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Leeward bank margin *Halimeda* meadows and draperies and their sedimentary importance on the western Great Bahama Bank slope

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Abstract. Bryopsidalean algal meadows in water depths of 20–40 m on the leeward side of western Great Bahama Bank (WGBB) lie between non-skeletal-dominated sand flats on the bank top to the east and a cemented steep escarpment to the west. The meadows contain dense populations of rhipsalian *Halimeda* species, as well as *Udotea* and *Rhipocephalus*. Extensive populations of other *Halimeda* species (opuntioids) occur at greater depths on the cemented rocky escarpment, growing as drapes or vines rather than as upright thalli. These meadows and draperies are important sources of coarse-grained carbonate sediments. This is shown by (1) deeper bank-edge sediments (30–60 m) containing considerably more *Halimeda* fragments than do the bank top, non-skeletal sands, and (2) the coarser fraction of slope sediments (down to 200 m) dominated by *Halimeda* plates, partly or extensively altered and internally cemented by magnesian calcite and aragonite. A transect across the bank margin from bank top (<10 m) to lower slope (300 m) provides a useful comparison for the locus of sediment production and accumulation. The production of *Halimeda* in these bank-edge habitats approximates that in the Great Barrier Reef or off Indonesia and Nicaragua in similar water depths. The apparent lack of thick sediment accumulation in WGBB compared to that seen elsewhere may reflect the high rates of downslope transport off Great Bahama Bank.

Introduction

Calcareous algae are recognized as important producers of carbonate sediment on coral reefs and in adjacent lagoons (Milliman 1993). In particular, *Halimeda* has long been shown to be a prolific contributor to both recent and ancient carbonates in the Pacific (Judd 1904; Chapman and Mawson 1906; Emery et al. 1954). In the Atlantic, *Halimeda* plates are the dominant skeletal component of reef-top sediments (e.g. Milliman 1974), although some species, *H. copiosa* specifically, have been described as prominent contributors to sediments in San Salvador and the Jamaican reef front at depths greater than 45 m (Goreau and Graham 1967; Moore et al. 1976; James and Ginsburg 1979, Jensen et al. 1985; Boss and Liddell 1987; Liddell et al. 1988) and on the shallow (9-50 m) reef front off Andros (Bathurst 1975). Recently, Ginsburg et al. (1991) observed that on the windward (eastern) side of Great Bahama Bank (GBB), ledges provide the substratum for "lush, vine-like growths" of *Halimeda,* which presumably are "the major source of sand-size sediment on and within the wall, as well as on the rocky slope to 350 m" (Ginsburg et al. 1991, p. 979).

On western Great Bahama Bank (WGBB), *Halimeda* also occurs in algal 'meadows' and 'draperies', where it is the major producer of the coarse-grained sediments on the bank edge, rocky escarpment and lower slope. Limited access to algal meadows by shallow-diving submersibles has allowed preliminary examination and sampling of these bank-margin habitats. Here we describe these environments and the sediments that they produce.

Meadows, draperies, mounds, banks and bioherms: definitions

Dense patches of *Halimeda* have been documented at depths greater than 20 m in lagoons and on the slope break of various reef areas of the Pacific (Drew and Abel 1985, 1988; Hillis 1985, 1986a,b,c, 1988, 1991; Colin et al. 1986; Roberts et al. 1987a,b, 1988; Orme and Salama 1988) and the Atlantic (Goreau and Graham 1967; Hine et al. 1988; Liddell et al. 1988; Ginsburg et al. 1991). The terms 'meadows' (Orme et al. 1978; Drew and Abel 1985), 'mounds', 'banks' (Orme 1985; Phipps et al. 1985) and 'bioherms' (Davies and Marshall 1985; Roberts et al. 1987a,b, 1988; Hine et al. 1988) have been used to describe these habitats.

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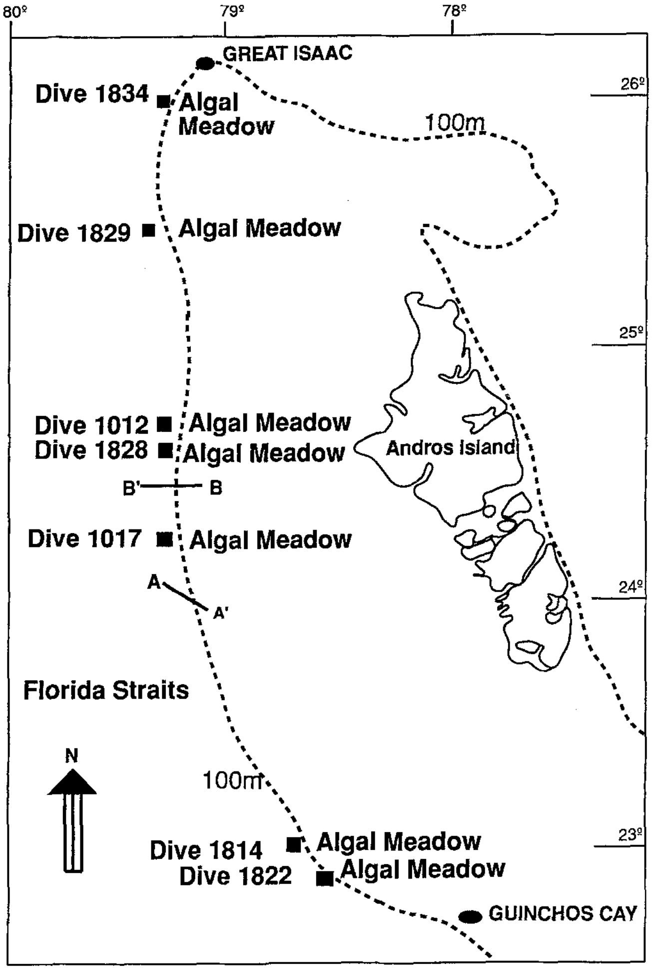


Fig. 1. Location map showing *Halimeda* meadows observed along the bank-edge margin of western Great Bahama Bank. Meadow locations present at Delta dive sites (1834, 1829, 1012, 1828, 1017, 1814, 1822). *Line A-A'* represents location of seismic line (Fig. 2), while line B-B' represents location of sediment analysis transect (Fig. 3)

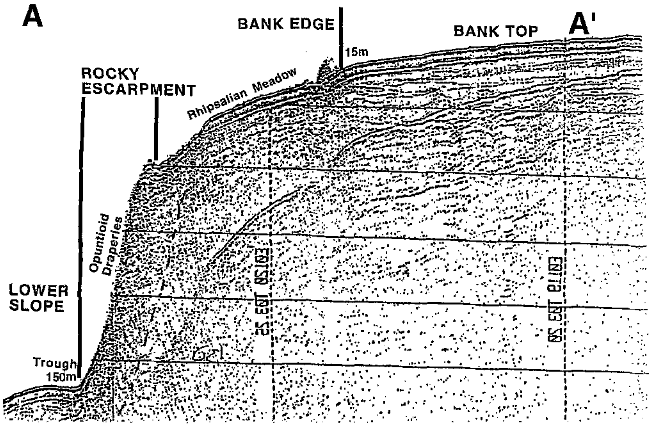


Fig. 2. Seismic line from bank-top to lower slope, showing the location of the bank top (<10 m); bank-edge rhipsalian *Halimeda* meadows (15–60 m) bordered on the east by patch reefs; cemented rocky escarpment (60–150 m) with associated *Halimeda* opuntioid draperies; base of the escarpment trough (150 m); and lower slope (>150 m). The topographic high on the outer bank edge may be a patch reef, although we do not exclude the possibility of it being a *Halimeda* mound

Along WGBB, we apply the term 'meadow' to relatively flat areas where sizeable and relatively dense upright living algal populations (i.e., rhipsalian *Halimeda*) occur; a meadow may exist as a long continuous zone or as a series of discontinuous patches along the bank edge (Fig. 1). The term 'draperies' describes a vertical meadow of loose sprawling plants (i.e. opuntioid *Halimeda*) that hang over the cemented escarpment ledges. Similar draperies have been described on Enewetak Atoll (Hillis 1986a,b, 1988, 1991) and are assumed to be prolific producers of deeper-water carbonates off Jamaica (Goreau and Graham 1967).

The terms 'mound' and 'bank' (Davies and Marshall 1985; Orme 1985; Phipps et al. 1985) have been used for gentle-gradient, convex-up forms, the material accumulating therein often being transported some small distance from the source area. Mounds and banks may be undergoing active cementation, but are actually sediment accumulations with a covering of living algae. A pinnacle-shaped form, where extensive living algal populations are generally absent, is called a 'bioherm' (Roberts et al. 1987a,b, 1988; Hine et al. 1988). *Halimeda* bioherms described off the Nicaraguan Rise (Hine et al. 1988) in water depths of 40–50 m do not exhibit living algal populations, whereas those off Indonesia and the Great Barrier Reef can have an extensive cover of *Halimeda* (Roberts et al. 1988; Searle and Flood 1988). The difference in these terms, as they appear in the literature, may be more related to their areal extent than to anything else.

Methods

Observations of the bank edge (15–60 m) and slope (60–310 m) were made from the mini-submersible *Delta* during two 10-day cruises onboard the R/V *J. W. Powell* (March 1989, June 1990) along the western margin of GBB, from Great Isaac Cay to an area just west of Guinchos Cay (Fig 1). Sediment and algal samples were collected from the submersible with a mechanical arm, although no more than five samples could be collected on any given dive due to space limitation. Sediments and visual observation (video and 35-mm photographic slides) were collected along transects perpendicular to GBB margin, from the shallow bank top (<10 m) to the deep slope (>300 m). A complete transect included the bank top, bank edge, rocky escarpment, and lower slope sediments. Bank-top sediment was collected from the shallower parts of the bank edge by divers.

Grain-size analysis was completed on washed splits of the samples following standard procedures (see Folk 1974). Thin sections of the coarse (500–2000 μm) and fine (125–500 μm) sand components were made (see Miller 1988) and point-counted (see Harwood 1988) to characterize the sedimentary constituents. Scanning electron micrographs were taken of the sediment and algae to characterize crystal and grain morphologies.

Results

Bahamian algal meadows and draperies

Bank edge

A bank-edge algal meadow exists discontinuously along the leeward western margin of GBB, from 26° 02'N, 79°

13'W to 22° 59'N, 78° 37'W (Fig. 1), at depths between 20 and 40 m (Fig. 2). The meadow's discontinuity is inferred because in some areas deep-slope surface sediments contain almost exclusively non-skeletal components, thereby suggesting the lack of any *Halimeda* influx (see below). Nevertheless, meadows were observed by the seven submersible dives that traversed the bank edge (60 m).

The bank-edge *Halimeda* meadow is situated between the shallow (<10 m) non-skeletal-dominated sand flats (peletoids and ooids) of the bank-top to the east, and the deeper (>60 m), steep, cemented escarpment to the west (Fig. 2). The bank top is a shallow (<10 m), current-swept, rippled, non-skeletal sand area containing very low populations of algae or the sea grass *Thalassia*.

The algal population in the meadows is dominated by three calcareous bryopsidalean taxa: *Halimeda* [sand growers belonging to the section Rhipsalis (Hillis 1980)], *Udotea*, and *Rhipocephalus*. They provide essentially 100% cover over at least 50% of the observed meadow area, as estimated from video footage and 35-mm photographic slides.

Rocky escarpment

Seaward of the bank edge is a rocky escarpment, a steeply, inclined (>45°) cemented slope. At the base of the escarpment (at approximately 150 m water depth), a linear, discontinuous 'trough' runs the length of WGBB (Wilber et al. 1990). The cemented slope generally has a step-like appearance. Most of the sediment produced on the escarpment, or introduced from above, is transported downslope; only a thin blanket of unconsolidated sediment occurs on the rocky escarpment itself. At the top of the escarpment, the steps or ledges are large (>5 m), rimmed depressions; at the base they are small (<1 m) and pillow-like in shape. Encrusting organisms, such as sponges, sea fans, and sea whips, occur on most surfaces, both top and bottom. The steps are submarine cemented rocks composed of in situ skeletal material as well as non-skeletal sands from the bank edge and bank top.

Living *Halimeda* occurs to at least a depth of 80 m, as clinging vines. Its growth habit, one of clinging vines, is distinct from the upright *Halimeda* in the meadows of the bank edge. *Halimeda* was not evident at the base of the escarpment wall (150 m), although elsewhere it grows to this depth (Hillis 1985, 1986a,b; Colin et al. 1986; Littler et al. 1986). The algal draperies consist predominantly of the opuntioids, *H. copiosa* and *H. goreauii*, which often cover up to 30% of the local substratum. They are especially evident as curtains covering cave-like openings within the ledges of the rocky escarpment. The vines, however, appear to be much less dense than the erect forms in the meadow zone.

Sediments

The sediment character along a transect from bank top (<10 m) to lower slope (300 m) reflects the varying nature of in situ skeletal production, aggregated and cemented grains as well as transport mechanisms on WGBB.

Bank top

The bank top along the western margin is characterized by medium to coarse non-skeletal sands; the mud-sized fraction (<63 μm) is less than 1%. Most of the bank-top samples (>60%) analyzed in this study contain more than 50% coarse-grained (>500 μm) particles (Fig. 3a).

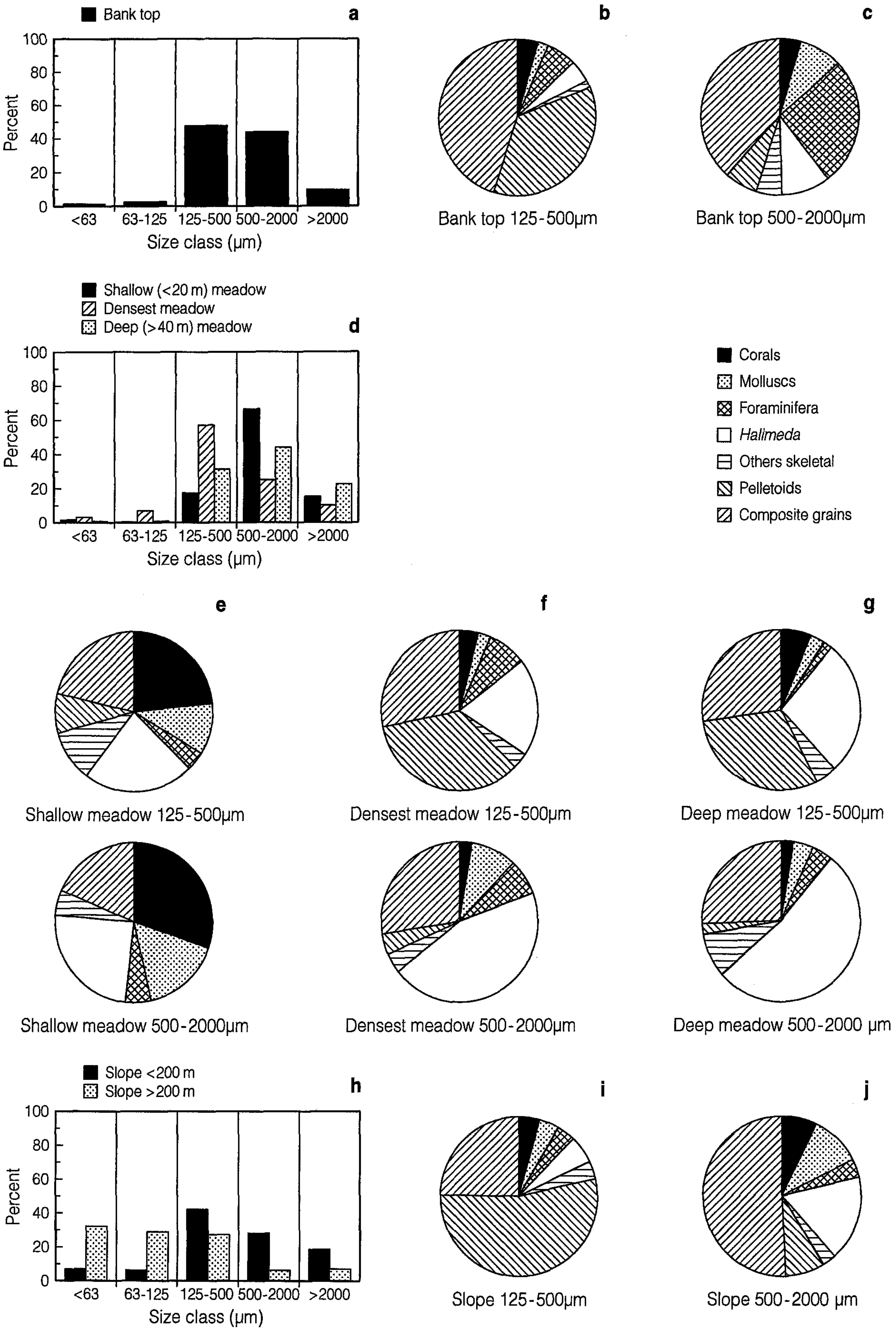
More than 50% of the coarser-grained (500–2000 μm) sediment and over 70% of the finer-grained (63–500 μm) sediment is composed of pelletoids, aggregate grains and ooids (comparable to the oolitic and grapestone lithofacies of Purdy 1963) (Fig. 3b,c). Recognizable *Halimeda* accounts for less than 20% of the coarse-grained fraction of the bank-top margin.

Samples with a preponderance of finer-grained material (<500 μm) have a modal size around 250 μm, dominated by ooids and oolitic-coated pelletoids. The coarser-grained fraction of some samples contains up to 50% skeletal material (Fig. 3c), primarily benthic foraminifera (peneroplids). The material, however, is heavily altered, often abraded and/or coated, as well as bored and infilled with micrite and/or cement.

The lack of very fine-grained sediment and the numerous circular depressions or sand 'blow-outs' on the bank top margin reflect its high-energy environment. The oolitic coatings or rinds present on most of the grains are further evidence of this high-energy regime (Bathurst 1975; Peryt 1983). The rapid alteration (borings, micritization, or precipitation of aragonite and magnesium calcite) of grains presumably destroys evidence of any skeletal input from the bank top proper.

Bank edge and cemented rocky escarpment

In the densest algal meadow zone (20–40 m depth) sediments tend to be finer-grained (<500 μm) than those of the bank-top margin, with an average of 75% very fine to medium sand (63–500 μm) and 5% mud (<63 μm) (Fig. 3d). The *Halimeda* meadow acts as a baffle and entrains some of the fine-grained material that is locally produced or transported offbank from the bank top. This preponderance of fine-grained material in the densest meadow zone is in marked contrast to adjacent areas to the east (shallow meadow), and to more distant areas to the west (deep meadow). In both flanking areas the percentage of coarse-grained (>500 μm) material is greater than or equal to 60% (Fig. 3d). The coarser sediment to the east is explained locally by abundant shallow-water patch reefs as well as the higher energy regime (i.e., winnowed sediment). Not surprisingly, both the coarse and the fine fractions in proximal areas near the patch reefs are dominated by skeletal fragments (>75%), with up to 30% coral fragments (Fig. 3e). The *Halimeda* plates of the bank-edge sediments are mostly unaltered.


a
Bank top
Percent
100
80
60
40
20
0
<63
63-125
125-500
500-2000
>2000
Size class (µm)
b
Bank top 125-500µm
c
Bank top 500-2000µm
d
Shallow (<20 m) meadow
Densest meadow
Deep (>40 m) meadow
Percent
Size class (µm)
Corals
Molluscs
Foraminifera
Halimeda
Others skeletal
Pelletoids
Composite grains
e
Shallow meadow 125-500µm
Shallow meadow 500-2000µm
f
Densest meadow 125-500µm
Densest meadow 500-2000µm
g
Deep meadow 125-500µm
Deep meadow 500-2000 µm
h
Slope <200 m
Slope >200 m
Percent
Size class (µm)
i
Slope 125-500µm
j
Slope 500-2000 µm

The coarse fraction of the densest algal meadow zone as a whole (20–40 m) is mostly (>60%) skeletal material, dominated (>65% of skeletal) by fresh to moderately altered *Halimeda* plates (Fig. 3f). The finer fraction (<500 μm) is dominated by pelletoids (30%) and non-descript cryptocrystalline lumps (30%) (Fig. 3f). Slopeward (40–60 m) in the deep algal meadow zone, the coarser-grained (>500 μm) fraction (>60%) is mostly skeletal material (Fig. 3g), dominated (>70%) by moderately to heavily altered *Halimeda*. Of the non-skeletal grains 70% are cryptocrystalline lumps or aggregates, which in at least some cases consist of heavily altered or totally micritized and cemented *Halimeda* fragments. The fine-grained sand fraction in this zone (>50%) is composed of pelletoids and composite grains (Fig. 3g).

The escarpment rock contains numerous cemented *Halimeda* plates among other coarse-grained fragments. The rock is mainly a grainstone, comparable with the sediment and lithified fragments in bioherms from the Nicaraguan Rise (Hine et al. 1988) and the eastern Java Sea (Roberts et al. 1988). The cements tend to be either fibrous or pelloidal aragonite at shallower depths and blocky high magnesium-calcite in deeper areas.

The percent of finer-grained (<500 μm) material generally increases throughout the lower slope (Fig. 3h). The fine-grained fraction of the lower slope sediments is dominated by pelletoids and cryptocrystalline lumps (75%), and the rest is equally divided between the skeletal (e.g., coral, molluscs, foraminifera and algae) components (Fig. 3i).

Although the percentage of coarser-grained (>500 μm) material generally decreases downslope, it reaches up to 70% of the surface sediment in the trough (150 m). In deeper waters (>200 m), the coarse fraction decreases (i.e. <30% at 220 m and 1–3% at depths greater than 300 m) (Fig. 3h). In some areas 30% or more of the >500 μm particles in the escarpment steps and on the lower slope trough are *Halimeda* plates (Fig. 3j) at different stages of alteration.

The lower slope (trough) surface sediment has an 'oatmeal' or 'corn-flake' texture because of the abundance of platy *Halimeda* grains. In the coarse fraction some *Halimeda* plates are almost fresh in appearance, even at depths greater than 200 m. On the lower slope, specially in the trough, the coarse fraction surface sediment is composed principally of *Halimeda* plates in all stages of alteration; in thin section some 35–50% of the plates are moderately to heavily altered.

Different species of *Halimeda* are often distinguishable from one another as dissociated plates in the sediment. For instance, the trilobed plates of *H. incrassata* differ from the more broad and flat plates of a species such as *H. copiosa* and the smaller plates of *H. goreauii* (for distinctions see Hillis 1980). The predominant plate type in the lower slope sediment varies with locality along the WGBB margin. Both the bank-edge meadow and the rocky escarpment draperies, however, appear to contribute sediment to the lower slope. Where present, the bank-edge meadow contribution far exceeds the rocky escarpment input to the lower slope.

Fig. 3. a Bar graph showing grain size percentages for the sediment fraction of the bank top. **b** Pie graph depicting associated compositional elements for the <500 μm bank-top sample. **c** Pie graph depicting associated compositional elements for the >500 μm bank-top sample. **d** Bar graph showing grain size percentages for the sediment fraction of the complete (shallow, densest, and deep) meadow zone. **e** Pie graph depicting associated compositional elements for the <500 μm and >500 μm shallow meadow (<20 m) zone. **f** Pie graph depicting associated compositional elements for the <500 μm and >500 μm densest meadow (20–40 m) zone. **g** Pie graph depicting associated compositional elements for the <500 μm and >500 μm deep meadow (>40 m) zone. **h** Bar graph showing grain size percentages for the sediment fraction of the lower slope at less than and greater than 200 m. **i** Pie graph depicting associated compositional elements for the <500 μm lower slope. **j** Pie graph depicting associated compositional elements for the >500 μm lower slope. These values are for one representative transect only (B-B') in Fig. 1). (For more complete point-count and grain size data see appendix in Freile 1992)

Discussion and conclusions

Carbonate productivity and accumulation

Meadow area

Areal covering by algal meadows along the western bank edge is extensive. Meadows were observed at the most northerly and southerly dive sites, Δ 1834 and Δ 1822 respectively (Fig. 1), as well as each time the submersible ascended to depths less than 60 m (the slope break) on the bank edge. The WGBB bank-edge margin is 395 km long and approximately 300 m wide. We estimate at least 50% cover by bryopsidalian algal meadows along the bank edge, based on the relative abundance of *Halimeda*-dominated versus non-skeletal-dominated lower slope sediments. This indicates a total area of about 6×10^7 m^2. Furthermore, we estimate that at least 50% of this area has approximately a 100% algal cover, giving a figure of 3×10^7m^2 containing a standing algal population.

Sediment productivity

High productivity within the meadows is indicated by the observed density of the calcareous algal populations, resulting locally in a virtual green blanketing of the bank edge, and the abundance of *Halimeda* plates in the sediment. Although we have no exact measure of *Halimeda* production at this depth, a first approximation of carbon ate productivity can be obtained using data from Hillis (1980 pp. 273–274, 1991): 0.8 g $CaCO_3$/*H. incrassata* thallus, with 1% cover considered equivalent to 10 thalli/m^2. Using these data a conservative first estimate of carbonate productivity for GBB is 800 g $CaCO_3$/m^2/per year per standing crop at 100% cover. If we assume a turnover rate of three crops a year, a possibly conservative assumption based on current data and unpublished field observations (see review by Hillis 1991), then carbonate productivity would be 2400 g $CaCO_3$/m^2/per year. Along WGBB this production would translate to 7.2×10^{10}g $CaCO_3$/per year.

Comparisons with existing biological data must be made with care until considerably more information is available on number of generations (crops) per year and on variation of generation time with factors such as species, depth, latitude, temperature, salinity, currents and photosynthetic photon flux density. Nonetheless, the estimate of 2400 g $CaCO_3/m^2$/per year is similar to the estimates of Drew (1983) and Abel and Drew (1985) for the Great Barrier Reef (2234 and 2519 g $CaCO_3/m^2$/per year respectively) and of Payri (1988), for a Tahitian reef (2300 g $CaCO_3/m^2$/per year). In situ accumulation of these *Halimeda* sediments alone would produce a vertical build-up of 2 m/1000 y, assuming a total grain and sediment porosity of 60% and a density of 2.92 g/cm^3. Because *Halimeda* grains constitute only half the sediments present in the bank-edge meadow area, total vertical accumulation might be on the order of 4 m/1000 y. These calculated accumulation rates are comparable to *Halimeda* accumulations noted in the Pacific of 3.5–5.9 m/1000 y and elsewhere (Davies and Marshall 1985; Marshall and Davies 1988; Orme and Salama 1988; Robert et al. 1988; Searle and Flood 1988; Milliman 1993).

As the 20–40 m depths of the Bahamas probably have been below sea level for the past 7000–8000 y (Wilber, personal communication), the total Holocene thickness of a *Halimeda*-generated sediment would be on the order of 20–30 m. Seismic reflection profiles along the WGBB, however, show a maximum 15-m-thick sequence of Holocene sediment at the bank-edge depocenter, but much of the Holocene sequence appears far thinner (Wilber et al. 1990). These sediment thickness observations suggest that a substantial portion, nearly half, of the *Halimeda* produced in the bank-edge meadows is exported to deeper waters, and this is supported by the dominance of *Halimeda*-rich sediments on WGBB slopes. Similar conclusions were drawn by Moore et al. (1976) in Jamaica, and Payri (1988) suggests that half of the production on Moorea also could be exported. The observed differences in form between rhipsalian and opuntioid plates in the sediment of the trough further attest to the off-bank transport at WGBB. In contrast to the work by Boss and Liddell (1987), who showed how deep- and shallow-water species of *Halimeda* could prove useful as a paleoenvironmental indicator, the highly advective regime along WGBB would preclude this type of use of opuntioid and rhipsalian species. However, the presence of different forms of plates might be used as an indicator of relative transport distances and energies as well as proximal and distal environments.

Hine et al. (1988) have suggested that the deep-water *Halimeda* bioherms off eastern Nicaragua are the results of upwelling, which limits reef growth while favoring *Halimeda* production. They have asked why *Halimeda* bioherms "have not been found in well-studied areas such as the Bahama Banks?" Our work shows that *Halimeda* accumulations do occur on the bank edge of WGBB. Production seems comparable with other deep-water *Halimeda* environments. We suggest absence of more obvious examples of biohermal build-ups is probably the result of lateral and downslope transport by the Florida Current and gravity-related processes, both leading to the *Halimeda*-rich sediments found on the slope. Similar sediments have been noted on reef fronts and slopes elsewhere in the Caribbean (cf. Ginsburg et al. 1991).

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