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# "MIGRATION" OF BLOWOUTS IN SEAGRASS BEDS AT BARBADOS AND CARRIACOU, WEST INDIES, AND ITS ECOLOGICAL AND GEOLOGICAL IMPLICATIONS

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## ABSTRACT

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Blowouts are grass-free depressions within seagrass beds at Barbados and Carriacou and reported in the literature to be common elsewhere in the Caribbean region. They are typically crescent-shaped in plan view with the convex side seaward, and are characteristic of elevated seagrass beds in regions of moderate to strong wave action. The seaward edge is steep and exposes rhizomes of *Thalassia* while the leeward edge slopes gently upward onto the seagrass plateau and is usually colonized by *Syringodium*. The general morphology of the blowouts, the zonation of organisms across them, and the existence at some blowouts of a lag deposit of cobble-sized material at the scarp base continuous with a rubble layer below the seagrass carpet suggested the blowouts "migrate" seaward. Measurements of erosion at the scarp and of advance of *Syringodium* onto the blowout floor over a period of one year confirmed this. It is estimated that in the region of blowouts any one point will be recurrently eroded and restabilized at intervals of the order of 5—15 years. Such processes limit successional development of the seagrass beds, disrupt sedimentary structures, and may result in deposits much coarser than those characteristic of the sandy seagrass carpet.

## INTRODUCTION

Seagrasses encourage accumulation of sediments by: (1) binding the substrate and protecting it from erosion; (2) creating a baffle in which fine sediments can settle; and (3) creating a habitat suitable for a variety of calcium carbonate-secreting organisms (Ginsburg and Lowenstam, 1958). Frequently this results in an elevation of the seagrass "plateau" above the surrounding grass-free bottom.

Numerous workers have noted the occurrence in elevated seagrass beds of steep, sometimes undercut erosional scarps at which seagrass rhizomes are exposed. Their observations may be summarized as follows.

(1) Margins of elevated beds, particularly of beds which fringe the shore are

frequently irregular in outline, indented areas of steep erosional scarps alternating with gently sloping salient areas of new seagrass growth (Molinier and Picard, 1952; Folk and Robles, 1964; Rigby and McIntyre, 1966; Taylor and Lewis, 1970).

(2) Rapid accumulation of sediments in *Posidonia* beds in the Mediterranean results in formation of a "*Posidonia* reef" (Molinier and Picard, 1952). As the reef approaches the surface, *Posidonia* degenerates and sediments are eroded with resulting formation of depressions and meandering channels or "intermattes". The intermattes usually become colonized by the seagrass *Cymodocea.*

(3) Frequently noted by workers in the Caribbean are depressed, more or less crescent-shaped grass-free areas within the confines of the seagrass beds. These have variously been referred to as "blowouts" (Hoskin, 1963), "sand holes" (Ginsburg, 1956), "pot holes" (Thomas et al., 1961) and "grass-free cusps" (Kelly and Conrod, 1973).

The present paper is concerned with erosional structures of type 3 above. The term "blowout" is retained and is used in the sense defined in the Glossary of Geology (Gary et al., 1972), substituting "wave and current" for "wind": "a general term for a small saucer-, cup-, or trough-shaped hollow, depression, basin, or valley formed by wind erosion on a preexisting dune or other sand deposit especially in an area of shifting sand or loose soil, or where protective vegetation is disturbed or destroyed; the adjoining accumulation of sand derived from the depression, where readily recognizable, is commonly included".

Aerial photographs illustrating blowouts are given in Ball et al. (1967), Kelly (1969) and Kelly and Conrod (1973). Hoskin (1963) and Ball et al. (1967) believe the blowouts are produced by storm waves. Hoskin (1963) remarked that the "most deeply intended part of the crescent invariably points to seaward, and the grass-free area is deepest to seaward and becomes shallower towards the interior of the reef. This is interpreted as meaning that spilling storm waves erode the grass most rapidly at the plunge point of the beakers... it seems particularly significant that the steep edges of crescents expose a well developed root system of *Thalassia*." Scoffin (1970) observed similar structures, but in that case erosion was clearly associated with currents.

This paper reports observations on blowouts which suggest that while erosion leading to their initial formation may result from storm waves, erosional and depositional processes associated with the "normal" wave regime result in a seaward "migration" of the entire blowout structure. The significance of this process in controlling rates of sedimentation, in forming diagnostic sedimentary structures, and in limiting successional development of seagrass beds is discussed.

## REGIONAL SETTING

Initial studies and seasonal observations were made on blowouts in a seagrass bed at Bath, on the east, windward coast of Barbados (Fig. 1) during the period 1967—1970. Barbados is a small island of non-volcanic origin lying in the trade

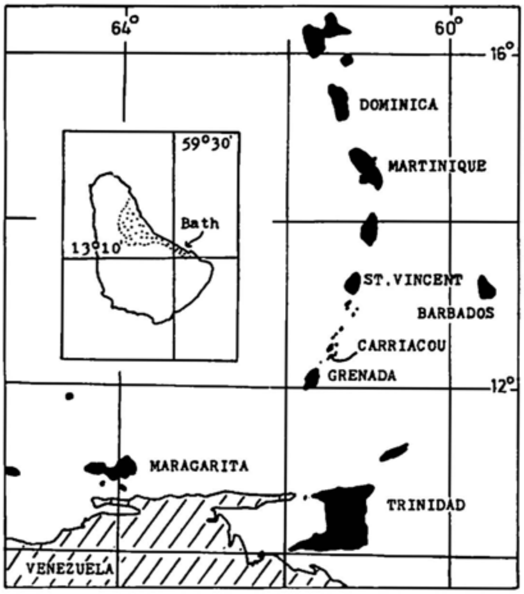


Fig. 1. Index map, Carriacou is the largest of the Grenadine Islands which lie between St. Vincent and Carriacou in the southern Caribbean. These islands are all volcanic, and some are still active. Barbados is a coral-capped, non-volcanic island lying about 150 km east of the Grenadine Islands. Inset shows location of Bath, at Barbados, at the southern edge of the Scotland District (stippled) where Tertiary sediments outcrop under the coral limestone.

wind belt and region of equatorial currents in the southern Caribbean. The Bath seagrass bed in general aspect is similar to the shallow lagoonal seagrass beds at Veracruz, Mexico desciibed by Rigby and McIntire (1966). Because of the lack of large reef lagoons and semiprotected bays at Barbados, seagrass beds there are not extensive. Reconnaissance studies were carried out on seagrass beds around the island of Carriacou (Fig. 1) in March 1969, and in April 1970. This is a small island of volcanic origin, lying about 200 km east of Barbados in the Grenadine Islands chain. Seagrass beds there are more extensive. In general aspect, these seagrass beds resemble those of the "back reef sub environment" described by Ginsburg (1956).

## METHODS

These studies were carried out in connection with studies of the general ecology of *Thalassia* and the associated community. Details of methods are given in Patriquin (1971). Maps of hydrography, distribution of seagrasses and bottom types were prepared by making use of details which could be distinguished in aerial photographs together with data from transect and tidal observations. The proportion of pebble- and cobble-sized material in substrates was estimated by sieving a measured volume of substrate through a 5.2 mm mesh sieve and determining the volume of retained material, or was estimated by visual observation at erosional scarps. Standard sedimentological techniques were used for determination of particle size distribution. Constituent nature of sediment particles was determined by treatment with HCl, by examination of particles under a dissection microscope and by examination of thin sections of resin-embedded material under polarized light (Ginsburg, 1956). Wave heights and currents were measured with a 2 m pole and wristwatch following detached seaweed movement for current speed measurements.

## RESULTS

### *The Bath (Barbados) blowouts*

*Hydrography and substrates of the seagrass bed*

Seagrasses at Bath, including *Thalassia testudinum*, *Syringodium filiforme* and *Halodule* sp., lie partially in the lee of algal- and coral-encrusted rocks lying about 300 m offshore (Fig. 2). The seagrass bed has a complex topography

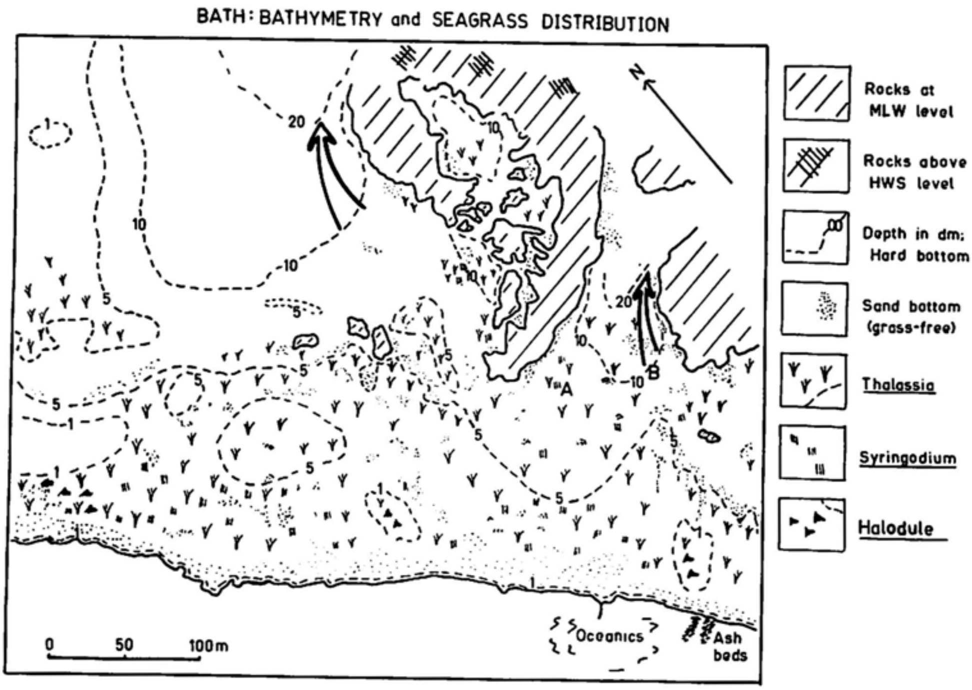


Fig. 2. Generalized bathymetry, and distribution of seagrasses at Bath, Barbados. Depths refer to approximately mean low-water level. Arrows show regions of seaward return flow of water during periods of strong wave action. Positions A and B are referred to in text. Exposed marls and interspersed ash beds of the Oceanic Formation bordering the shore are one source of sediment for the seagrass bed.

and distribution of sediments as a result of the irregular topography of the bedrock, the complex wave regime, and prolific biogenic production of sediment of clay to cobble size. Mean tidal range is approx. 0.7 m, and the diurnal range, 1.1 m (Lewis, 1960). The seagrass bed is shallow, and conditions are generally turbulent except for a few hours at low water. There are weak (0—21 cm/sec) currents associated with an overall northwesterly flow of water across the bed. In regions of strong seaward return flow of water (Fig. 2), currents reach speeds of 45 cm/sec and greater. Waves over the seagrass bed are generally of the order of 30—60 cm height at high water, and break over the entire seagrass bed area. During winter months when the east coast of Barbados is frequently subject to large swells (Dorm and McGuinness, 1959), waves over the seagrass bed may reach heights of 1 m and greater, and longshore currents may reach speeds in excess of 60 cm/sec.

The seagrass bed sediments are predominantly (> 75%) of local biogenic origin, and generally contain less than 10% fines (sizes less than 62 $\mu$). *Halimeda*, corals (chiefly *Porites furcata*) articulated red algae, forams (*Homotrema*, *Rotalia* and others) and gastropods are the main contributors to the sand-sized carbonate fraction. Four substrate types are distinguished on the basis of the quantity and nature of pebble- and cobble-sized material (Fig. 3):

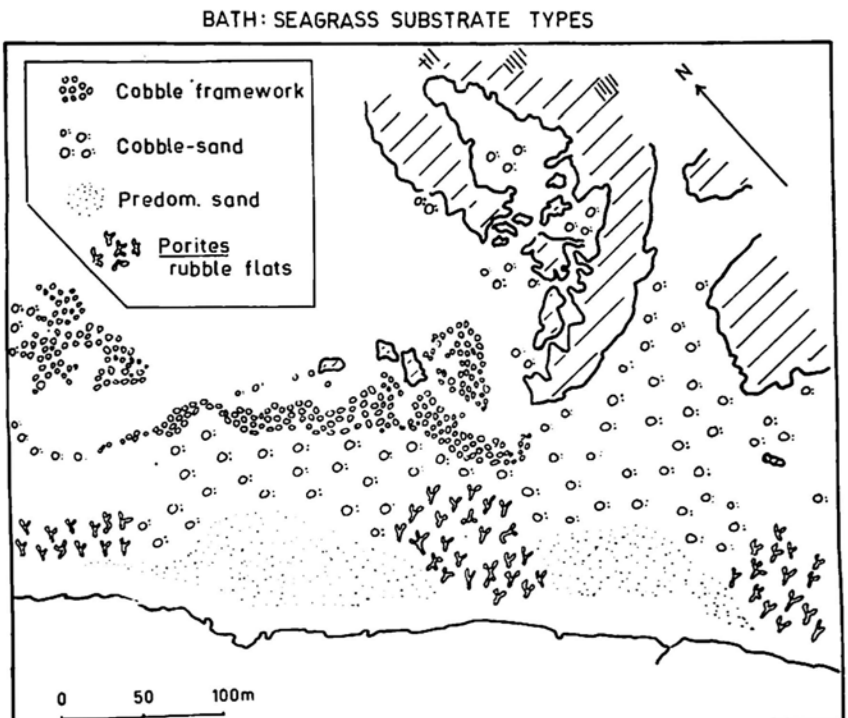


Fig. 3. Distribution of substrate types in seagrass bed at Bath, Barbados.

(1) *Thalassia*-colonized "cobble framework" substrates occur at the seaward face of the seagrass bed where accumulations of rhodiles (Bosellini and Ginsburg, 1972; Ginsburg and Bosellini, 1973) and coral debris originating from the hard bottom seaward rise to within 25 cm of the water surface and occupy over 70% of the sediment volume (Fig. 4).

(2) *Thalassia*- and *Syringodium*-colonized "cobble-sand" substrates in which pebbles and cobbles are up to one-half of the substrate volume, occur over most of the seagrass bed.

Fig. 4. Photograph of an erosional scarp in cobble framework substrate at Bath, Barbados. Greater than 70% of the substrate volume is occupied by rhodiles (chiefly *Archaeolithothamnium* sp. surrounding coral nucleus) derived from the coral—coralline algal bottom to the seaward.

(3) "*Porites* rubble flats" occur in several nearshore areas where accumulations of stick-like skeletons of the coral *Porites furcata* originating from the cobble-sand substrates form a platform which is largely exposed at low water of spring tides. The *Porites* skeletons occupy about 50% of the sediment volume. Most of the *Porites* rubble flats are colonized by *Thalassia*, but in a few areas, mounds of *Halodule* and sand forming over the rubble substrate rise to about mean low water level. In more wave exposed areas the *Porites* rubble flats have become overgrown by sponges and coralline algae, and *Thalassia* excluded.

(4) *Syringodium*- and *Thalassia*-colonized "predominantly sand" substrates in which pebbles and cobbles are less than 5% of the substrate volume, occur inshore between the *Porites* rubble flats.

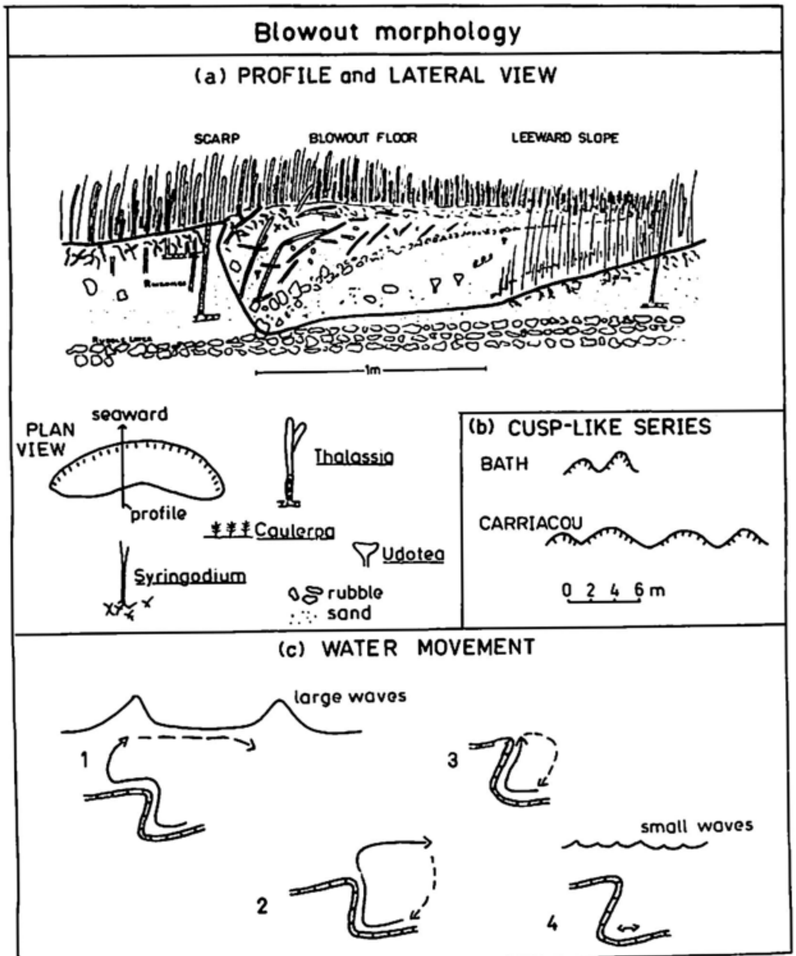


Fig. 5. Features of blowouts. (A) Idealized cross section and lateral view of a crescent-shaped blowout at Bath, Barbados. (B) Examples of organization of blowouts in cusp-like series. (C) Patterns of water motion associated with waves at a blowout at Bath; 1 to 4 in order of decreasing wave heights.

*Blowout distribution and morphology*

Blowouts occur in all substrate types of the Bath seagrass bed, but within these substrate types are largely restricted to areas where there is not a dense epifauna and algal flora characteristic of advanced stages of seral development of the seagrass bed. However blowouts do occur in the region of position A (Fig. 2), a region of dense rhizophytic algal (*Avrainvillea rawsonii* and *Halimeda opuntia*) and coral (*Porites furcata*) growth. Wave action in this area is very intense.

Some morphological features of the blowouts are illustrated in Fig. 5. In the predominantly sand and cobble-sand substrates blowouts are crescent-shaped in plan view with the points of the crescents directed to the lee of the dominant wave front, usually shoreward. The seaward margin is bordered by a steep erosional scarp, and the leeward margin by a gentle slope upward onto the seagrass plateau. The blowout floor is deepest and the scarp relief greatest at the central part of the crescent; both decrease towards the points of the crescent. Morphometric data for five crescent shaped blowouts are given in Table I.

Well defined crescent-shaped blowouts (Fig. 5a) are confined to sand and cobble-sand substrates. Irregular-shaped blowouts (Fig. 6) also occur in these substrates and in the *Porites* rubble flats and cobble framework substrate. Over most of the seagrass bed these irregular-shaped blowouts are oriented with the scarp seaward and the whole structure broadly parallel to the dominant wave front similar to the crescent-shaped blowouts. Where the scarp orientation is not parallel to the dominant wave front, the scarp is on the upstream side of the blowout in a region of currents. At position A (Fig. 2), for example, crescentric blowouts occur with the scarp seaward; at position B there are similar structures but the orientation is 180° reversed. This latter area is a region of strong seaward return flow during periods of heavy wave action.

The underground stems or rhizomes of the seagrasses (*Thalassia* and *Syringodium*) are usually restricted to and branch extensively within the upper 20 cm of the sediment, and scarps are typically undercut (Fig. 7). At some scarps in predominantly sand substrates, erect stems of *Thalassia* extend from the base of the scarp to near the sediment surface with little branching

TABLE I

Morphometric data for five crescentric blowouts at Bath, Barbados

| Scarp relief (cm) | Long axis of crescent (m) | Short axis of crescent (m) |
|---|---|---|
| 15 | 3.8 | 1.9 |
| 38 | 4.0 | 3.5 |
| 46 | 2.9 | 1.2 |
| 46 | 2.3 | 2.0 |
| 61 | 10 | 5.5 |

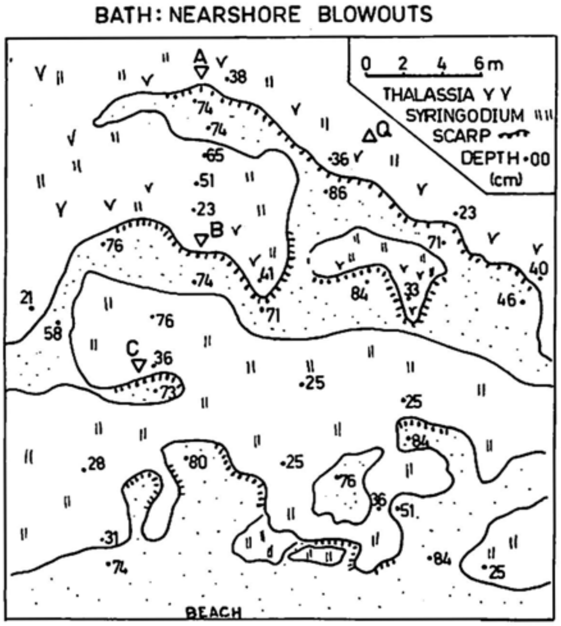


**Fig. 6. Map of inshore area in predominantly sand substrate at Bath, Barbados, showing distribution of seagrasses and irregularly shaped blowouts, depths and positions (positions A, B, C) of erosion measurements in December 1968. Position Q referred to in text.**

(Fig. 8) and the scarp is not undercut. Pebbles and cobbles are prominent on the scarp face (Fig. 7), the sandy matrix apparently being more rapidly eroded away. Sand from the blowout floor has modes 1 to 2 $\varphi$ coarser than sand from grass stabilized sediment (Fig. 9). A "rubble layer" continuous with lag deposit of pebbles and cobbles at the base of the scarp can be traced seaward of the scarp below the seagrass-stabilized sediment, and leeward of the scarp below loose sand of the blowout floor and recently stabilized sand at its edge (Fig. 5a). The transition between the sand and rubble layers is abrupt. The rubble layer is very well packed, and extremely difficult to penetrate, even with a shovel.

Water motions in the region of the scarp were studied by observing fluorescein dye released from a bottle placed in a crescentric type depression of 1.5 m depth next to a scarp of 36 cm relief (Fig. 5c). During passage of high amplitude waves, a current of water moved swiftly along the bottom towards the scarp, up the scarp face and seaward (Fig. 5c). Most waves with heights greater than 40 cm were capable of lifting *Porites* debris at the base of the scarp partially up the scarp face, and occasionally onto the seagrass plateau above. This seaward movement of eroded sediment at the scarp is probably responsible for the slightly greater relief of the seagrass plateau just seaward of the scarps (Fig. 5a).

Fig. 7.

Fig. 8.

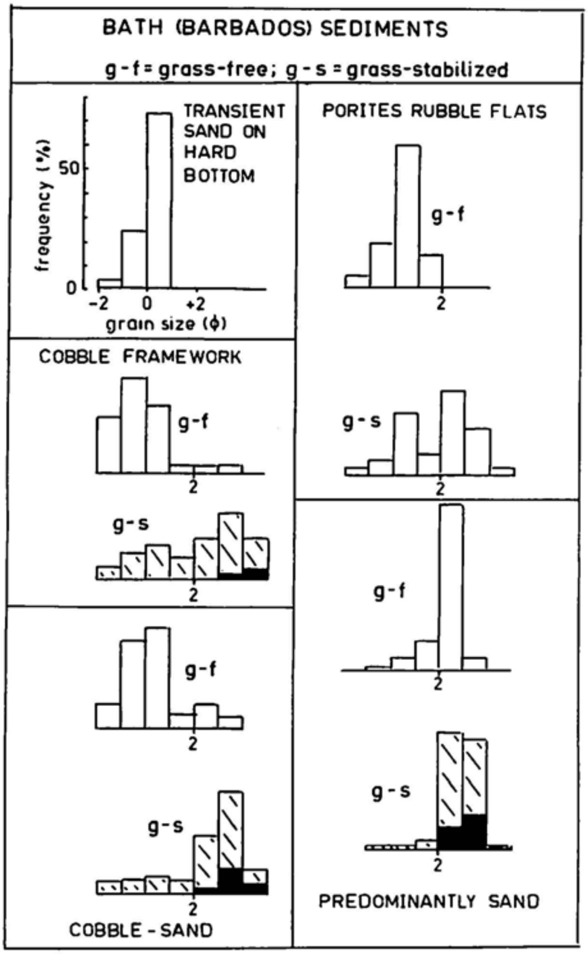


Fig. 9. Size distribution histograms of representative sediment samples from various seagrass substrates and blowout floors at Bath, Barbados. Size classes represent 1-$\varphi$ intervals (decreasing grain size from left to right) except for the finest which includes all material finer than 4 $\varphi$. Shaded areas represent acid insoluble material in three samples.

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Fig. 7. Photograph of undercut erosional scarp in a predominantly *Syringodium* stand in a predominantly sand substrate at Bath, Barbados. *Porites* debris and occasional rhodiles are prominent at lower part of scarp. Scarp relief about 0.5 m.

Fig. 8. Photograph of erosional scarp in a predominantly *Thalassia* stand in predominantly sand substrate at Bath, Barbados. Long unbranched stems of *Thalassia* are about 25 cm in length.

*Zonation of organisms*

The overall zonation of organisms leeward of the scarp corresponds to a successional sequence (Margalef, 1962; Welch, 1965; Patriquin, 1971). Blue-green algae (*Microcoleus* sp.) and green algae (*Udotea cyathiformis* and *Caulerpa* spp.) occur on the blowout floor, *Syringodium* occurs on the leeward slope, and mixed *Syringodium—Thalassia* stands occur farthest from the scarp. The stand eroded by the scarp usually consists of both *Thalassia* and *Syringodium*. This zonation is typical of blowouts in predominantly sand and cobble-sand substrates. Where blowouts are closely spaced perpendicular to shore, *Thalassia* may be absent in the intervening areas, and where blowouts occur within pure *Thalassia* stands, *Syringodium* is absent from the leeward slope.

Recent colonization of the leeward slope by *Syringodium*, where it occurs, is indicated by orientation of rhizome apices towards the scarp on top of sediment adjacent to the blowout floor. Older rhizomes, leeward of advancing apices are covered with sediment and shoots are oriented in rows parallel to the wave front, a feature the author has observed to be very characteristic of new seagrass growth.

*Erosion and recolonization measurements*

The general morphology of the blowouts, the existence of a rubble layer continuous with the lag deposit at the base of the scarp, and the zonation of organisms across the blowouts all suggested that the blowouts are dynamic rather than static structures, erosion at the scarp being more or less balanced by redeposition and restabilization of sediments on the leeward slope. To test this hypothesis, measurements of erosion at the scarp face, and of *Syringodium* advance onto the blowout floor were made at two locations in a nearshore region of irregulary shaped blowouts (positions A and B, Fig. 6) at intervals over a period of 1 year. Measurements were made by determining distances of scarps and *Syringodium* rhizome apices from fixed marker posts. The positions of the scarp and *Syringodium* apices at a third location (position C, Fig. 6) were determined at the beginning and end of this period.

The results (Table II) show that blowout migration did occur at all three locations, but the average rates of advance of *Syringodium* apices (5.54, 4.23 and 5.25 mm/day for positions A, B and C) were greater than average rate of erosion of the scarps (3.16, 3.96 and 3.98 mm/day for positions A, B and C) and thus the blowouts became reduced in width. At position B, in the middle of the study area, rates of erosion at the scarp and of advance of *Syringodium* apices did not vary greatly during the year. In contrast, at position A, the most seaward, erosion was retarded at the scarp towards the end of the period of observation but *Syringodium* advance was not retarded and the blowout became considerably reduced in width. Inspection of position A several months later revealed no further erosion, and the blowout was almost completely overgrown. Blowouts that had been completely overgrown but that still retained their characteristic shape were observed elsewhere in the Bath seagrass bed.

TABLE II

Measurements of erosion at the scarp and of advance of *Syringodium* rhizome apices onto the blowout floor at Bath (Fig. 6)

| Date | Interval (days) | Position A (cumulative cm) | | Position B (cumulative cm) | | Position C (cumulative cm) | |
|---|---|---|---|---|---|---|---|
| | | Scarp erosion | *Syringodium* advance | Scarp erosion | *Syringodium* advance | Scarp erosion | *Syringodium* advance |
| November 13 (1968) | 0 | 0 | | 0 | | 0 | 0 |
| December 10 | 27 | 15 | | 17 | 0 | | |
| January 11 (1969) | 32 | 20 | 0 | 30 | 5 | | |
| February 23 | 43 | 35 | 18 | 47 | 25 | | |
| April 30 | 66 | 43 | | 67 | 30 | | |
| May 28 | 28 | 51 | 54 | 87+* | 91 | | |
| July 19 | 52 | 62 | 64 | 107+ | 101 | | |
| September 13 | 56 | 110 | 123 | 127+ | 126 | | |
| October 16 | 33 | 110 | 154 | 132+ | 146 | | |
| November 12 | 27 | 115 | | 137+ | | 145 | 191 |
| December 2 | 20 | | | 152+ | 151 | | |

* Scarp had eroded past reference post.
Measurements initiated.

It is evident that blowouts do migrate, but because growth of *Syringodium* into the leeward area occurs at slightly greater rates than erosion at the scarp, and because of a slowing down and eventual cessation of erosion at the scarp, the structures eventually become overgrown and migration ceases. The time required for overgrowth of a blowout must depend in part on its initial dimensions. Presumably initial stages in the formation of blowouts involve erosion without restabilization. Storm waves in early January, 1969 gouged a hole about 1 m in diameter and 75 cm deep at position Q (Fig. 6). This hole had enlarged 43 days later to approx. 1.5 m diameter and 81 cm depth. Subsequently the scarp leeward of this region migrated into the area, and the individual character of the hole was lost. Perhaps under other circumstances erosion would have continued only at the seaward face and a crescent type structure been formed.

*Frequency of erosion cycles*

Any point in regions where blowouts are closely spaced along on axis perpendicular to the wave front must be subject to recurrent cycles of erosion and redeposition of sediments, and of denudation and regrowth of seagrasses, at short intervals. The time between successive erosion—redeposition cycles at position A (Fig. 6) was estimated as follows.

When erosion measurements at position A (Fig. 6) were initiated, *Syringodium* shoots were approx. 3 m behind the scarp and the *Thalassia* shoots, 6 m. Assuming the scarp migrated through this area at a rate of 3.7 mm/day, this suggests that *Syringodium* first colonized the grass-free area at about 2.2 years, and *Thalassia* at about 4.4 years after the erosion. The exact times depend on the initial dimensions and age of the blowout as well as on growth rates of the seagrasses. At typical, active (i.e. not in the final stages) blowouts elsewhere at Bath, *Syringodium* was generally between 2 and 6 m behind the scarp face and *Thalassia*, between 4 and 7 m.

Scarps in *Thalassia* stands in predominantly sand substrates typically expose long, mostly unbranched stems extending from the bottom of the scarps to close to the sediment surface (Fig. 8). The deepest horizontal rhizomes in such areas appear to be growing close to the rubble layer. Virtually all of the erect shoots were supporting living leaves, and there was no evidence of older, decayed stems being present. The erect stems of *Thalassia testudinum* can be aged by counting leaf scars and leaves (Patriquin, 1973). The age of the oldest stems found at the scarp thus gives an estimate of the time at which the stand was first colonized by *Thalassia*, and this is also a minimum estimate of the time since the previous erosion in that area. At the end of the period of erosion measurements at position A (Fig. 6), the oldest stem found was 5.1 years old. Assuming that 4 years intervened between erosion and first growth of *Thalassia*, this suggests that the area was eroded 9 years previously. The next scarp leeward of position A was approx. 9 m behind. Assuming an erosion rate of 3.7 mm/day for this scarp, it would reach position A in 6.7 years. These two estimates thus suggest that position A is eroded at intervals of approx. 8 years.

*Accretion of the rubble layer*

It seems likely that the sorting of sediments associated with blowout migration leads to the formation of the rubble layer observed in the region of scarps, and also elsewhere at depths of 10 cm to about 1 m below the seagrass sandy carpet. The tight packing and large size of the constituent particles in the rubble layer presumably make the layer erosion resistant. Continued cycles of erosion and associated deposition of rubble in the rubble layer must result in gradual accretion of the rubble layer. The rate at which this layer accretes is dependent on the quantity of rubble in the sandy layer, or seagrass carpet, above, and on the frequency of erosion processes. At position A (Fig. 6), on the border between nearshore predominantly sand substrates and cobble-sand substrates further offshore, pebble- and cobble-sized material was estimated to occupy 5.9% of the volume of the sandy seagrass carpet. The scarp was 53 cm in height. Thus assuming an 8 year erosion cycle, the average rate of accretion of the rubble layer is estimated as $(0.059 \times 530)/8 = 3.9$ mm/year, or approx. 3.1 cm per erosion cycle. Blowouts are more widely dispersed in cobble-sand substrates further from shore but the quantity of rubble is greater, so rates of accretion of the rubble layer may be of the same order of magnitude.

## *The Carriacou blowouts*

*Hydrography and substrates of the seagrass beds*

The general hydrography and distribution of seagrasses at Carriacou are shown in Fig. 10. Seagrasses, including *Thalassia testudinum*, *Syringodium filiforme*, *Halodule* sp. and *Halophila baillonis*, are most abundant in shelf lagoons lying behind barrier reefs on the east, windward coast. These reefs have minimum depths of about 0.3—1 m, and the maximum lagoonal depths are approx. 5, 13 and 15 m for Windward Bay, Jew Bay and Grand Bay, respectively.

The spring tide range at Carriacou is approx. 0.6 m. Secondary waves with periods of 2 to 2.5 sec and heights of 30 to 45 cm are typical of spring conditions in Windward Bay, with periods and heights greater during winter months (W. Clack, Geology Department, McGill University, personal communication, 1973). Strong oceanic currents occur in the region of Carriacou, associated with wind-driven circulations, passage of the Equatorial Current over the Grenadine Island platform, and tidal streams. Outside the east coast reefs, these currents attain velocities up to 1.5 m/sec. W. Clack (personal communication, 1973) observed reversing, usually northward-flowing currents inside the reef at Windward Bay with velocities up to 40 cm/sec and decreasing velocities towards shore. He observed no currents behind the barrier reefs at Jew Bay and Grand Bay. The author experienced strong currents near the headlands in these bays in March 1969. In general the author noted no currents over fringing seagrass beds in the east coast bays and Manchioneal Bay, except close to their seaward margins.

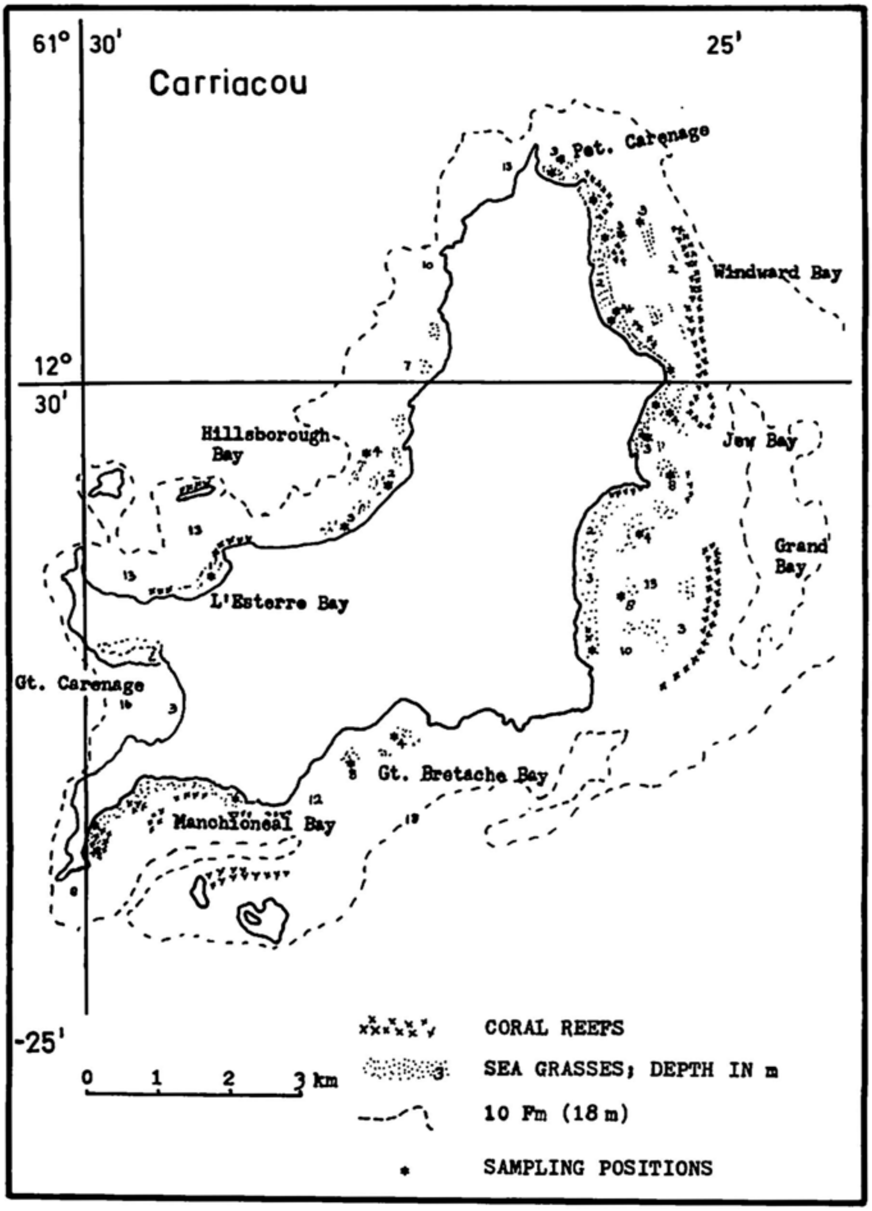



Fig. 10. General hydrography, distribution of seagrasses and reefs and location of sampling positions at Carriacou. Depths from Admiralty Chart 2782.

Physiographically the seagrass beds may be classified into six types:

(1) "Fringing beds" of *Thalassia* and *Syringodium* border most of the shore and extend seaward 200—300 m in the east coast lagoons and in Manchioneal Bay, and along part of the shore at Hillsborough Bay and Petit Carenage Bay. Except for some cobble-sand substrates in nearshore areas of fringing beds in Petit Carenage Bay and the southern part of Grand Bay, the substrates in these beds are the predominantly sand type.

(2) "Streaks" of seagrasses (*Thalassia* and *Syringodium*) with elevations up to 0.7 m occur in predominantly sand and cobble-sand substrates oriented along the axis of strong, usually northward-flowing currents in Watering Bay and Petit Carenage Bay.

CARRIACOU: COBBLE FRAMEWORK BANKS

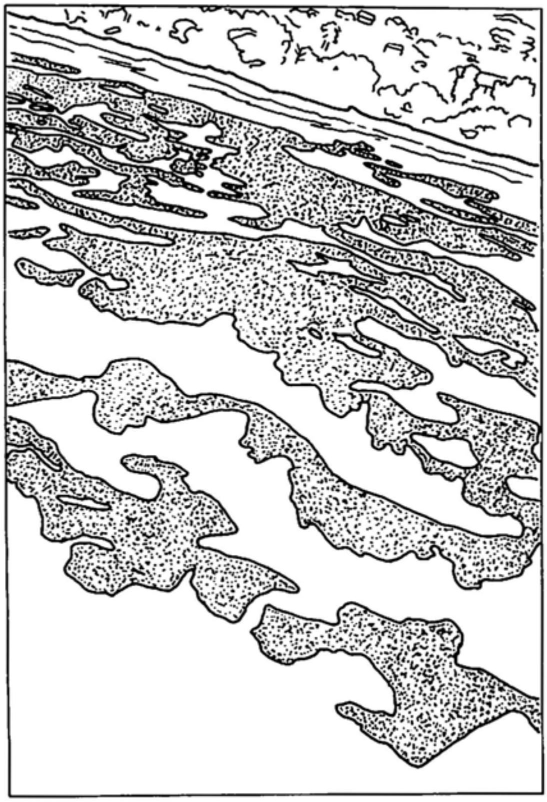


Fig. 11. Lateral aerial view of cobble framework banks in L'Esterre Bay, Carriacou, from aerial photograph taken on approach to airport. At about 100 m from shore the banks have a relief of 65 cm and minimum depth of 52 cm. Banks sit on top of a largely dead coral rock bottom. Living coral assemblages occur seaward of the banks. Erosional scarps occur on the leeward sides of the banks, and the banks are believed to "migrate" seaward across the hard bottom.

(3) Irregularly oriented and distributed "patches" of seagrasses (*Thalassia*, *Syringodium*, occasionally *Halodule*, *Halophila*) occur in predominantly sand substrates in the mid lagoonal areas of the east coast bays, and offshore in Great Bretache Bay, Hillsborough Bay and Petit Carenage Bay. Most of the deeper water (greater than 4 m) patches are not, or are only slightly, elevated above the surrounding bottom.

(4) *Thalassia*-stabilized "cobble framework banks" of about 0.3—0.8 m relief form irregularly shaped bands oriented broadly parallel to shore (Fig. 11) in the east part of L'Esterre Bay on top of a coral rock bottom.

(5) "Patch reefs—*Thalassia* complexes" occur in nearshore regions of Windward Bay and Manchioneal Bay subject to currents.

(6) A "reef flat *Thalassia* bed" in a cobble-sand substrate occurs in the lee of a fringing reef and seaward of a Mangrove swamp at the northern headland of Windward Bay.

Skeletal carbonates predominate in the sediments except in immediate nearshore areas where terrigenous material is prominent. Angular fragments of *Halimeda*, and lesser amounts of molluscs, derived from locally growing organisms are the main constituents of the sand-sized carbonate fraction in fringing beds. Sediments of mid-lagoonal beds include large amounts of rounded coral fragments, presumably derived from the barrier reefs, as well as locally derived *Halimeda* and mollusc fragments.

*Occurrence and characterization of blowouts*

Blowouts are restricted to and are common and prominent features of the fringing seagrass beds. Bottom profiles of fringing beds around Carriacou are shown in Fig. 12. Fringing beds of the east coast bays are in general characterized by an extensive uniformly flat bottom which shallows only near the shore, and erosional scarps are restricted to the shallowing, nearshore areas. The seagrass communities in the regions of scarps are in relatively primitive stages of succession, as evidenced by the presence of *Syringodium* (Fig. 12) which is eliminated early in the successional sequence (Welch, 1965; Patriquin, 1971). They also lack corals, sponges, alcyonarians and red algae characteristic of more advanced stages of succession at Carriacou (unpublished data). Blowouts are notably absent from fringing beds in the lee of patch reefs (Fig. 12, profiles A, B and M). Any transect perpendicular to shore in the exposed areas will cross at least one, usually two, and sometimes many erosional scarps.

Blowouts in the fringing beds of the east coast lagoons are invariably oriented parallel to shore, and tend to assume a crescent or indented outline as at Bath. Frequently 2—5 crescent-type blowouts lie side by side forming a continuous cusp-like series extending laterally as much as 20 m (Fig. 5). Inshore blowouts at Manchioneal Bay were oriented parallel to shore, but near the seaward edge of the bed where a strong westward-flowing current was experienced during transect observations (Fig. 12, profile L) a blowout 8 m in length was oriented normal to shore with a scarp of 37 cm relief on its east, upstream side. Blowouts with scarps of lesser relief on their west sides were also present in this area. Similarly, in Hillsborough Bay blowouts are oriented parallel to shore with the scarp seaward, and normal to shore with scarps on the north and (or) south sides of the depressions, the latter being the more prominent. These orientations presumably reflect the presence of reversing currents, of which the northernly-flowing and westernly-flowing currents are strongest in Hillsborough Bay and Manchioneal Bay, respectively.

Zonation of organisms across the blowouts is similar to that at Bath. In most of the fringing beds there is very little cobble-sized material in the seagrass bed sediments and no compact rubble layer below the seagrass carpet. There was, however, a greater amount of coarse material in sediments from below the base of the scarps than in overlying sediments. At the second scarp seaward in profile G of Fig. 12 for example, sediment in the seagrass carpet contained 0.3% by volume of material greater than 5.2 mm while sediment below the base of the scarp contained 4.2%. 92% of this material consisted of skeletons of organisms growing in the seagrass bed; the remainder was of non-carbonate, terrestrial origin. Organisms producing large skeletal particles, including the corals *Porites*, *Siderastrea* and *Manicina*, and the molluscs *Strombus*, *Bulla* and *Codakia* are sparsely distributed in the fringing beds, and this accounts for the small amounts of rubble deposited at scarps. Only in southern Grand Bay, where cobble-sized, non-carbonate rocks derived from adjacent cliffs were abundant in nearshore parts of the bed, was a rubble layer evident (profiles I and J, Fig. 12). Blowouts were considerably more abundant in this region than elsewhere in Grand Bay (profile H, Fig. 12) and in Jew Bay (profiles D—G, Fig. 12). The general trend of bottom profiles at southern Grand Bay, excluding irregularities associated with blowouts, also differed from those of northern Grand Bay and Jew Bay in having a gentle rather than abrupt slope onto the shore.

Stems of *Thalassia* at a number of scarps in the fringing beds were aged (see profiles D, G and J, Fig. 12). Assuming 3—5 years between erosion and initial growth of *Thalassia*, these data suggest that regions of blowouts in the fringing east coast beds at Carriacou are eroded at intervals of the order of 5—15 years. At 38 m on the Grand Bay profile J (Fig. 12), pebble- and cobble-sized material constituted approx. 4% of the volume of the sandy seagrass carpet. Assuming an erosion cycle of 6 years and given a scarp height of 46 cm, these data suggest accretion of the rubble layer at that point at an average rate of 3.1 mm/year or 1.8 cm per erosion cycle. Higher rates would be expected shoreward of the 38 m scarp where rubble is more abundant, and lower rates seaward of the 38 m scarp where both the amounts of rubble and frequency of scarps are less. At 100 m the quantity of rubble and frequency of scarps are apparently insufficient to give rise to a compact, erosion-resistant rubble layer.

*Migrating seagrass beds*

At the southern end of Grand Bay there occur in a series extending seaward,

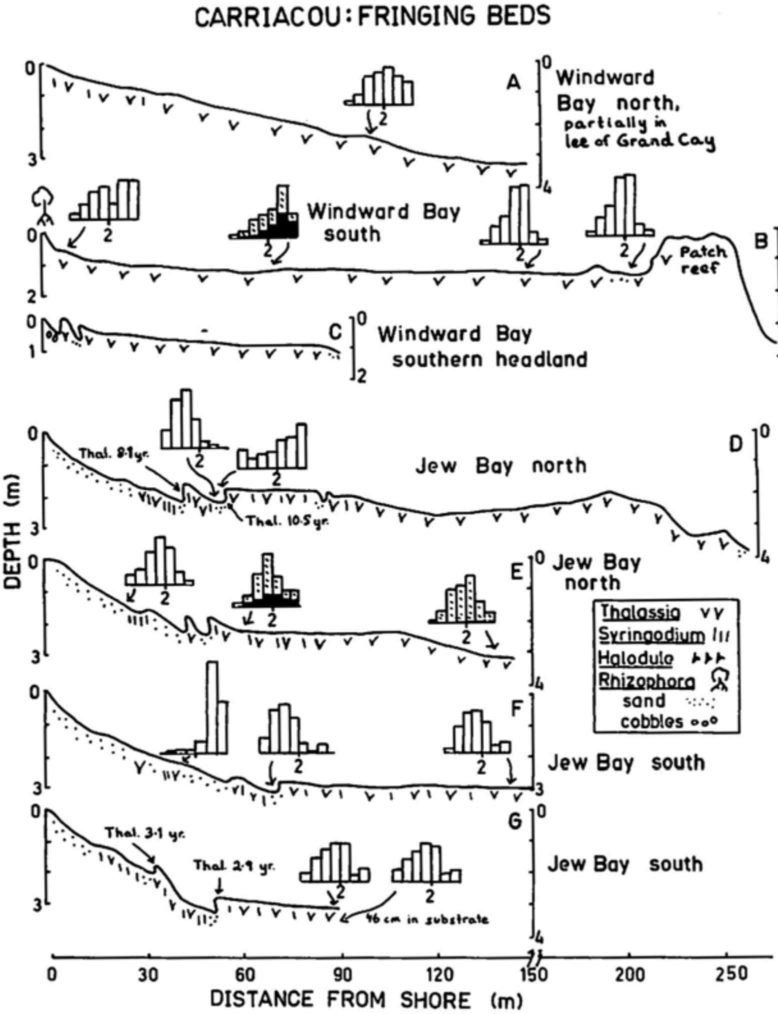
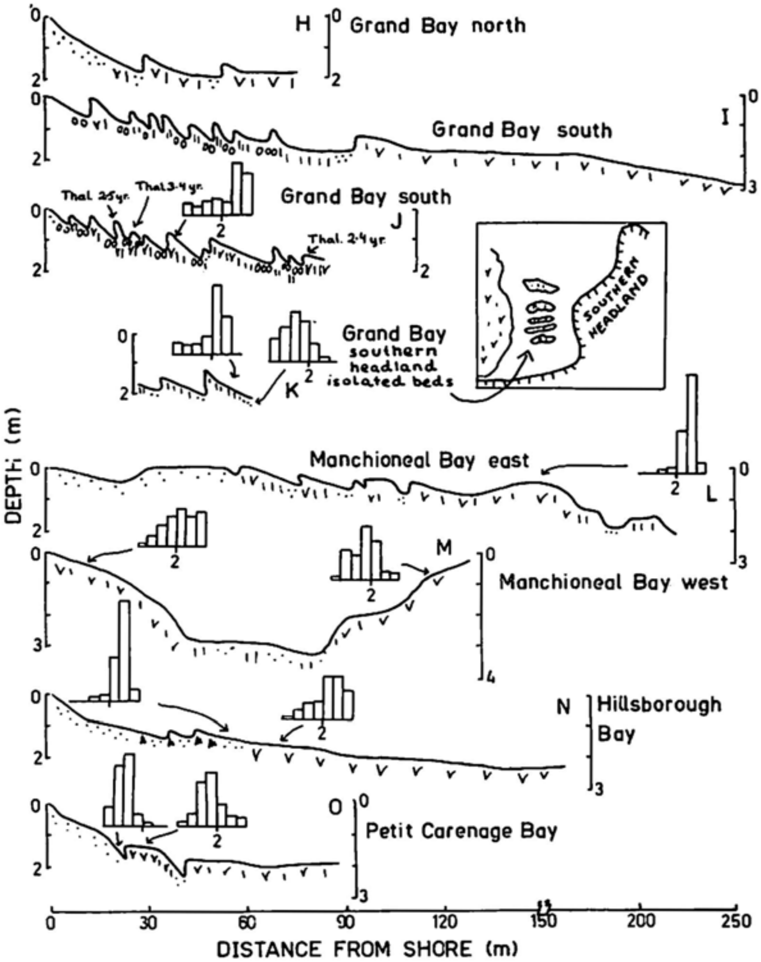



**Fig. 12. Bottom profiles, sediment size histograms and ages of *Thalassia* stands in fringing seagrass beds at Carriacou. Profiles are perpendicular to shoreline, and in some cases include only the nearshore area. Size histograms as for Fig. 9. Profiles including ages were surveyed in April 1970, others in March 1969. Depths refer to approximately mean low-water level.**

isolated, elevated pure *Syringodium* beds in predominantly sand substrates (Fig. 12 (II), inset). The long axis of each bed is oriented parallel to shore. The leeward faces of the beds are steeply eroded and indented, and there is a downward slope to the seaward (Fig. 12, profile K). This is an area of very intense wave action, and it appears that each bed behaves as an "island of seagrass" migrating seaward across the sand. These structures are thus analagous to blowouts migrating across seagrass beds, except that there is no lateral




continuity between the seagrass islands. Similarly, steep erosional scarps occur on the leeward edges of *Thalassia*-stabilized cobble framework banks in L'Esterre Bay, and these beds probably also migrate across the hard bottom.

## DISCUSSION AND CONCLUSIONS

In summary, the following features characterize blowouts at Barbados and Carriacou.

(1) Distribution: blowouts occur in all substrate types, but within these are restricted to shallow water areas (<4 m) exposed to moderate to strong wave action. They are uncommon in regions where there is a well developed epifauna and flora.

(2) Morphology and orientation: in plan view the blowouts tend to assume a crescent shape with the long axis parallel to the dominant wave front and the convex side seaward. The convex edge is steeply eroded and exposes seagrass rhizomes; the leeward edge slopes gently upward onto the seagrass plateau. Where the wave regime is complex, and in substrates which contain a high proportion of cobble-sized material, the shape tends to be irregular, but the overall orientation is the same, that is with the steeply eroded edge seaward. In a few areas where strong currents occur the blowouts are oriented with the convex or steeply eroded edge on the upstream side.

(3) Zonation or organisms: the zonation of organisms leeward of the scarp (green algae on the blowout floor, *Syringodium* on the leeward slope and mixed *Thalassia—Syringodium* leeward of this) corresponds to a successional sequence.

(4) Rubble layer: a rubble layer continuous with the lag deposit of cobble-sized material at the scarp base occurs below the sandy seagrass carpet in areas where cobble-sized material occupies more than about 1—2% of the sediment volume.

(5) Migration: erosion at the seaward edge of the blowout under the influence of "normal" wave action, and concurrent advance of *Syringodium* onto the blowout floor from the leeward edge of the blowout result in a seaward migration of the entire blowout. This migration eventually ceases because the rate of advance of *Syringodium* onto the blowout floor is greater than the rate of erosion at the scarp.

*Comparison with other areas*

The available information suggests that blowouts elsewhere in the Caribbean region (Hoskin, 1963; Ball et al., 1967; Kelly, 1969; Scoffin, 1970; Kelly and Conrod, 1973) are similar in general aspect to those observed in the present study and are probably also "migratory". The most significant difference is that blowouts elsewhere may be much larger, the long axis being up to 30 m or more in length (Plate V in Ball et al., 1967; Kelly and Conrod, 1973). Kelly and Conrod (1967) noted *Halodule* or *Thalassia* on the leeward slope, and they also observed blowouts that had nearly been grown over. Blowouts observed by Hoskin (1963), Ball et al., (1967), Kelly (1969) and Conrod and Kelly (1973) are illustrated or described as having the convex side seaward or into the dominant wave front, and occur in regions of moderate to strong wave action. Only Scoffin (1970) attributed formation of the blowouts to currents. The blowouts he studied were crescent-shaped with the scarps on the upstream side in a region where tidal currents had speeds up to 90 cm/sec. He noted upcurrent eddies in the lee of the scarps, and over a 3 month period erosion of the *Thalassia* carpet took place at an average rate of 2.2 mm/day. None of these authors noted the occurrence of a rubble layer below the blowout floor but this does not preclude its existence. The floor of one blowout examined by Kelly (1973) consisted of basement rock.

*Dynamics of erosion*

Details of sediment and water motion in the region of blowouts remain obscure. "Sheetflood" mechanisms postulated to operate in the formation of other cusp-like structures (Gorycki, 1973) may be responsible for the characteristic blowout shape.

Erosion at the scarps in both current dominated (Scoffin, 1970) and wave dominated situations appears to be associated with eddies forming in the lee of the scarps. Rates of erosion at scarps in areas of *Syringodium* growth could not be maintained for long at rates of less than 2—3 mm/day because the eroded area would be quickly overgrown by *Syringodium*. Slower rates of erosion could be maintained in pure *Thalassia* stands as in the *Porites* rubble flats and cobble framework substrate at Bath because greater periods of time would be required for the sediment to become suitably stable (Welch, 1965) and anoxic (Patriquin, 1972) for *Thalassia* rhizome growth. Also, growth rates of *Thalassia* rhizomes (Patriquin, 1973) are about one half those observed for *Syringodium* rhizomes in the present study. Growth of seagrasses onto the blowout floor apparently occurs by extension from preexisting stands rather than through dispersal by seed or settlement of torn-off fragments of plants.

While it is evident that erosion at the scarp takes place under "normal" wave action, more severe disturbances may be required for the initial formation of blowouts. On the basis of experiments with an underwater plume Scoffin (1970) reported: "extensive removal of sediment around *Thalassia* rhizomes and gradual erosion of roots starts at a current velocity of about 50 cm/sec in sparse grass, 100 cm/sec in medium grass and about 150 cm/sec in dense grass (current velocity measured just above the blades)". Grass cover in the seagrass beds at Barbados and Carriacou would according to Scoffin's classification be described as "medium". In most of the areas studied, current velocities were less than 50 cm/sec, and current induced blowouts were accordingly sparse. However, wave-produced blowouts appear to be common in shallow water seagrass beds of the Caribbean. Considerations of shallow water wave theory (King, 1959, pp. 100—120) suggest that maximum bottom orbital speed associated with the waves observed under "normal" conditions in the seagrass beds at Barbados and Carriacou might be of the order of 50 to 100 cm/sec. Annually occurring storm waves or oceanic swells would produce maximum bottom orbital speeds well in excess of 100 cm/sec and these probably lead to the initial disruption of the seagrass mat. An irregularity in the substratum may provide the locus for initial erosion as suggested by Scoffin (1970). Apparently even very severe disturbances are generally unable to erode the bottom where there is a dense epifauna and algal flora. The erosion measurements suggest that once the seagrass mat is disrupted and underground parts are exposed, normal wave action with bottom velocities of the order of 50—100 cm/sec is sufficient to continue erosion at the seaward face of the disrupted area.

It seems then, that in the region of erosional scarps much of the sand-sized sediment is at such a depth with respect to the particular wave regime that it be eroded and transported in the absence of the protective baffle (Ginsburg and Lowenstam, 1957) provided by the seagrass blades. The difference in modes between the grass-stabilized and blowout floor sediments supports this contention. The blowouts are thus characteristic of elevated seagrass beds or portions of seagrass beds, and the erosional processes associated with blowout migration are interpreted as tending to maintain the equilibrium bottom profiles (Johnson and Eagleson, 1966) that would exist in the absence of grass cover. The fact that cobble framework substrates and the *Porites* rubble flats at Bath are generally shallower than the cobble-sand and predominantly sand substrates presumably reflects higher bottom velocities required to erode the larger particles predominating in these substrates. The rubble layer present below the mainly sand-sized sediments of cobble-sand and predominantly sand substrates is presumably stable with respect to the wave regime, and in fact may be accreting at a relatively high rate in comparison to sea level changes with concurrent elevation of the seagrass carpet. The estimated rates of accretion of the rubble layer at Bath and Grand Bay south, of the order of 3—4 mm/year, are significantly greater than the average rate of sea level rise, about 1 mm/year (Milliman and Emergy, 1968) over the last 5 000 years. The high density of blowouts in regions where a rubble layer is present is evidence of the highly metastable position of the sand-sized sediments of the seagrass carpet, and suggests that considerable shallowing has occurred in comparison to regions of sand substrates not underlain by a rubble layer.

*Ecological and geological implications*

Blowouts occurring at Bath and Grand Bay south, and those illustrated by Ball et al. (1967), Kelly (1969) and Kelly and Conrod (1973) occupy of the order of 10—20% of the seagrass bed areas. It can readily be appreciated that in such areas migration of the blowouts must result in periodic disruption of the major part of the seagrass community and overturn of associated sediments.

The most important effect of this instability on the ecology of the seagrass community is to limit seral development of the community. The absence in the region of the blowouts of a well developed epifauna and flora, which is characteristic of advanced stages of seral development of the seagrass community (Margalef, 1963; Welch, 1965), is evidence of this phenomenon. *Syringodium* frequently precedes *Thalassia* in the colonization of grass-free areas, apparently because of its greater tolerance of unstable, somewhat aerobic substrates and higher rhizome growth rates (discussed above), but *Thalassia* is invariably the terminal dominant of the Caribbean seagrass community in shallow water (Welch, 1965). The persistence of *Syringodium* at Bath, and areas such as Grand Bay south can be attributed directly to recurrent regression of the seagrass community resulting from erosion associated with blowouts. Where blowouts are closely spaced, the bottom is never stable long enough for *Thalassia* to become established and pure stands of *Syringodium* are maintained.

Observations on the distribution of organisms in relation to blowouts are particularly useful as they allow some estimation of the time and stability required for organisms to colonize the substrate. For example, observation of *Udotea cyathiformis* on the blowout floor, *Halimeda incrassata* on grass stabilized bottom between blowouts, and *Halimeda opuntia* outside of blowout regions suggests that times and/or substrate stabilities required for these organisms to colonize the substrate increase in the order *Udotea*, *H. incrassata* and *H. opuntia.* The estimates of the times between erosion and recolonization by *Thalassia* and *Syringodium* are also examples of this; these carry the proviso of course that colonization is by extension from pre-existing stands.

Lateral erosion associated with blowout migration will have two important effects on the geologic record: (1) it will disrupt sedimentary structures, such as mollusc shells in growth positions, characteristic of the intact seagrass carpet; and (2) it will result in deposits coarser than those characteristic of the seagrass carpet. Blowouts would be expected to be most common during periods of slow sea level rise when gross rates of sedimentation in coral reef ecosystems are greatly in excess of net rates of sedimentation (Chave et al., 1972). Under conditions in which a rubble layer is formed, a conglomerate type of deposit quite unlike the calcarenite of the seagrass carpet, would result.

Particularly diagnostic of these processes in a limestone would be the occurrence within a calcarenite of lenses of conglomerate containing partially abraided skeletons of molluscs and corals characteristic of the seagrass bed fauna. This might be overlain by intertidal type deposits, for example coralline algae or sands (associated with *Halodule* growth) as occurs on the *Porites* rubble flats at Bath. It should be noted that a conglomerate deposit might also result from lateral accumulation of debris as at the seaward face of the Bath seagrass bed. Both types of processes may have contributed to formation of the *Porites* rubble flats at Bath.

Some possible examples of these types of deposits in the geologic record occur in the late Pleistocene reef complexes in northern Barbados. Nearshore and very shallow biofacies which are interpreted as ancient seagrass communities contain many of the sedimentary elements described herein (James, 1972). In the rock record these deposits range from thick (15 ft) accumulations of *Porites furcata* with scattered small heads of *Eusmilia*, *Agaricia*, *Siderastrea* and *Manicina* to lenses and beds rich in *Porites furcata* and molluscs such as *Strombus*, *Bulla* and *Codakia.* Within these beds are also concentrations of rhodiles whose nucleus is most often one of the above molluscs or *Porites furcata.*

Whether or not blowouts are common in seagrass beds in regions other than the Caribbean remains to be reported. It seems reasonable to expect they would occur in beds of other members of the *Halodulo—Thalassietea* (Den Hartog, in press) formation. At least for the Caribbean it is evident that blowouts play important roles in the seral and physiographic development of the seagrass beds.

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