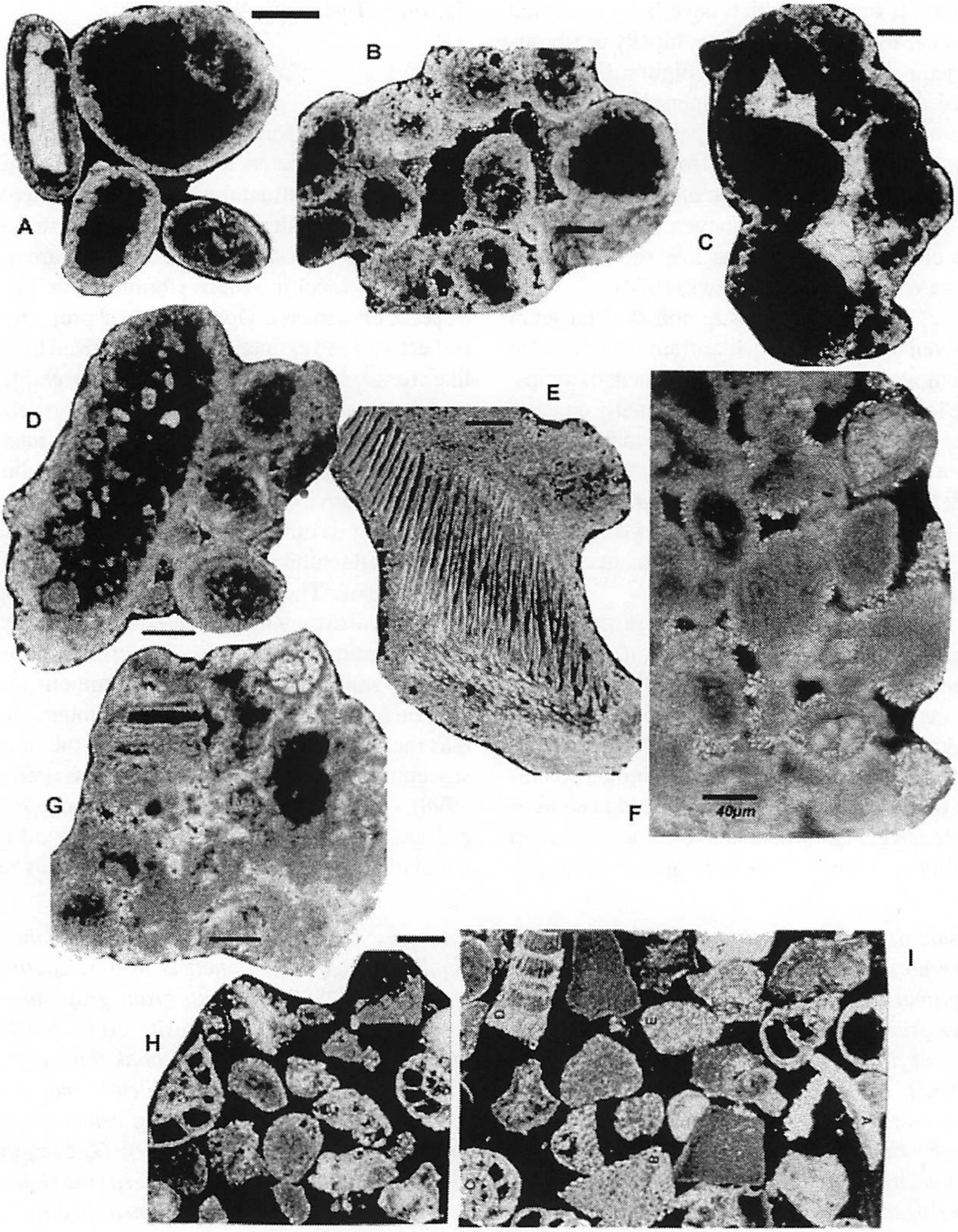
The term composite non-skeletal grain is given to either a ring-like framework feature or a more regular outline arrangement of grains. The lump-like composite grain usually consists of pelletoids in a cryptocrystalline matrix, many are cemented by fibrous aragonite between pelletoids. Composite skeletal grains contain not only pelletoids and a microcrystalline matrix, but also visible skeletal fragments (Figure 3G).

These aggregate grains are prominent along the whole of WGBB margin. They account for 15-25% of the sediment on the bank top margin, at depths less than 15m and on the bank edge margin, and are found (probably as a result of off-bank transport) in similar quantities on the slope. They are produced in areas of moderate energy where active cementation can readily take place. This is thought to occur primarily behind protective shoals (Zeller and Wray, 1956; Wells and Illings, 1964; Winland and Matthews, 1974; Schneidermann and Harris, 1985; Tucker and Wright, 1990).

Skeletal Grains

Biogenic fragments are identifiable by a variety of parameters which may include size, shape and microstructures. Under the microscope, some physical characteristics (distribution of void spaces, sutures, chambers) are diagnostic to specific groups (foraminifera, gastropods, bryozoans). Optical mineral properties (reflectivity and extinction under polarized light) like cross-laminae, in molluscs, and total extinction in echinoderms, for instance, are also used to identify certain groups. Skeletal grain identification is important with regard to; 1) delineating paleoenvironmental settings and; 2) in understanding whether a grain is produced *in situ* or is an allochthonous constituent in a given environment. The type of alteration visible on the grains also may help in determining the true paleoenvironmental setting. Micritization of skeletal grains (Figure 3E) is a common process on WGBB. Micritization can potentially bias the record by under-representing the most susceptible skeletal grains to this process (Perry, 1998). On WGBB the determination of skeletal grains is used in the latter sense, to aid in understanding environmental mechanisms as

Figure 3. (Right) Photomicrographs of sediment types; bar indicates 100µm, unless otherwise noted. A) Bank top sample P90SS6, pellets, mollusc fragment as nucleus in one, coating apparent, dark (organic) material present; B) Bank top sample P90SS6, composite grain, grapestone, open framework, ring-type structure; C) Bank top sample W105RD-3, composite grain, blocky cement filling of void space; D) Very altered Halimeda cemented to pelletoids, bank top sample P90SS1, meniscus cemented grapestone structure; E) Micritized rims around skeletal , mollusc, fragment, bank top sediment, sample P90SS3; F) Pellets, many with oolitic rims, cemented by blocky isopachous high Mg-calcite, from rocky slope, sample 1009 (152m depth); G) Skeletal composite grain, lump-like structure, crystal filled chambers apparent on foraminifera (top right), micritized mollusc (top left), bank edge sample 1829 (88m depth); H) Fine grained mixture of pellets and forams and other non-descript grains, sample 1834 (236m); I)) Fine grained mixture of pellets, forams, and other skeletal grains () A- mollusc fragment, B- echinoderm fragment, C- foram, D- coralline algae, E- coral) and other non-descript grains, sample 1829 (305m).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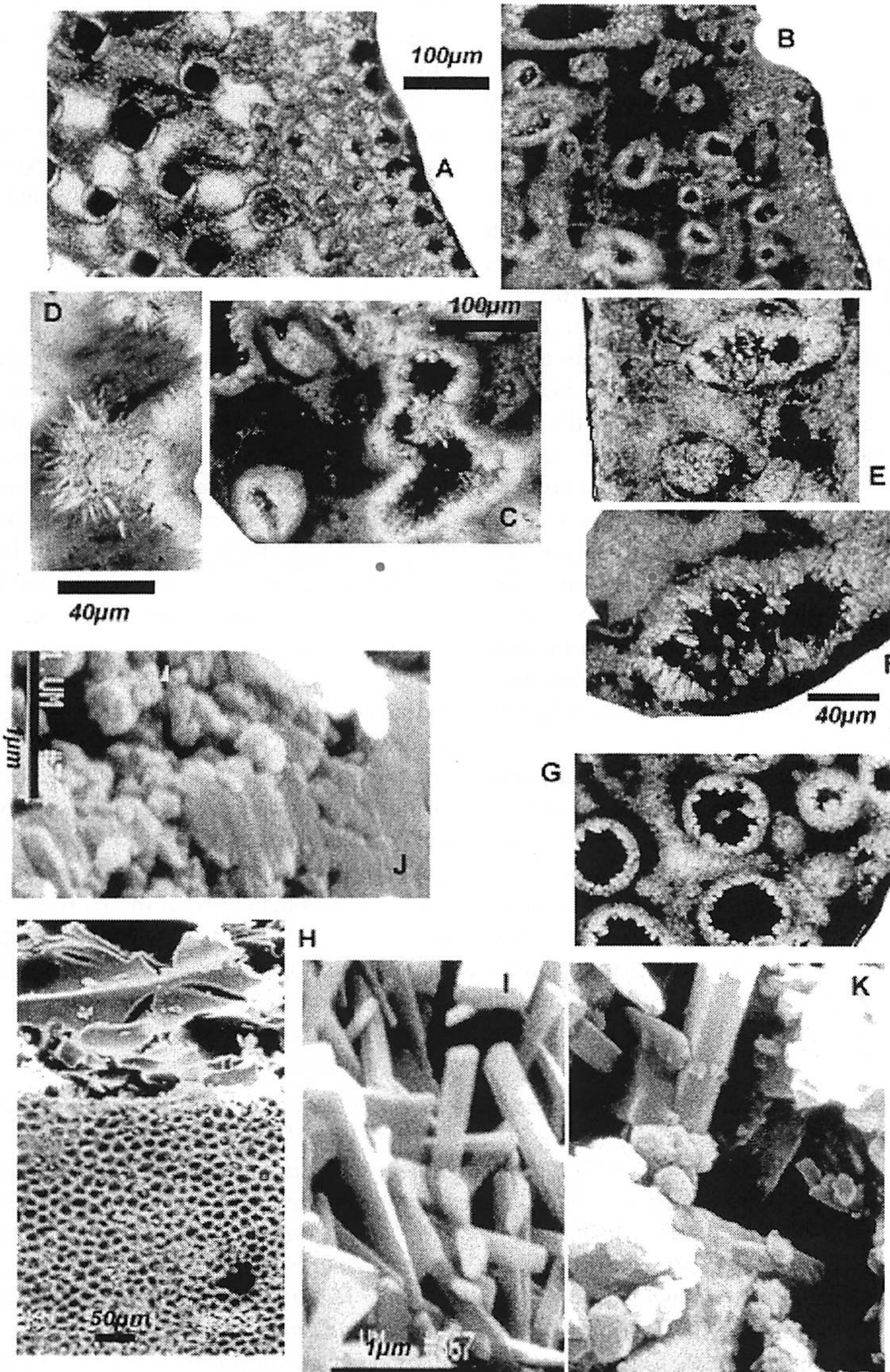
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well as rates of off-bank transport.

Halimeda.

Calcareous green algae of the family Codiaceae have a tubular thalli composed of intertwining and branching filaments (Hillis, 1959; Hillis-Colinvaux, 1968, 1980). Calcification is primarily an extracellular phenomenon which begins at or near the surface and proceeds inwards (McConnell and Hillis-Colinvaux, 1967; Borowitzka et al., 1974; Bohm, et al., 1978; Hillis, 1991). The calcareous algae, *Halimeda*, *Penicillus*, *Rhipocephalus* and *Udotea*, are aragonitic. *Halimeda* is the more recognizable of the species under thin-section and SEM (Milliman, 1974 and references therein). Cenozoic reef systems have seen an increase in *Halimeda* as a volumetrically important producers of sediment (Hillis-Colinvaux, 1986a; Flugel, 1988; Mankiewicz, 1988). These algae rival or exceed the production of their framework counterparts (Hillis-Colinvaux, 1974, 1977, 1986c; Payri, 1988; Freile et al., 1995; Freile and Hillis, 1997).

Thin-sections of fresh *Halimeda* plates exhibit a diagnostic 'Swiss cheese'-like appearance (Figure 4A). The void spaces observed are the utricles which give the plate a porous appearance. Scanning electron micrographs of fresh *Halimeda* plates show the smooth texture of the utricle walls (Figure 4H). Both the circular and tube cross-section of the utricles are clearly observed. Under higher magnification, the utricle wall of a fresh *Halimeda* plate appears to be composed of characteristic blunt-terminated aragonite needles (Figure 4I). Even slightly altered *Halimeda* is recognizable (Figure 4B,E,G). Up to 60% of the sediment along the bank-edge margin algal meadow zone as well as up to 40% on the bank top margin and slope is *Halimeda*.

Corals.

Among the metazoans, the cnidarians (principally the anthozoans) are major contributors of carbonate in tropical seas: framework reef building scleractinians and their associated soft counterparts, the gorgonians (sea whips and sea fans) are massive producers of carbonate (Hubbard et al., 1990; Crossland et al., 1991).

Scleractinians can be easily diagnosed in thin-section by their varied fibrous aragonitic needles, sheath-like structures, irregular shape, high order interference colors, twinkling or wavy extinction. Under plain light 'growth' lines are clearly visible. High concentrations of corals (up to 30% along the bank-edge margin in 15m of water depth) are evident. These are associated with a series of patch reefs along the margin of WGBB. In general, however, corals account for less than 10% of the sediment in the bank edge and less than 6% on the bank top margin and slope of WGBB.

Figure 4. (Left) Photomicrographs and scanning electron micrographs of Halimeda (scale bar as noted). A) Unaltered, clean utricle walls; B) Partially to completely filled utricles with blocky crystals, probably high Mg-calcite; C) Fibrous peloidal cement infilling partially dissolved (note cavity enlargement) utricle wall, also micritized rims, rocky slope sample, 1829 (88m); D) Close-up of C, note botroydal fibrous cement; E) Radial, bladed aragonite crystals infilling utricle wall on a bank top sample, P90SS3; F) Close-up of E, note bladed crystal morphology; G) Blocky high Mg-calcite rims as well as completely filled utricles, sample 1829 (88m); H) Fresh Halimeda under SEM, note smooth, clean utricle walls; I) Close-up of H, note bluntly terminated aragonite crystals; J) Partial dissolution of Halimeda segment wall as evidenced by pits and crevices; K) Blocky equant high Mg-calcite overgrowths on prismatic to bladed aragonite crystals from a surface sample of the slope at 169m.

Foraminifera.

Calcareous forams are of two types; porcellaneous (identified by their low order-brown interference colors) and hyaline (laminar calcite sheets with a radial fibrous extinction) (cf. Milliman, 1974). In WGBB, the porcellaneous benthic peneroplids are clearly visible as a minor constituent (<8%) of the bank-top margin sediments. However, in some areas (Sample 1019) they can account for 27% of the sediment. The planktic hyaline forams are a major (up to 35%) constituent of the fine fraction in the slope sediments (Figure 3H,I). Forams have been found to produce and contribute sediment to reefal areas in amounts comparable to corals, coralline algae and calcareous green algae in Pacific coral reefs (Hallock, 1981). However, they are of limited importance on WGBB.

Mollusca.

The types of molluscs observed are primarily pelecypods and gastropods, though some scaphopods are also observed. Gastropod shells in thin-section tend to be infilled by pelloidal sediment. Under polarized light, the striae (cross-lamellar structure), aragonitic needle shard texture and undulose extinction is clearly evident. In plain light growth structure is clearly visible. The lenticular platelets in fragments observed under SEM can often be identified as molluscan. On the bank top margin, molluscs account for a maximum of 12% of the sediment, but normally do not exceed 5% of the sediment. Similar quantities are evident on the bank edge and slope. Molluscs as a whole are not an important contributor in WGBB.

Other skeletal grains.

Coralline algae known also as red algae (Rhodophyta) precipitate both intra- and extra-cellular carbonate, primarily high Mg-calcite. They are restricted to shallow depths and primarily act as encrusters that may cement particles together (Milliman, 1974). They are easily recognizable in thin-section and their cellular structure is readily observable under plain and polarized light (Figure 4I). In WGBB coralline algae comprised no more than 3% of the sediment on the bank edge. None is found on the bank top margin and less than 1% is observed in the slope sediment.

Calcispongea (Porifera) are soft bodied organisms that shed their calcareous, usually calcitic spicules. Sponges grow on a hard substratum, as components in reefs and patch reefs. On WGBB they are abundant on the cemented ledges of the rocky escarpment. Nevertheless, they never account for more than 2% of the sediment.

Bryozoans inhabit reefal water depths of between 20 and 80 meters (Milliman, 1974). They tend to be present as encrusters on other grains and are not so easily recognizable, oftentimes being misdiagnosed as corals. They account for less than 6% of the sediment in the bank edge and less than 3% on the slope. No visible bryozoans are found on the bank top margin. However, when observed under a binocular microscope, they are often seen encrusting *Halimeda* plates.

Echinoderms, primarily echinoid spines and plates are readily observable in the sediments of WGBB, though in low (<10%) quantities. In thin-section, their characteristic total extinction upon rotation in polarized light and their honey-comb like structure in plates and spines differentiates them from other grains. Echinoderms are found throughout the bank top and bank edge margins as well as the slope in quantities of less than 4%.

Serpulids (annelids) which build calcified tubes are mostly encrusters and are not a major constituent (<7%) of the sediment. They are found throughout the region (<2%), but achieve the greatest numbers on the bank edge margin.

Organic spheres, which resemble calcispheres like the reproductive cysts of Acetabularia (Marszalek, 1975), are an accessory component of the sediment, occurring on the rocky escarpment and lower slope.

Descriptions: Sedimentary Facies

The basis of interpretation and diagnosis of the facies is depth zonation. Depth imparts a specific energy regime to an area, with a characteristic set of constituent grains. Perpendicular to WGBB, there exists a zonation from coarse grained (winnowed) high energy rippled bank top margin to a relatively calm, fine-grained deep slope. The slope is periodically modified by strong off-bank currents (Wilber et al., 1993). In between is a marked skeletal zone, lying at the bank edge break between the flat-topped platform and the steep escarpment (Freile et al., 1995)(Figure 2). Here, *in situ* biological productivity, is at a maximum due to nutrient rich upwelling and off-bank transport. This bank edge meadow (Freile et al., 1995) is not only responsible for producing quantities of biogenic (*Halimeda*) sediment, but also entrains particles that are transported off-bank.

Bank Top-Facies A.

The bank-top margin is a high energy, current swept, rippled environment everywhere less than 15 meters deep and most often in water depths less than 10 meters. The coarse-grained (500-2000μm) fraction has a strong non-skeletal component (Figure 3 A-E). They are dominantly oolitic coated grains with a composite, pelletoid or skeletal, aggregate or grapestone component. There are few fresh skeletal fragments present, but most skeletal components are micritized (Figure 3E). The existing fresh skeletal grains tend to be mainly echinoderms, some corals, and many peneroplid foraminifera. The fine-grained (125-500μm) material has a strong non-skeletal component as well. It is mainly a pellet or pelletoid facies with many of the constituents exhibiting a surficial oolitic coating.

Point-counts of the bank-top margin reveal a strong non-skeletal component (70-80%) characterized by the presence of pellets or pelletoids, microcrystalline lumps and aggregates and grapestones in the finer (125-500μm) fraction. A more or less equal distribution of skeletal and non-skeletal grains does exist in the coarser (500-2000μm) fraction. The skeletal grains are altered; mostly abraded, micritized, infilled or bored (Figure 3E).

Many particles on the bank-top margin show an oolitic coating (Figure 3A,B,C); this is a sign of a high energy environment (cf. Bathurst, 1975). The high energy conditions prevalent on the bank-top margin are observed in its current swept rippled bottom which shows numerous sediment blow-outs and very few grasses and algae (Purdy, 1963a,b; Queen, 1977).

The bank-top can be divided into two areas: 1) the area in the immediate proximity of Andros Island (the *mud and pelleted mud facies* of Purdy (1963b)) is a very fine-grained low energy area where *Thallasia sp.* grasses and *Callianassa sp.* burrows predominate. This area was not studied in this work since numerous studies (Newell et al., 1959; Purdy, 1963b; Queen, 1977) have previously described it. 2) The bank top, high energy, margin; the area of study.

The rim of the bank-top, the area called the bank top margin, is characterized by medium to coarse grained sediments. No mud (<63μm) fraction is present. In the areas identified previously as oolitic shoals (Newell et al., 1960; Purdy, 1963b) the predominant (>70%) grain size is 125-500μm, with the bulk being in the 250μm size class. In other areas of the bank top margin, a grapestone or composite grain facies exists. Its predominant size is in the 500-2000μm size class. Few particles (approximately 8%) are in the over 2000μm size class, but locally values can be as high as 40%, depending on the fragmented and whole skeletal (mainly echinoids) component present.

Bank-Edge: Algal meadow zone-Facies B1.

The bank-edge, algal meadow, is a moderate energy area in water depths between 15 and 65m (Figure 2) that is normally below wave base but not necessarily below storm wave base. Submersible observations have shown this environment to have a large standing biotic community primarily consisting of calcareous algae, with patch reefs of corals and sponges forming a fringe around the meadow (Freile et al., 1995). On average, the bank edge has a 10° slope and is fairly smooth; only at its shallow end (15m) do a series of patch reefs break-up the gently sloping terrain.

Sediment is characteristically coarse-grained, and skeletal. It consists mostly of *Halimeda* plates- unaltered to moderately altered (Figure 4A-G). Less than 5% of the sediment is under 63μm in diameter. In some areas of the meadow, however, the algal covering acts as a baffle. These areas entrain many of the fine-grained particles which are being transported off-bank. The finer grained (<500μm) components are largely composed of non-descript cryptocrystalline lumps. They are most likely micritized *Halimeda* grains.

This area is mainly characterized by skeletal fragments, both in the coarse and fine fraction. Though *Halimeda* predominates locally near patch reefs, the skeletal component of corals can constitute up to 30% of the sediment. In areas where the algal meadows are discontinuous, deeper areas of the bank-edge can contain appreciable amounts of non-skeletal components. In the coarse grained fraction these tend to be mostly composite grains. In the fine fraction, they are composite grains, pellets and pelletoids.

The sediment within the algal meadow area is primarily in the 125-500μm size class. The cluster of grain sizes being more in the 500μm size: the size fraction of dissociated *Halimeda incrassata* plates. The fine (63-125μm) fraction in the meadow area can locally reach 13%, but the mud (<63μm) never exceeds 6% . Overall the bank-edge contains less than 3% mud and 6% very fine sand.

Overall this area is similar in grain size to the bank-top margin. This area, however, has a greater amount of mud (up to 5%). It is mainly a medium and coarse grained sediment zone. The shallow portions tend to be dominated by sediment primarily in the 500-2000μm size classes, as are the areas on or near the rocky slope zone. The shallow bank-edge is rimmed by patch reefs subjected to wave-action and bio-erosion. Thus the area immediately adjacent would contain a coarser sediment population. Similar conditions for bio-erosion exist in the cemented ledges of the rocky slope. That coarse material can remain *in situ* , trapped behind the rimmed lips of the steps or be transported downslope to the trough. Another factor influencing grain size on the bank edge and rocky slope is the relatively large (>500μm) size of the dissociated plates of the deeper water species of *Halimeda*, such as the opuntiod *H. tuna*. Their contribution is oftentimes very apparent in the sediment of the ledges and the trough at the base of the slope.

Rocky Slope (Cemented Escarpment) Facies B2.

The rocky slope (Figure 2) is a cemented ledge-like area. The escarpment exists in water depths of 65 to 150 meters. The ledges in the upper portion are large (1-5m) features which act as steps or traps for cascading sand from above. The escarpment is a steep (>45°) wall-like structure similar to others found around the Bahama Bank slopes (cf. Ginsburg et al., 1991) and in other areas of the Caribbean, like the reef walls of Jamaica (Moore et al., 1976) and Belize (James and Ginsburg, 1979). The upper portion is heavily encrusted with sponges, soft corals and vine-like *Halimeda*. The deeper portion tends to be more abiotic. No encrusting organisms are visible and the ledges are smaller (<1m) and more bulbous or pillow like. The ledges or steps that make up the escarpment are composed of *in situ* materials (mostly opuntiod *Halimeda* plates) and bank-top derived components (aggregates and pelletoids) cemented together by both fibrous and bladed aragonite (Figure 4C,D,E,F) as well as pelloidal and blocky Mg-calcite cements (Figure 4G). The ledges undergo some bio-erosion, but overall they are accreting rapidly, both vertically and laterally (Wilber and Rasmussen, pers. com., 1989; Grammer et al., 1993).

Skeletal material produced *in situ*, primarily from the opuntiods *Halimeda copiosa and H. tuna*, is cemented to bank-top derived non-skeletal pelletoids and grapestones by either fibrous, pelloidal or prismatic aragonite or blocky Mg-calcite cement (Figure 4). The resulting 'rock' can be classified as a grainstone (*sensu* Dunham, 1962) (Figure 3F). Depth is the limiting factor in the type of cement that is generated. Aragonitic cements are seldom found in deep (>75m) areas, here high Mg-calcite predominates (Schlager and James, 1978; Alexandersson and Milliman, 1981). The grainstones found on the rocky slope exhibit lithification by either type of cement, depending on the depth of formation.

At many locations, alteration, as micritization, is apparent within the rocky escarpment. The borings and subsequent infilling by cryptocrystalline cements give some of the rocks of the escarpment a more packstone (*sensu* Dunham, 1962) appearance (Figure 3G). The very fine grained peloidal micrite cement within the void spaces of skeletal grains is what changes the rock classification of the escarpment from grainstone to packstone. This, however, does not appear to be depth related.

Lower Slope and Trough-Facies C.

The lower slope (Figure 2) is a deep, greater than 150m, very low energy, environment that is only occasionally affected by severe downslope movements through the actions of severe storms or hurricanes or by some type of hyperpycnal flow (Wilson and Roberts, 1992, 1995; Wilber et al, 1993). Evidence of downslope movement was observed during the course of the study. In 1989, five one meter long, lead weighted, sediment traps were deployed on the lower slope perpendicular to the bank margin (Halley, pers. com., 1989). In 1990, four of the traps were observed to be lying on their sides, perpendicular to the slope, the fifth, at a depth of 300m, was the only one which remained upright. The conclusion is that downslope currents affect the lower slope, but the deeper portions are less affected. Thus, one would expect more bank-top and bank-edge margin derived material closer to the base of the escarpment. This is borne out by the constituent grain types (Figure 3H,I) found on the lower slope trough and 'dump-bump' (Wilber et al., 1990)(Figure 2).

The lower slope has a lower percentage (<20%, oftentimes less than 5% at depths greater than 200m) of coarse-grained material. This coarse grained fraction is evident on the surface. At depths of 150m along the axis of the trough, it appears as an 'oatmeal' or 'corn-flake' sand, which is primarily composed of skeletal, *Halimeda*. This material shows varying degrees of moderate to heavy alteration. *Halimeda* plates comprise a significant portion of this coarse-grained fraction (>15%). The fine-grained fraction is a pelletoid/pelleted sand with varying amounts of deep water and planktic foraminifera.

The non-skeletal component in the slope sediment increases towards the escarpment wall. This again is due to downslope movements. The trough demarcates the limit of the downslope transport from the bank-top and bank edge margins. The deeper slope contains more hyaline planktic foraminifera. The deeper (>200m) lower slope tends to have more influx from water column processes, than off-bank processes.

The deeper and thus the farther seaward a sediment sample originates, the greater the percentage of mud (<63µm) found in the sample. There are, however, some exceptions to this rule. The relative amount of mud and coarse sediment observed on the slope is also influenced by what type of margin exists on the bank edge. In areas where no patch reef or calcareous algal meadow rims the slope, the amount of coarse material drops and the amount of mud increases. This is due to two factors: 1) the mud from planktic sources is not obscured by periods of coarse sedimentation from the bank-top and bank-edge margin and; 2) there is no barrier or sediment trap that entrains material in suspension from the bank-top from by-passing the bank margin and arriving at the lower slope (Figure 5). Thus, the facies is dominated by relative dilutions of coarse vs. fine components.

The areas where coarse material (>500µm) predominates, in the lower slope, tend to be in the portion of the bank north of 24°45'N, the area between Bimini and Riding Rocks Cay (see Figure 1). This area is where the Florida Current has the most affect on the bank. In this area bank-parallel flow can attain velocities of 3m/sec and can undercut the bank margin (Wilber et al., 1990). This area would normally be winnowed of the fine component.

Halimeda alteration: A case study.

The alteration of some *Halimeda* plates on the western bank edge of Great Bahama Bank includes partial micritization/recrystallization to/by Mg-calcite. The external morphology of the plates retain the characteristic, microscopically diagnostic, "Swiss-cheese" texture. However, SEM photomicrographs show both acicular, needle (2-3µm long) aragonite and equant (0.5µm Mg-calcite secondary growths within the utricles (Freile et al., 1992; Freile, 1996) (Figure 4K).

The mineralogy of the internal cements of *Halimeda* plates shows a predictable relationship with respect to depth and distance from the algal meadow zone (presumed sediment source) present along the western margin of GBB (Freile et al., 1995). The rapid alteration of these plates is illustrated by the superposition of composite needle (aragonite) and equant (calcite) crystals (Figure 4K).

The original provenance of the aragonitic grain can be masked by diagenetic processes, because at the bank-edge margin of Great Bahama Bank *Halimeda* grains can be transported downslope considerable distances. Clearly, alteration/recrystallization can take place within a short time (Milliman, 1966; Alexandersson, 1972; Friedman et al., 1974; Reid et al., 1992; Maliva, 1995; Freile, 1996; Macintyre and Reid, 1995), and the original provenance of the material can be masked from the record (Reid et al 1992, 1998; Freile et al., 1992; Freile, 1992). Grain alteration is an important consideration in provenance studies, since the grains' origins can otherwise be easily overlooked and attributed to some indeterminate 'cryptocrystalline' aggregate. In this way, source areas can be easily ignored, thus, under-representing the relative contribution that a specific biolithofacies might have. This rapid alteration narrows the time and distance possible for the transport and conversion from fresh to altered particle.

It is important to note that alteration can be a very rapid process in this area, occurring over the span of weeks, months or even days. This short time period for alteration is postulated on two grounds: 1) because all the alteration observed was on plates collected from surface sediment and accumulation rates in these areas is such that sediment is not allowed to be maintained on the surface for long before burial and; 2) calcified plates on an otherwise living thallus showed evidence of alteration (Freile, 1992, 1996); since *Halimeda* has an average turn over rate of 8 crops/year (Hillis-Colinvaux, 1980), this would imply alteration having to take place within an approximate 6 week period. Whether these diagenetic changes take place due to water column processes, sediment-water interface phenomena or pore water mechanisms is not known.

Alteration and cementation of other grains.

Submarine cementation and lithification is also apparent in other grain types. Both fibrous and prismatic aragonite needles as well as pelloidal and blocky high Mg-calcite are evident.

In particular, void spaces in gastropods and forams tend to be filled by drusy aragonite needles or micritic pelloids. Equant high Mg-calcite cement is also seen to be cementing pellets within the walls of serpulid tubes (for examples see Freile, 1992).

Micritization of skeletal grains is also very apparent. In some cases this appears as a micritized rim around a skeletal grain as was explained earlier. Other times the micritization is complete and other physical processes which might round a grain obscures the original grain type.

DISCUSSION AND CONCLUSIONS

Facies Model

A central idea in the study of modern carbonate environments is to define a particular facies by its components and grain size, and characterize the environment of deposition based on the conditions requisite for producing the observed components and grain sizes. This is especially relevant in areas of low to moderate energy, where little to no transport of material is experienced. Purdy's (1963b) *pelleted mud* facies is an example of this type of low energy environment, where export of material is nil. In other areas, the availability of biogenic material defines the observable facies, i.e. *coral* or *coralgal* facies (*sensu* Purdy, 1963b). Thus, biological input and ambient energy have often been the basic criteria used to describe a facies. This tends to assume both an *in situ* production of quantifiable material and no allogenic input. In recent years this concept has been questioned by various workers (Hine et al., 1981a and b). They showed, through sedimentological and petrographic data that sediments on Great and Little Bahama Bank move in a westerly direction across the bank tops and are deposited on the leeward slopes during high stands of sea level. This pattern of westerly transport is again observed to occur on the western margin of GBB (Wilber et al., 1990, 1993). Though Purdy's (1963b) original bank top facies are still valid, the relative proportions of each that are transported and re-deposited and cemented in other areas, specially the bank edge margin and slope has to be reevaluated.

Based on the observed sedimentary components, we characterize the bank top margin, bank edge, rocky slope and lower slope as follows: 1) facies analysis of the sediment support a westerly transport model (Figure 5). The same types of non-skeletal, oolitically coated grains that comprise the bulk of the bank top margin exist albeit in lesser amounts on the cemented rocky slope and the lower slope (Figure 6). Micritized and bored interclast of the bank edge margin and rocky slope can be found admixed with the relatively fresh planktic foraminifera of the lower slope. A progradational sequence of sediments is observed traversing across the leeward side of GBB, with the sinks, mainly the ledges of the rocky escarpment, temporarily storing and altering the sediments as they are transported across the platform break to the slope (Figure 5). Due to the existing current regimes and the accumulation and subsequent cementing of sediments in the lows of the ledges, it is the finer fraction which mainly is transported (in suspension) across the bank and subsequently deposited on the lower slope (Figure 6). The coarse material of the lower slope tends to originate from the *in situ* production of the bank edge algal meadow zone (mostly *Halimeda* plates) and not necessarily the bank top (mostly non-skeletal), though some material does by-pass the natural 'traps' of the rocky escarpment and are found in the lower slope sediment-mainly in the trough. In areas where the bank edge margin algal meadow is discontinuous, the lower slope

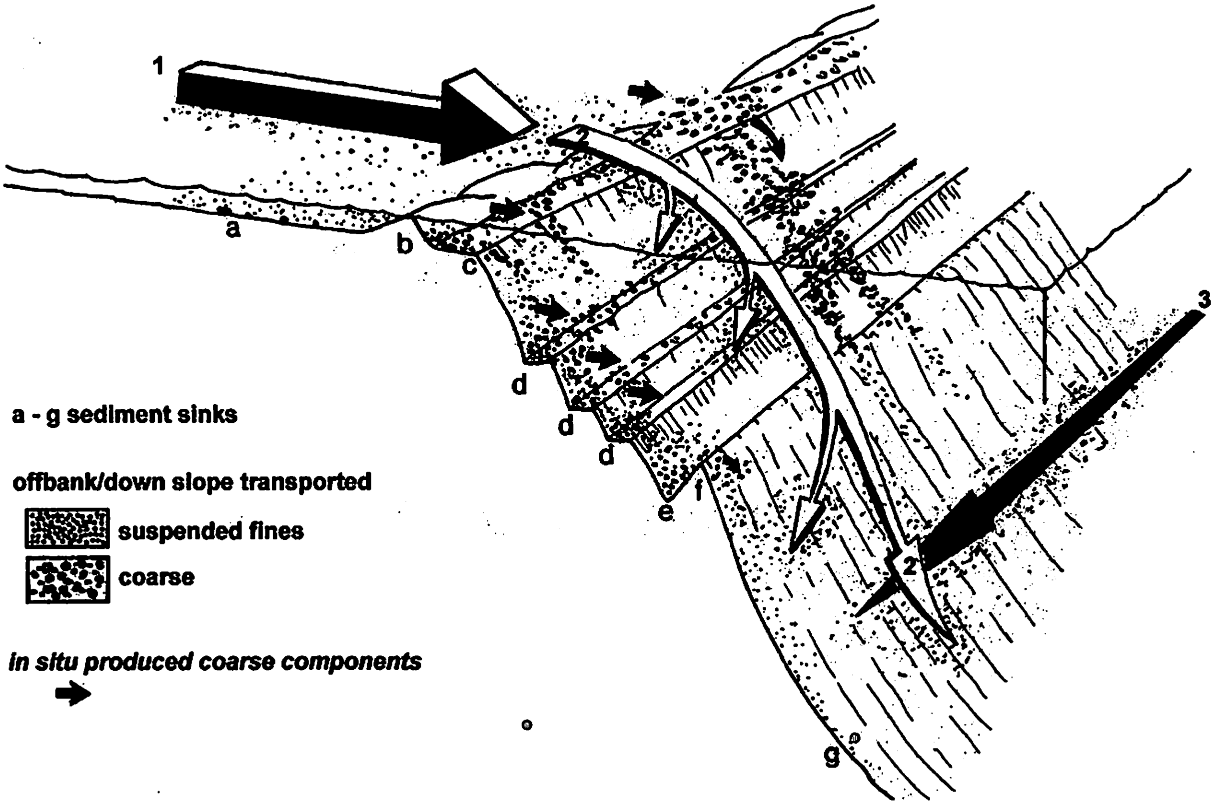

Figure 5. Sedimentation model of WGBB margin. Schematic transport of grains along bank-top, bank-edge and slope (sources and sinks). Mobile, coarse sediment derived from the bank top and in situ production on the upper slope is trapped in sediment sinks. Sediment traps: (a) non exported bank top; (b) oolitic shoals, patch reefs and/or algal meadows; (c) bank-edge; (d) rocky escarpment; (e) slope- 'trough'; (f) 'dump-bump', and (g) lower slope. Large arrows indicate main transport domains; (1 & 2) westward sediment transport (storm dominated); and (3) fast, northward flowing Florida Current parallel to bank margin. Fines escape the upper margin of the bank and are carried as far as the lower slope. All environments and sinks receive more or less input from pelagic sources.

does not exhibit the 'corn flake' or 'oatmeal' texture, that a small percentage (<15%) of *Halimeda* plates can impart to it. Instead, in these areas, the coarse fragments present are the interclasts which have been eroded from the rocky escarpment and a few aggregates and grapestones, which appear to originate on the bank top margin. A similar distribution of facies associations and progressions was proposed for the central region of the Great Barrier Reef by Scoffin and Tudhope (1985).

2) In tropical waters cementation proceeds in either fibrous, pelloidal, acicular or botryoids of aragonite crystals or as bladed, peloidal or blocky high Mg-calcite crystals (Milliman, 1966; Ginsburg et al., 1967; Ginsburg etal., 1971; Alexandersson, 1972; Friedman et al., 1974; James et al., 1976; Macintyre, 1977; Alexandersson and Milliman, 1981; Grammer et al., 1993; Reid et al., 1990; Maliva, 1995). The cements form in isopachous, polygonal or meniscus arrangements between grains. Cementation often results in composite aggregates or grapestones. Composite grains, as the name implies are composed of pelletoids, ooids, and / or skeletal fragments bound together first by a mucilaginous matrix or forams and then cemented together by crystals of calcium carbon-

ate. Most of the grains in facies A, B and C exhibit one type of diagenetic change or another.

Alteration of grains proceeds in either individual grains or in composite grains in much the same manner. The grain itself can be bored and infilled with cryptocrystalline calcium carbonate or micrite and the whole particle may be micritized (Bathurst, 1966; Reid et al., 1992; Perry, 1998). This will give a once identifiable grapestone or grain a indeterminate cryptocrystalline lump appearance, so care must always be exercised in determining grain provenance in carbonate sequences.

Among the grains that are best suited for diagenetic study are those whose original composition are homogeneous. If a grain is known to have a monomineralic origin, then any other mineral phase present is a sign of diagenesis. *Halimeda* is such a grain, since it is composed solely of bladed aragonitic crystals. Numerous studies have found that *Halimeda* precipitates only aragonite (McConnell and Hillis-Colinvaux, 1967; Wilber et al., 1969; Perkins, et al., 1972; Borowitzka et al., 1974), thus any other mineral component present is a sign of alteration (Freile, et al., 1992; Freile, 1996; Macintyre and Reid, 1995; Reid and Macintyre, 1998).

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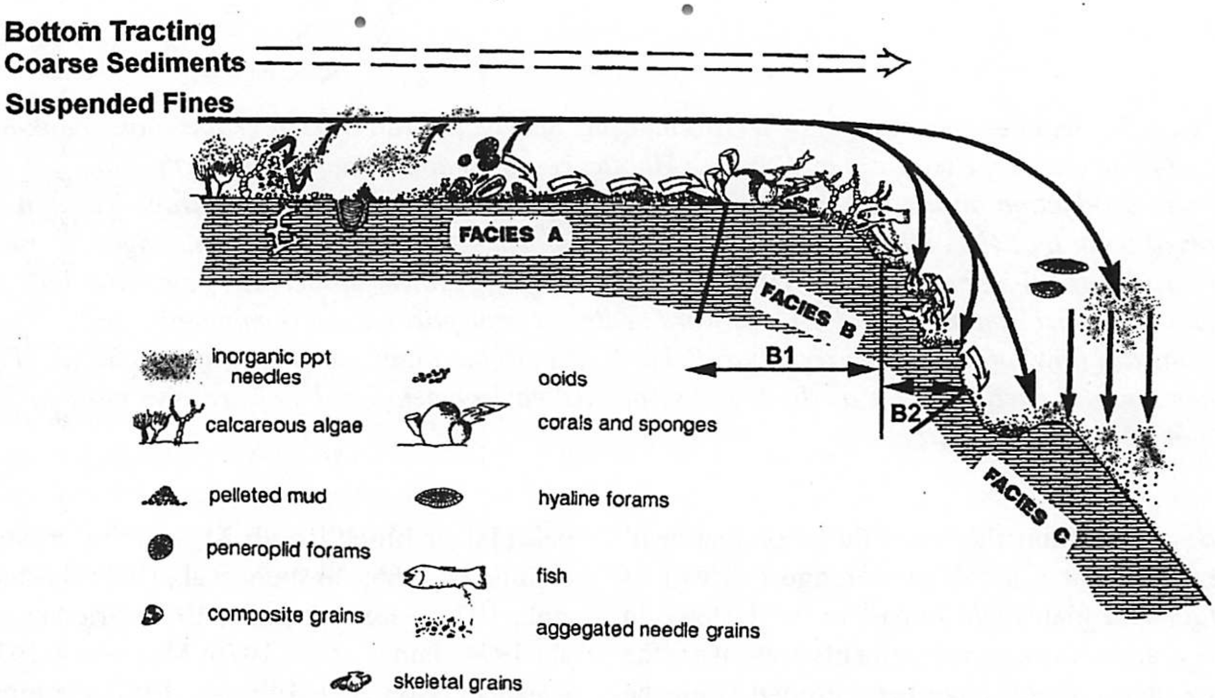

Figure 6. Schematic diagram showing sources and sinks of carbonate production and transport on WGBB. The various physiographic features (see Figure 5) at the bank edge margin, primarily the algal meadow zone (facies B1) and the cemented steps of the rocky slope (facies B2), serve as sediment traps which prevent the wholesale downslope transfer of coarse grained sediments derived from the bank top shoals. These traps, however, do little to mitigate the volumetrically important quantities of bank top derived muds that are transported across the bank in suspension. The resulting facies sequence in the rock record would show an overall upward coarsening motif, with the lower parts of the slope dominated by 'escaped' down-slope transported bank top fines and in situ fines admixed with pelagic components.

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