PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Sedimentation Trends in the Lee of Outer (Ribbon) Reefs, Northern Region of the Great Barrier Reef Province

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Sedimentation trends in the lee of outer (ribbon) reefs, Northern Region of the Great Barrier Reef Province

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[Plates 1 and 2; pullout 1]

A programme of surface sediment sampling, continuous high resolution seismic reflexion profiling, and side-scan sonar surveys, carried out in the Northern Region of the Great Barrier Reef Province between latitudes 14° 31′ S and 14° 45′ S, extending between the continental shelf edge and a line of mid-shelf continental islands, has demonstrated the diversity of sedimentation factors controlling sediment distribution patterns, and revealed complex petrological variations and unsuspected stratigraphic relations.

The granulometric characteristics of many inter-reef sediments are imparted chiefly by mixing, whereas sorting under high energy conditions, and the effectiveness of the 'Sorby Principle' are primarily responsible for the granulometric characteristics of the reef-top sediments. Terrigenous end-members of mainland and/or continental island provenance are important on the southwestern margin of the area, but *Halimeda* debris dominates sediments coinciding with luxuriant *Halimeda* growth on back-reef 'banks' and ridges.

A major disconformity indicating marine regression and shelf emergence is the most prominent seismic reflector, which outcrops near Cook's Passage to coincide with the rocky, current swept, seabed at −45 m, and which is incised near the shelf edge to −69 m. The succeeding transgression resulted in the filling of the incised channels with sediment, followed by rapid sedimentation in the back-reef area and the establishment of platform reefs on this surface. Periods of still-stand or minor regressions are indicated by marine terraces at −22.5 m and −30 m, and by erosion surfaces within back-reef sedimentary deposits and reef masses. The seismic profiles suggest that the Holocene sedimentation pattern is a repetition of an ancient trend.

1. Introduction

A general picture of the nature and distribution of sediments throughout the entire Great Barrier Reef Province has been provided by Maxwell (1968*a*). Factors effecting and affecting sedimentation, reef distribution and form, have been discussed in general terms by a number of workers (see, for example, Maxwell 1968*a*, 1973; Maiklem 1970; Fairbridge 1950, 1967; Maxwell & Swinchatt 1970; Frankel 1974; Orme, Flood & Ewart 1974). These include the apparently restricted dispersal of reef-derived sediment, the importance of the mixing of sediments from different sources in determining sediment facies characteristics and distribution, and the influence of relict sediments (Maxwell 1968*b*) related to eustatic changes of sea level. The implications of the granulometric characteristics of sediments from both the reef-top (Maxwell, Jell & McKellar 1964; Orme *et al.* 1974; Flood & Scoffin 1978, this volume) and inter-reef environments (Flood, Orme & Scoffin 1978, this volume) have received some consideration. Elsewhere, namely British Honduras, the influence of inherited features on reef configurations and present sediment facies patterns has been demonstrated (Purdy 1974*a*, *b*).

In the area here investigated, the narrow continental shelf is characterized by a well developed almost continuous barrier of shelf edge reefs, a mid-shelf zone of continental islands, platform reefs, a bathymetrically complex back-reef area, and a general meridional arrangement of sediment facies, which reflects the relative importance of terrigenous sediment from the mainland and carbonate production on the outer shelf. Consequently a complex interrelation between bathymetric, hydrological, ecological and provenance factors could be expected.

The primary objectives of this study were, therefore, to investigate the petrology of the sediments, to determine the nature and importance of provenance and dispersal factors, to obtain a more precise picture of the bathymetric diversity of the area, to examine any evidence of eustatic sea level changes and assess the importance of inherited features upon present facies distribution,

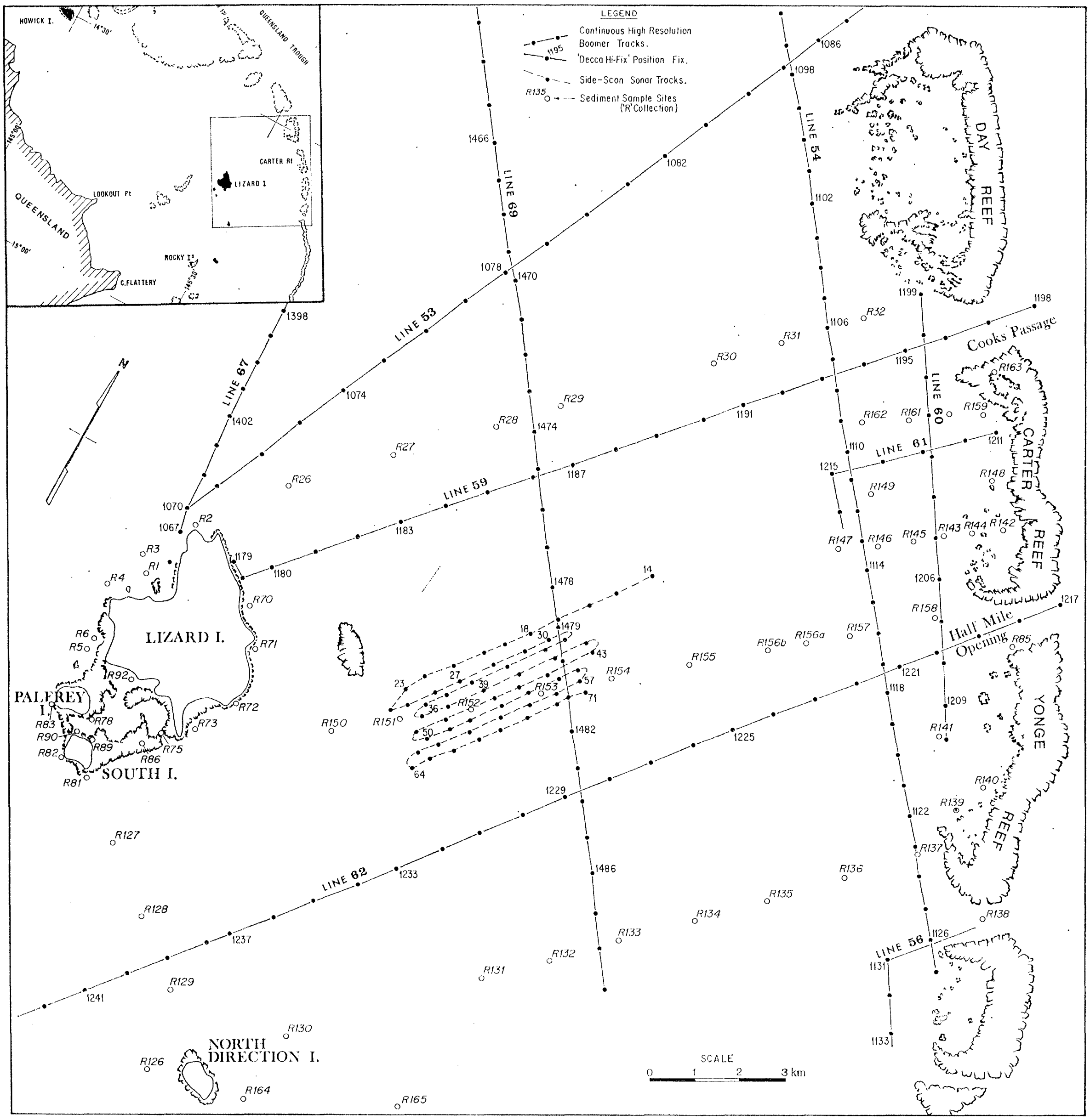

FIGURE 1. Map of the outer shelf near Lizard Island showing sediment sample sites, the locations of continuous seismic profiling traverses, and side-scan sonar tracks.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

and finally, to determine whether present sedimentation follows trends established during pre-Holocene times.

This paper presents preliminary results from part of the area investigated. It is concerned with the outer shelf area which lies between 14° 31′ S and 14° 45′ S, extending between the continental shelf edge and a line of continental islands at approximately 145° 25′ E (see figure 1).

2. General characteristics of the area

A line of shelf edge reefs, comprising Day, Carter, and Yonge reefs, together with an unnamed reef to the south, forms an almost continuous barrier between the Queensland Trough and the continental shelf, and restricts the exchange of Coral Sea and shelf waters. These ribbon reefs are separated by deep, narrow passages, namely, One-mile Opening, Cook's Passage, Half-mile Opening and Cormorant Pass.

Carter Reef is approximately 5.5 km in length and 1–1.5 km in width; its dimensions are similar to those of the adjacent ribbon reefs. All descend steeply to the Queensland Trough and show a zonation which includes outer moat, reef crest, inner moat, sanded zone, and zone of coral heads, running parallel with their shelf edge orientation (Fairbridge 1950).

Fringing reefs are developed around the continental islands and extend between Lizard, Palfrey and South Islands to enclose a shallow lagoon.

Shelf relief between Lizard Island and the shelf edge is diversified due to reefal shoals (e.g. Petricola, Stewart) and submarine banks and ridges. These banks occur at a fairly uniform depth of approximately 25 m with intervening channels at −37 m. The deepest part of the shelf lies at −69 m, where the rocky seabed is channelled at the lagoonal approaches to Cook's Passage. To the northeast the continental slope descends very steeply to the Queensland Trough.

3. Methods and techniques

Sediment samples were systematically collected from the seabed, spaced at approximately 1.5 km intervals along traverses, which coincided with some of the seismic profiling tracks. Closer sampling was undertaken in the vicinity of reefs and islands in the expectation that in such bathymetrically and environmentally diverse areas more subtle variations in sediment composition might be disclosed. In shallower areas the samples were collected directly by diving, in the deeper areas mechanical grabs were used. Alcohol was added as a preservative to some samples. Others were kept under refrigeration until treated with hydrogen peroxide to remove carbonaceous matter in preparation for sieve analysis.

Each sample was sieved using a 0.25 ϕ set of U.S. Standard sieves and each fraction was scrutinized microscopically in order to ascertain whether preferential size grades were adopted by certain grain types, which might in turn relate to ecological and/or dispersal factors.

Continuous seismic profiling with the use of a high resolution boomer was carried out along tracks running over and along the shelf forming a grid pattern in order to examine sub-bottom facies relations and shallow internal structures. The leeward side of Carter Reef and the approaches to Cook's Passage were given particular attention.

The equipment used comprised a 3.5 kV, 500 J triggered capacitor power supply unit driving either a Huntec ED10 high resolution boomer type device (loaned by N.E.R.C.) or a slightly smaller similar device (Sargent 1969). The reflexion seismic records were produced in real time on wet Alphax 'A' paper 9 inches wide (*ca.* 23 cm). A 10 element E.G. & G. hydrophone streamer, or similar device (also loaned by N.E.R.C., London), was coupled to a Khron-hite Model 3100 filter, usually set to a band pass of about 0.5–5 kHz, in turn coupled to an E.G. & G. 254 graphic recorder. Trigger rates were usually 1–2 p.p.s. Both intense swell and surface chop generated by continuous SE winds prevailed throughout the survey, to the extent that a substantial proportion of the available sea time was not usable for seismic reflexion work.

A side-scan sonar survey was carried out to the southeast of Lizard Island, individual traverses being run at a spacing of 250 m intervals to produce a map of the seabed in an area known to be occupied by *Halimeda*-covered submarine banks and ridges. Decca Hi-fix control was employed as a means of accurate position fixing, fixes being taken at 5 min intervals along all seismic and some sediment sampling traverses.

4. Sediments and sedimentation factors

The boundaries of the area with which this paper is concerned lie mainly within the limits of the 'High Carbonate Facies' and 'Impure Carbonate Facies' (Maxwell 1968*a*), the 'Transitional Facies' and the 'Terrigenous Facies' being of limited distribution. This preliminary account incorporates data from 70 systematically collected sediment samples.

Cursory examination indicated the presence of a number of subfacies, those occurring in the 'High Carbonate Facies' containing usually less than 5% insolubles, but others, particularly those strongly influenced by mainland and/or 'Continental Island' provenance, containing up to 78% insolubles (e.g. R4 and R128).

The sediments display great diversity in terms of both grain types and grain size characteristics. Their end-members may be considered broadly in terms of the insoluble (terrigenous) and the soluble (biogenic-carbonate) components. The insoluble end-members comprise bluish-grey mud, which occurs in most sediment samples. This may constitute only a very small proportion of the 'High Carbonate Facies', but is dominant in samples from the southwestern margin of the area where it reaches 58%. It is believed to reflect mainland provenance. Terrigenous quartz, feldspar, mica, heavy minerals and rock fragments are quantitatively important near the granitic continental islands (e.g. R5).

The carbonate grains are biogenic and predominantly skeletal, consisting of *Halimeda*, gastropods, pelecypods, foraminiferans, coralline algae, corals, encrusting and branching bryozoans, echinoid plates and spines, worm tubes, and spicules. Although representatives of each of these allochem types occur in most sediment samples there are considerable variations within these broad categories in terms of numbers of individuals and species, especially in the case of foraminiferans and molluscs. Acquired grain morphology is also very variable in relation to grain size and distribution. Furthermore, some worn skeletal grains are strongly iron stained and show signs of solution.

An investigation of the complex variations in composition of the sediment in terms of grain types and grain size characteristics is in progress and the following general account illustrates the salient characteristics of the end-members, their distributions, and implications regarding sedimentation in this part of the Great Barrier Reef Province.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

(*a*) *Distribution of end-members*

The fine-grained insoluble end-member, the bluish-grey mud, increases in quantity towards the southwestern margin of the area (see figure 2). Other detrital end-members, in which quartz is dominant, are conspicuous in sediments fringing the continental islands, especially where the masking effect of coral reef debris is not marked. They form dominant sediment components in areas to the northwest (leeward side of Lizard Island giving rise to a distinct quartz-rich terrigenous subfacies). Quartz is present also in the 'High Carbonate Facies' to the east of Lizard Island; it occurs even in samples taken from close to the shelf edge, but here it is present within

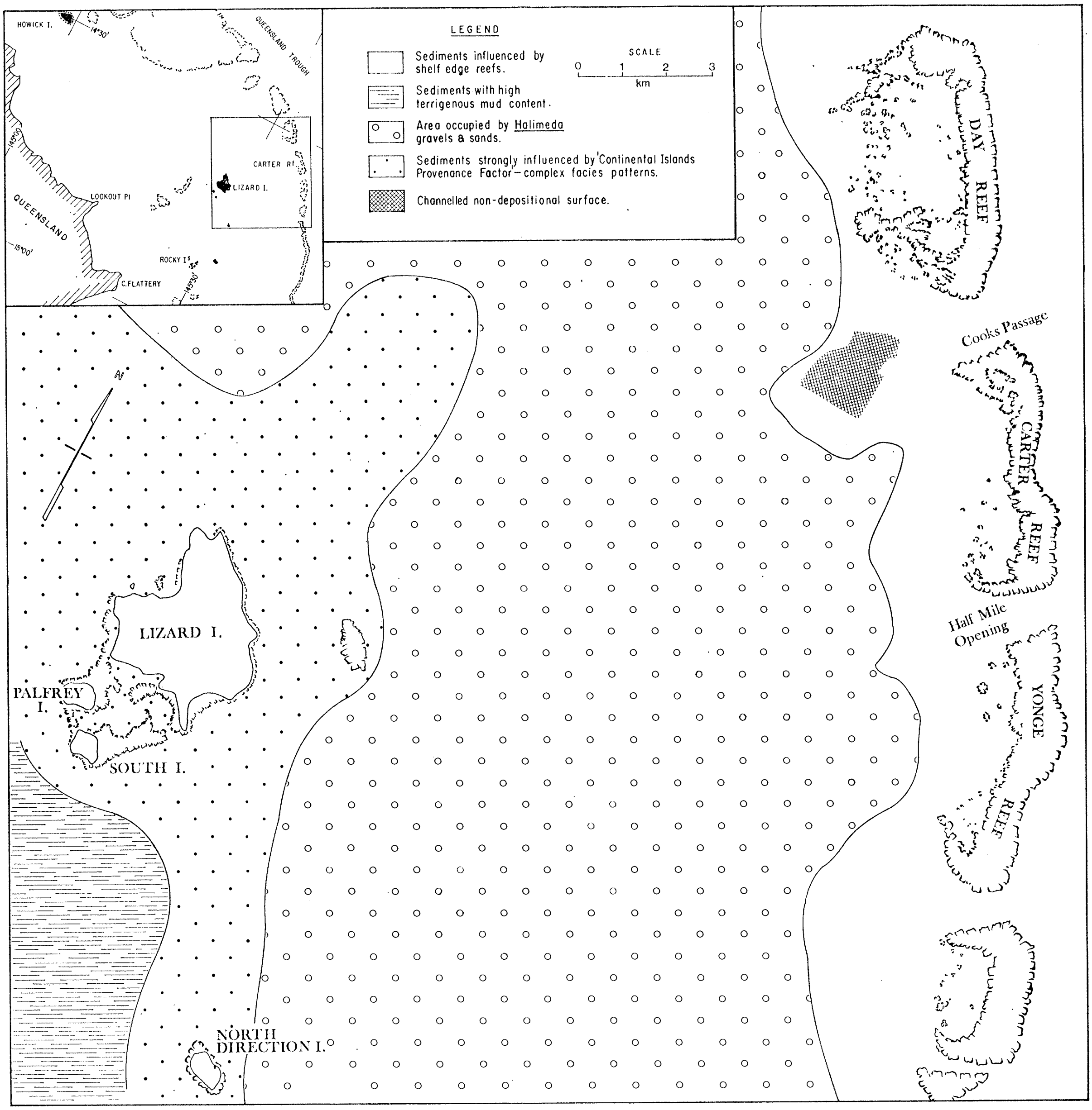

FIGURE 2. Map of the outer shelf near Lizard Island showing the general form of the sediment distribution pattern, and the salient source factors.

a restricted size range (2.5–3 ϕ), whereas a much wider size range of quartz (0–3.25 ϕ) occurs in sediment samples from the vicinity of Lizard Island.

The decrease in terrigenous quartz eastward is abrupt, so that over much of the 'back-reef' area it is sparse. Such a distribution pattern of igneous quartz shows the influence of continental island provenance, and of Lizard Island in particular. It also indicates the selective dispersal of the more readily transported quartz grades and the dilution effect of biogenic carbonate in the 'back-reef' zone.

Halimeda debris is ubiquitous, and is the principal constituent forming the sediments over most of the back-reef area. Unbroken plates are abundant in back-reef sediments and also in some reef top samples of the shelf edge. *Halimeda* debris is also present in the coarse fractions of the sediments fringing Lizard Island, and worn fragments occur in the terrigenous facies along the southwestern margin of the area. The acme of production of this component is associated with the extensive *Halimeda* 'meadows' which cover the submarine 'banks' of the back-reef area. Some *Halimeda* debris is probably transported away from this site by tidal currents.

Small gastropods are present in all samples and are well preserved in most. Molluscs are the dominant allochems in some areas, e.g. the windward side of Lizard Island (R71 and R75); they are also abundant in reef-top sediments and are present in gravels and sands of the *Halimeda* meadows. In most samples examined there is a general lack of abrasion of the small gastropods, which suggests that their occurrence more or less reflects an ecological situation.

The contribution made by foraminiferan tests is appreciable and represents a fauna which includes *Baculogypsina*, *Marginopora*, *Calcarina*, *Textularia*, *Alveolinella*, *Heterostegina*, *Amphistegina*, *Operculina*, and *Spiroloculina*. The foraminiferans from shelf edge reefs and from the fringing reefs of the continental islands are particularly varied and abundant. They are also conspicuous in sediment from the back-reef *Halimeda* 'banks', and some, particularly abraded *Marginopora* tests, are common in sediments from the terrigenous facies.

Coral-stick gravel is associated with reef-top deposits of the shelf edge and with the fringing reefs. However, coral debris is not common in the *Halimeda* sediments of the back-reef banks. Furthermore, many sediment grades in deposits adjacent to coral reefs are devoid of recognizable coral debris, which may be due to the discontinuous range of particle sizes produced by the breakdown of coral skeletons, the 'Sorby Principle' of Folk & Robles (1964).

The contribution made by coralline algae to sediment is small and becomes noticeable only on shelf edge reefs and the fringing reefs of continental islands.

(*b*) *Differentiation of sedimentary facies*

On the basis of the relative proportions of carbonate and terrigenous end-members present, a primary distinction may be made between High Carbonate Facies, Impure Carbonate Facies, Transitional Facies, and Terrigenous Facies, in the manner of Maxwell (1968*a*). Subdivision of these facies is possible according to dominant types of terrigenous particles and/or dominant carbonate allochems present. The frequency curves (figure 3) and cumulative curves (figure 4) illustrate the considerable granulometric differences which exist between representative samples of each subfacies.

(i) *High Carbonate Facies*

Halimeda *gravels and sands*. These represent the central part of the 'back-reef' environment, characterized by submarine banks and ridges, e.g. samples R154 and R133. This subfacies occupies most of the back-reef area and consists of whole and fragmented *Halimeda* plates, some gastropods and pelecypods, numerous and varied foraminiferans, together with minor components which include worm tubes, bryozoans, echinoid spines, spicules, and a minor component of blue-grey mud. A few quartz grains are also present. Variations occur between different samples of this subfacies according to the degree of wear displayed by allochems, the

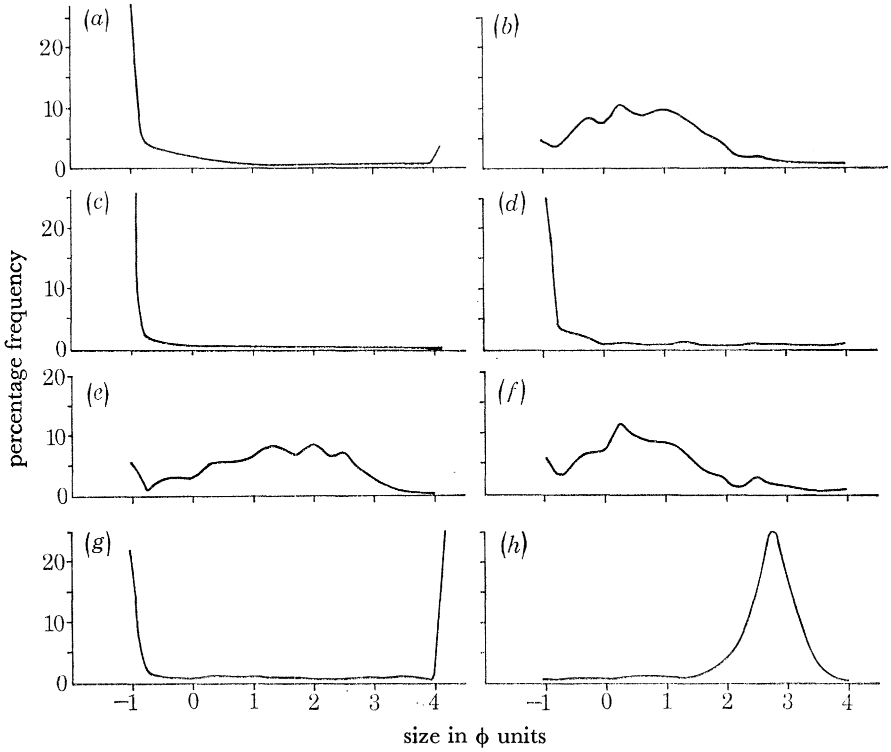

FIGURE 3. Frequency curves of representative samples of the main sediment types, illustrating the considerable variations in their granulometric characteristics. (*a*) R163: this sample is from a reef-top pool in the coral zone of Carter Reef. The bimodal curve represents a poorly sorted (σ = 1.50 ϕ) coral stick gravel to which *Halimeda* debris, foraminiferans and molluscs have been added; 71 % of the sample was coarser than −1 ϕ (M_z = −1.3 ϕ, Sk_I = +0.03, K_G = 2.66). (*c*) R133 and (*d*) R154: these represent the common sediment type of the back-reef lagoon which is dominated by luxuriant *Halimeda* growth. They are coarse grained, unimodal, very well sorted to moderately sorted, negatively skewed *Halimeda* gravels. For R133, 93 % was coarser than −1 ϕ (M_z = −2.30 ϕ, σ_I = 0.03 ϕ, Sk_I = −0.89, K_G = 0.96) and for R154, 80 % was coarser than −1 ϕ (M_z = −1.67 ϕ, σ_I = 0.65 ϕ, Sk_I = −0.22, K_G = 0.80). They reflect the major *in situ* contribution of *Halimeda* debris in this region mid-way between the shelf edge and the mid-shelf continental islands (see figures 1, 2 and 5, and plate 1, figure 5). (*h*) R5: quartz-rich terrigenous subfacies. Unimodal, well sorted (σ_I = 0.49 ϕ), coarse-skewed (Sk_I = −0.15), leptokurtic (K_G = 1.16) sand (M_z = 2.77 ϕ). The mode in the fine sand and very fine sand grades reflects the importance of terrigenous grains, chiefly igneous quartz derived from Lizard Island (see plate 1, figure 6). (*g*) R128: terrigenous facies, high mud subfacies. The bimodality of this curve is a reflexion of the mixing of terrigenous components from the mainland with coarse grained carbonate debris from both *in situ* post-mortem contributions, and transported allochems; 21 % was coarser than −1 ϕ and 57 % finer than 4 ϕ. Sorting is poor (σ_I = 6.8 ϕ). R128 is representative of many samples from the southwestern margin of the area (M_z = 3.5 ϕ, Sk_I = 0.00, K_G = 0.61). (*e*) R71 and (*f*) R75. High Carbonate Facies, molluscan–foraminiferan subfacies (see plate 1, figures 1 and 2). R71 is from a site adjacent to the fringing reef on the windward side of Lizard Island, and R75 is from the entrance to Lizard Island Lagoon. Their polymodal curves relate mainly to grade sizes favoured by post-mortem contributions. R71 has an admixture of terrigenous quartz (M_z = 1.23 ϕ, σ_I = 1.29 ϕ, Sk_I = +0.06, K_G = 1.09). R75 (M_z = 0.50 ϕ, σ_I = 1.11 ϕ, Sk_I = +0.38, K_G = 1.64). (*b*) R148 is from the deeper water of the 'sanded zone' in the lee of Carter Reef. It has a polymodal curve in consequence of its diverse components consisting of coarse grained coral fragments, a variety of molluscs and foraminiferans, together with some *Halimeda* debris. (M_z = 0.50 ϕ, σ = 0.95 ϕ, Sk_I = −0.11, K_G = 1.43).

abundance and variety of foraminiferans, and in the relative proportions of minor constituents. All samples are very well sorted and unimodal, owing to the dominance of *Halimeda* debris, which points to the importance of ecological factors favouring the luxuriant growth of *Halimeda* in the back-reef area. The characteristics of this subfacies are promoted largely by *in situ* contributions from *Halimeda* (see figures 3 and 4, and plate 1, figure 5).

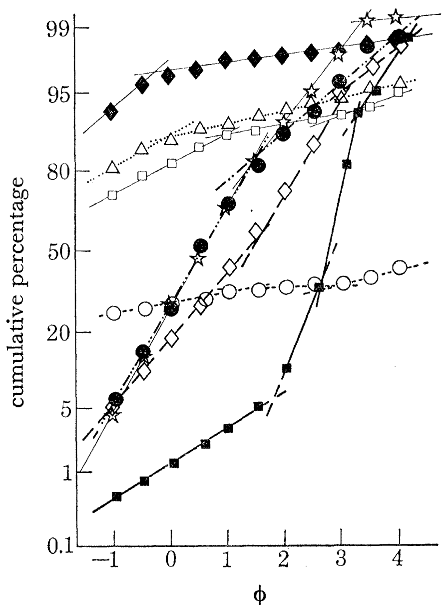

Figure 4. Cumulative curves for samples of the main sediment subfacies. The curves illustrate the considerable range of mean grain size and sorting, their wide separation indicating the great disparity between samples in terms of the relative importance of grain size populations. The high proportion of mud in R128 (○) ('Terrigenous Facies', 'high mud subfacies') distinguishes this from other curves. R5 (■) ('Terrigenous Facies', 'quartz-rich subfacies') shows marked inflexions at 2 ϕ and 3.1 ϕ, which may, to some extent, correspond with discrete grain size populations separated in response to different transportation modes, coarser than 2 ϕ representing the traction load, 2 ϕ to 3.1 ϕ representing saltation transport, and material finer than 3.1 ϕ approximating to the suspension load. The high gravel content of R133 (◆) and R154 (△) (the *Halimeda* dominated subfacies), and of R163 (□) (coral/algal subfacies) may be lag deposits, reflecting in part the influence of currents of removal. R75 (●) and R71 (◇), from the entrance to Lizard Island Lagoon, and a site near the windward fringing reef of Lizard Island respectively, are dominated by small mollusc shells and foraminiferan tests. ☆, R148.

Description of plate 1

Figure 1. Sample R75, from the entrance to Lizard Island Lagoon showing characteristic allochems: small pelecypods, gastropods, *Alveolinella* and *Marginopora*. An echinoid spine and a few small *Halimeda* fragments are also present.

Figure 2. Sample R71, similar in composition to R75. Mollusc shells and foraminiferans are conspicuous. *Halimeda* and bryozoan fragments are also present, together with a few small quartz grains.

Figure 3. Sample R148, from the sanded zone: Carter Reef. Entirely composed of carbonate grains, the foraminiferans and small gastropods being conspicuous. *Halimeda* fragments are also present.

Figure 4. Sample R4 (Terrigenous Facies, quartz-rich subfacies). The coarse fraction consists of worn, fragmentary mollusc shells and foraminiferan tests. The majority of the grains are quartz.

Figure 5. Sample R133, from the *Halimeda* covered banks. Gastropod shells and bryozoan fragments are also present.

Figure 6. Sample R 5 (Terrigenous Facies, quartz-rich subfacies). Well sorted sediment dominated by quartz. Some grains are iron stained.

The bar scale in figures 1 to 5 represents a length of 2 mm, and that in figure 6 represents 1 mm.

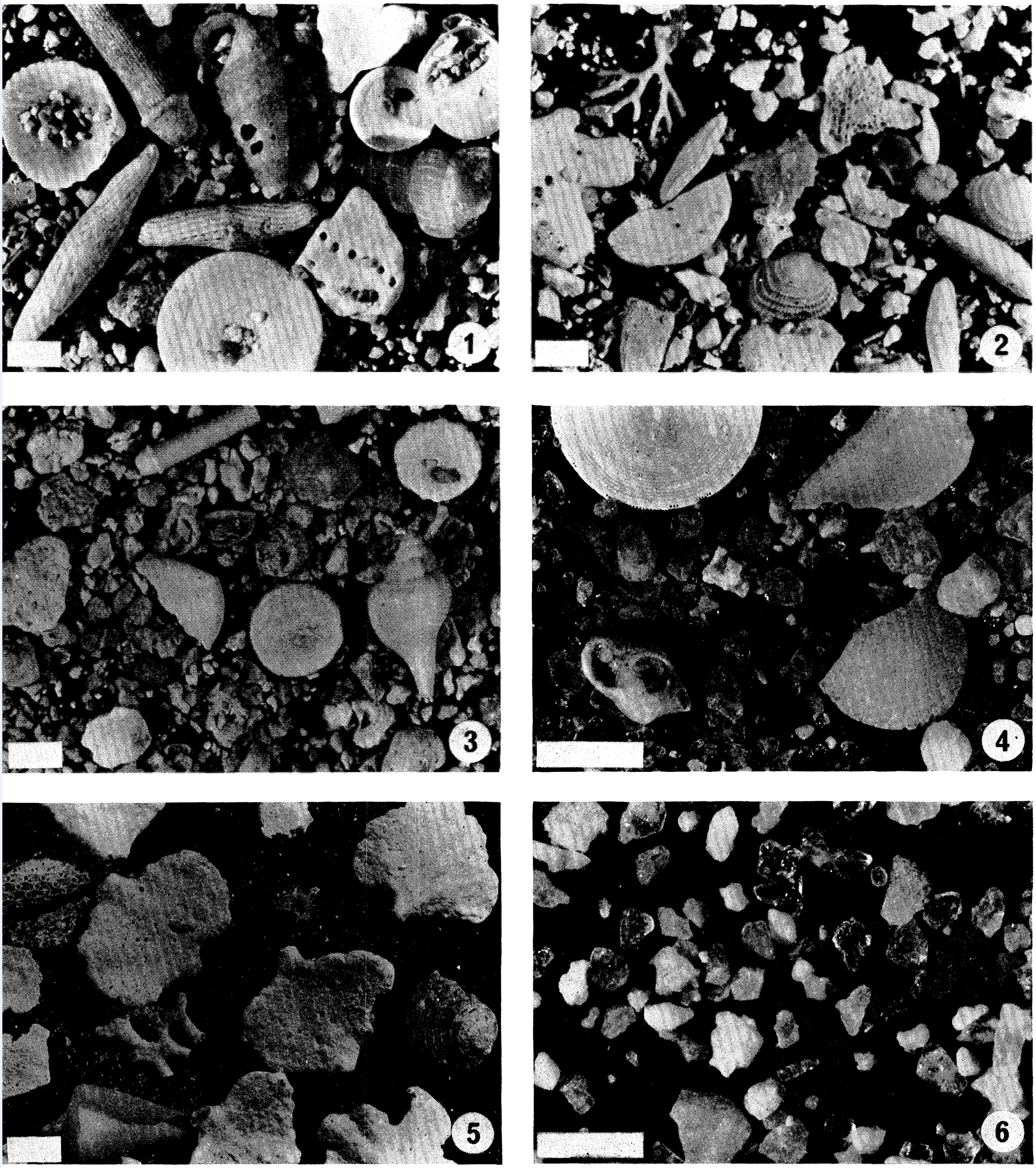

PLATE 1. For description see opposite.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

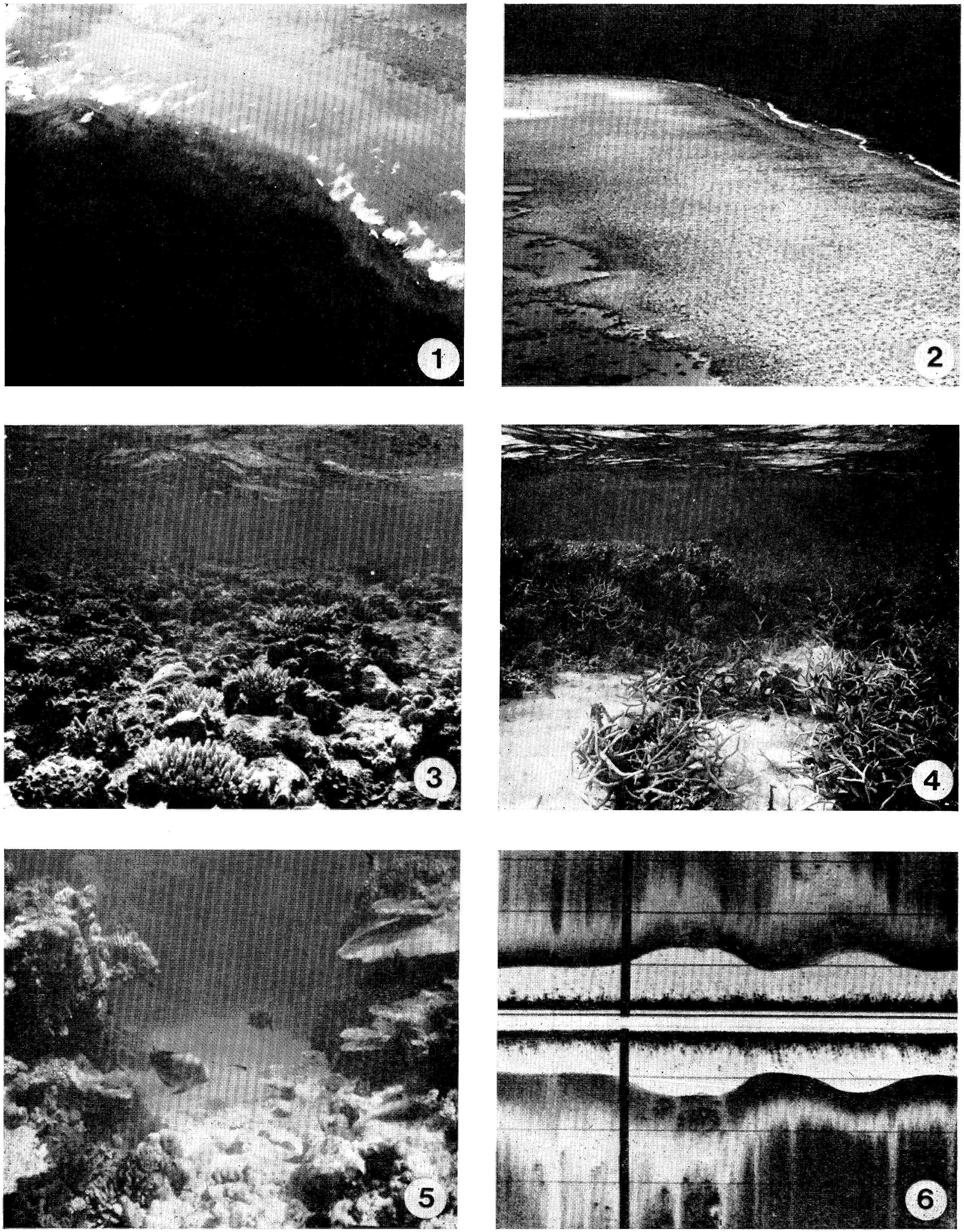

PLATE 2. For description see opposite.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Coral–algal gravels and sands. These represent the reef-top environment, particularly at the shelf edge, e.g. R163. This subfacies is restricted to reef-top situations. It is dominated by coral stick gravel with abundant *Halimeda*, coralline algal fragments, molluscs and foraminiferans. Worm tubes and bryozoans are among the minor components. Most samples of this subfacies are lag deposits but sample R163 (see figures 3 and 4) contains an extensive range of sand grade allochems, which washed into and were retained in the reef top pool from which the sample was collected. Of the sample, 71 % coarser than $-1\ \phi$ is mostly coral stick gravel.

Molluscan–foraminiferan gravels and sands. These represent a shallow lagoonal environment adjacent to reefs. Gastropods and pelecypods are dominant allochems with abundant and varied foraminiferans (compare R71, R75 and R148, figures 3 and 4, and plate 1, figures 1 and 2). Some coralline algal and coral fragments are present, and some samples also have a minor component of worn *Halimeda* fragments. Echinoid debris is conspicuous, and blue-grey mud is present. Some detrital quartz grains occur in this subfacies near to the continental islands. A conspicuous feature of the sediment adjacent to Lizard Island is the iron staining and partial solution of many contemporary allochems. This poorly sorted, polymodal sediment is characteristic near reefs and in Lizard Island Lagoon. The various modes of the frequency curve (figure 3) reflect variations in relative importance of the different allochems.

(ii) *Impure Carbonate Facies (35 % insolubles)*

Owing to an increase in the insoluble components, blue-grey mud and/or detrital quartz, the High Carbonate Facies passes to Impure Carbonate Facies near the southwestern margin of the region. Near Lizard Island, subfacies variations are complex.

(iii) *Transitional Facies*

Near the continental islands some sediments have intermediate proportion of insolubles due to mixing of terrigenous components (e.g. R1–58 % insolubles), mainly quartz and skeletal debris. This composition places such sediments in the Transitional Facies of Maxwell (1968*a*).

Description of plate 2

Figure 1. Oblique aerial view of part of Carter Reef from the northeast at half-tide, showing the fore-reef slope descending steeply to the Queensland Trough, and reef-top with 'sanded zone' at the top right hand corner of the photograph.

Figure 2. Oblique aerial view of the northern part of Carter Reef from the south showing the reef-top partly exposed at low tide, with algal zone, coral zone, and the leeward 'sanded zone' (bottom left). At the top right of the photograph is the deep water of the Queensland Trough, and the deep water to the left of this is Cook's Passage.

Figure 3. Underwater view of the coral zone at high tide: Carter Reef.

Figure 4. Underwater view of an *Acropora* thicket on the leeward side of Carter Reef near the margin of the 'sanded zone'.

Figure 5. A biogenic-sand covered channel in the 'Coral Zone' of Carter Reef.

Figure 6. Part of a side-scan sonar record of the seabed in an area of *Halimeda* covered banks to the southeast of Lizard Island (see figure 1). On each side of the centre line the record first shows a profile of the seabed, and thereafter extends continuously outwards as an oblique view of the seabed relief. The horizontal timing lines are spaced to show intervals of slant range of 25 m. Notable features are the uniform depth of the 'bank' tops, and their smooth profiles which contrast with the uneven 'rocky' surfaces of the hollows.

(iv) *Terrigenous Facies*

The insoluble end-members are of two types, namely blue-grey mud (mainland provenance) and coarse grained terrigenous end-members dominated by quartz (continental island provenance). The relative abundance of these two types of insolubles is the basis for subdivision of this facies.

Quartz-rich subfacies. The dominant grains are terrigenous, consisting of igneous quartz with feldspar, mica and tourmaline, together with some granite and beach-rock fragments. The biogenic carbonate allochems are fragmentary and worn, and consist of molluscs with a limited foraminiferan component which is chiefly represented by *Marginopora*. There is a lack of coral and coralline algal debris and only a limited number of *Halimeda* fragments. Many of the allochems are iron stained. It is a well sorted, unimodal sediment (see figures 3 and 4), with the mode in the fine sand range due to the dominant terrigenous end-members, particularly quartz. The inflexion in the cumulative curve at approximately 2 ϕ also reflects this characteristic. This subfacies is present, particularly to leeward of Lizard Island.

High mud subfacies. In the samples examined the blue-grey mud exceeds 50 %, and the quartz present is of a limited size range. The high gravel component (21 %) in the sample used to illustrate this subfacies (figures 3 and 4) comprises skeletal allochems dominated by molluscs, foraminiferans, and *Halimeda* fragments. Many of these are very worn and appear to have been transported. Coralline algae and corals are generally lacking.

(*c*) *Grain size distribution patterns*

In this outer shelf area there is a considerable diversity of bathymetric relief, sedimentary environments and ecological situations, in addition to complex provenance and dispersal factors, and owing to the varied interaction of such factors no simple interpretation of granulometric data will suffice. The cumulative curves (figure 4) illustrate the considerable granulometric differences which exist between sediments of this region. Marked points of inflexion on these curves separate discrete grain size populations, and indeed in R5, which is dominantly

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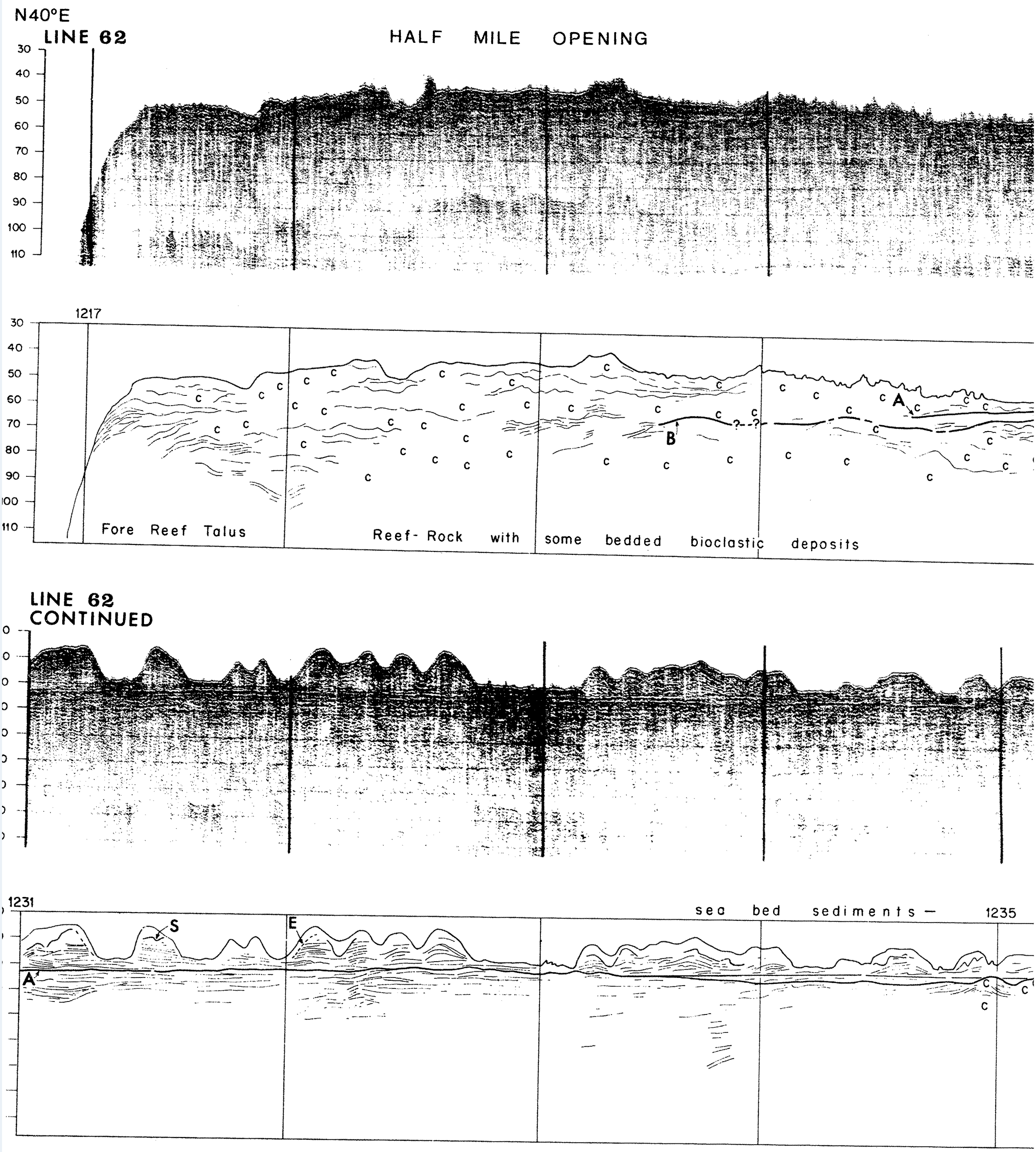
Description of figure 5

Figure 5. Continuous seismic reflexion profile (high-resolution boomer) and interpretation along line 62, extending southwestward from Half-mile Opening, and viewed from the northwest. (Note that the top of the record has been removed so that the profile begins at the 30 ms level, which is 22.5 m below sea level.)

A figure of 1500 m/s, centrally bracketing the seismic velocity of water, has been used throughout this work. The reproduction of original seismic profiles have reference timing lines at 0.01 s intervals corresponding to an interpreted depth scale of 7.5 m per timing line. The velocity used is not substantiated by drilling or seismic measurements. However, on the basis of extensive (substantiated) experience this figure of 1500 m/s is reasonable, and follows convention under the circumstances. An error of up to 10 % *under-estimation* of *sub-bottom* thicknesses is the most that is envisaged in deeply buried sections of these records.

The profile extends from the shelf edge to the mid-shelf region between Lizard Island and North Direction Island (see figure 1). It shows fore-reef deposits at the top of the continental slope, a reef mass below Half-mile Opening, a back-reef zone of interdigitating reef-rock and bedded deposits, and an accumulation of lagoonal deposits with low angle cross bedding, which overlie the most prominent sub-bottom reflector, disconformity 'A'. The varied nature of the seabed, ranging from the smooth profiles of the bedded back-reef 'banks' to the irregular surfaces of reef masses, is clearly shown. A rugged seabed exists in some hollows in the 'bank' area, but some of the apparent irregularity shown on the profiles is due to side reflexions from adjacent objects. A subsidiary reflector 'S' is an erosional surface which is detectable in part of the 'bank' deposits. It is partially obscured by the apparent reflector 'E', which follows the profile of the seabed, and which is really an instrumental effect. The marked depositional reflector 'R' probably represents a change of sediment type, a nodular or concretionary layer, or a hiatus, during which lithification of a uniform layer occurred.


N40°E
LINE 62
HALF MILE OPENING
1217
Fore Reef Talus
Reef-Rock with some bedded bioclastic deposits
A
B
LINE 62 CONTINUED
1231
sea bed sediments —
1235
S
E
A'

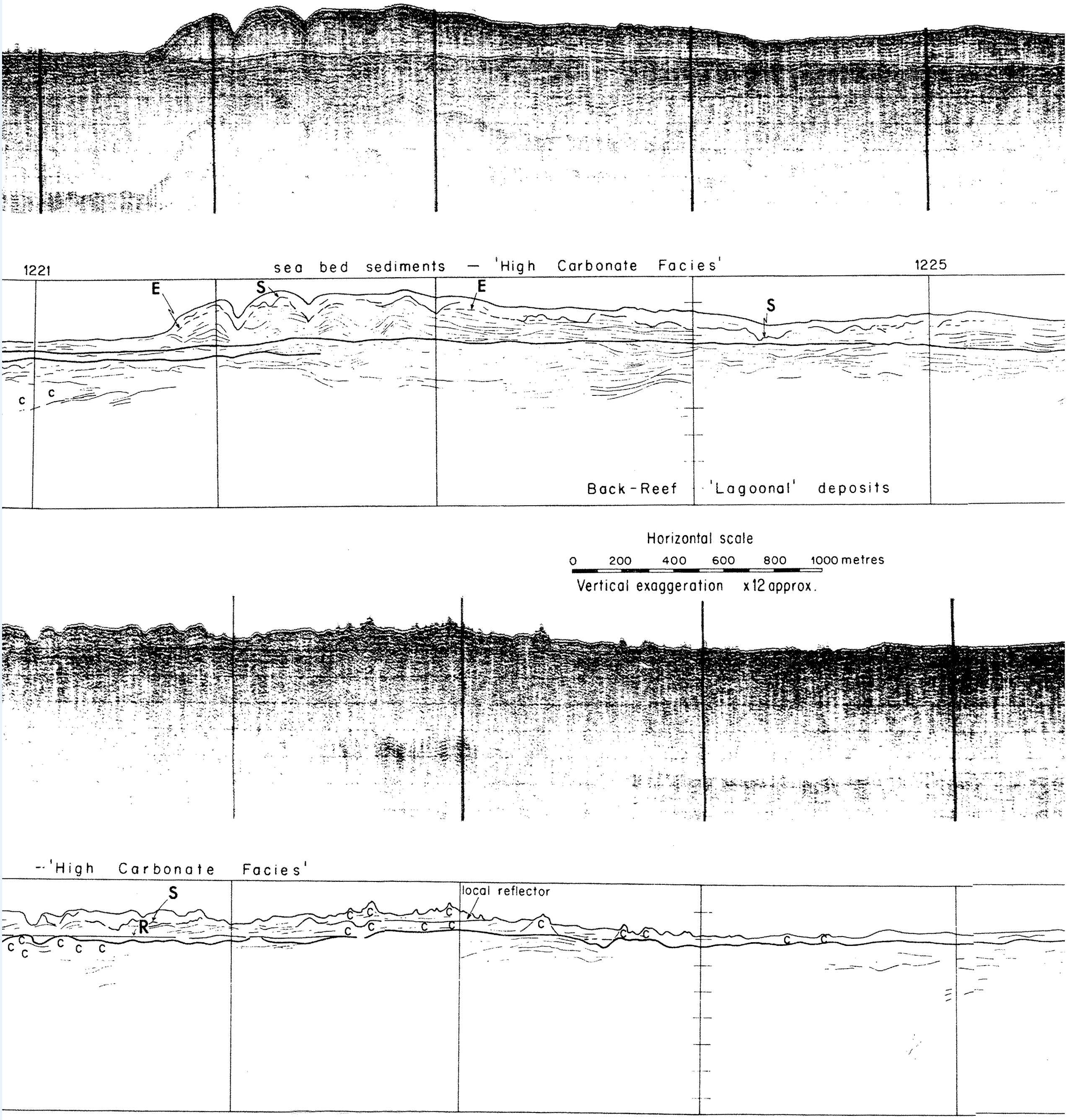
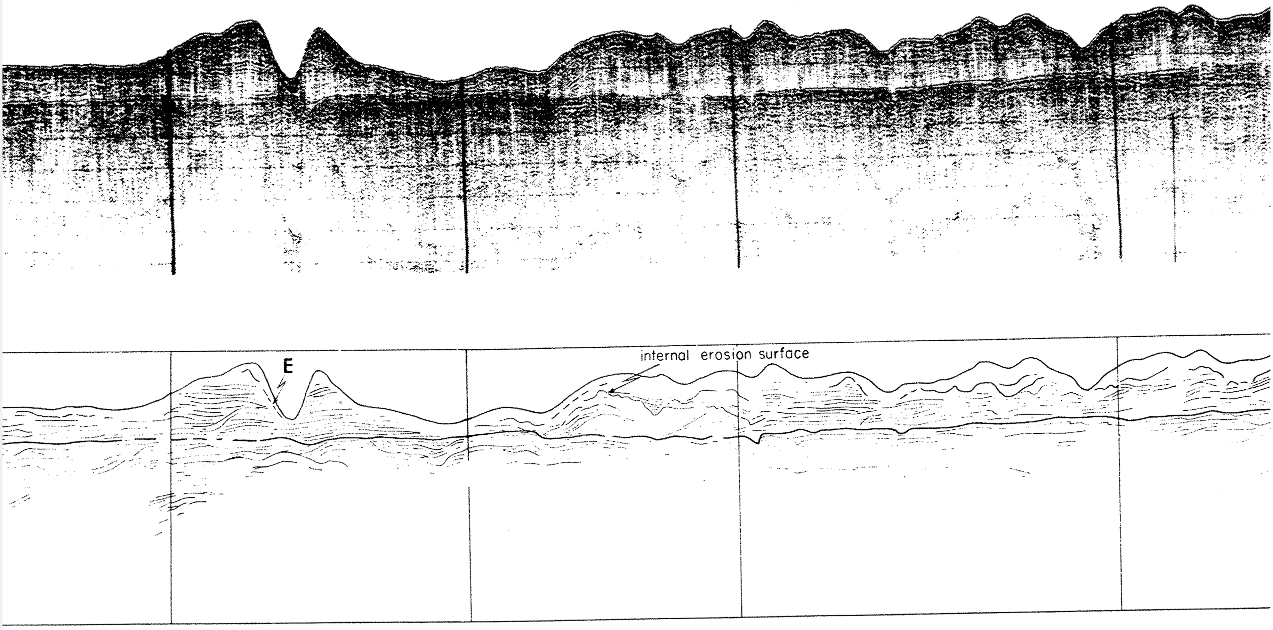
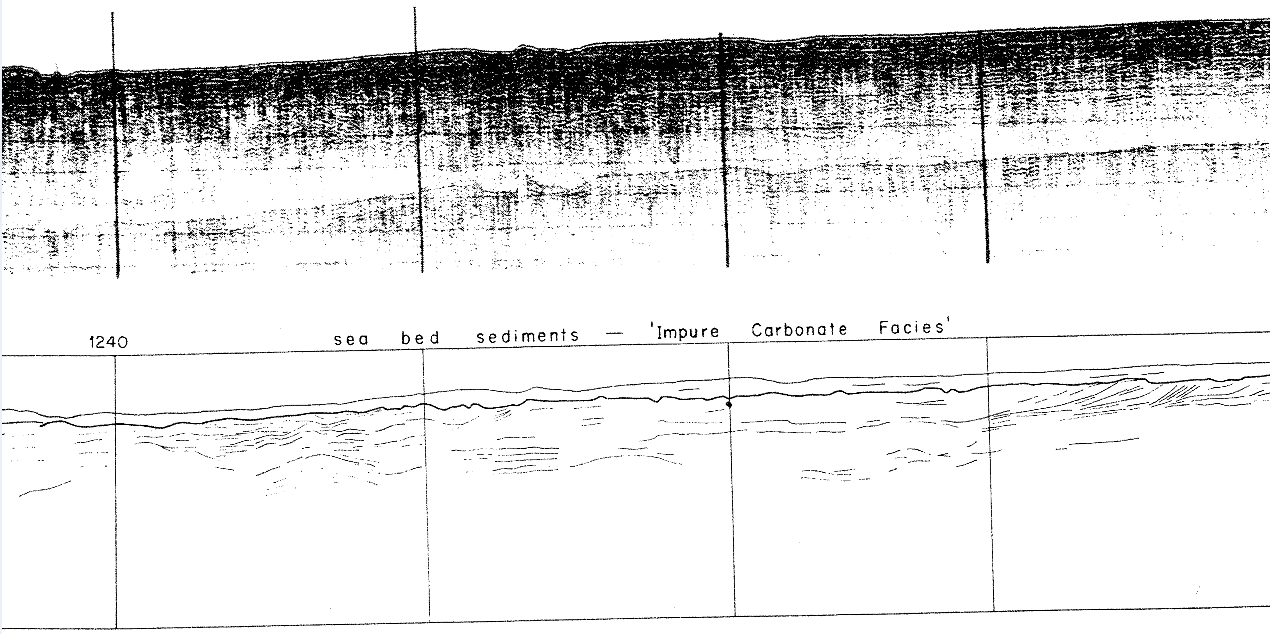
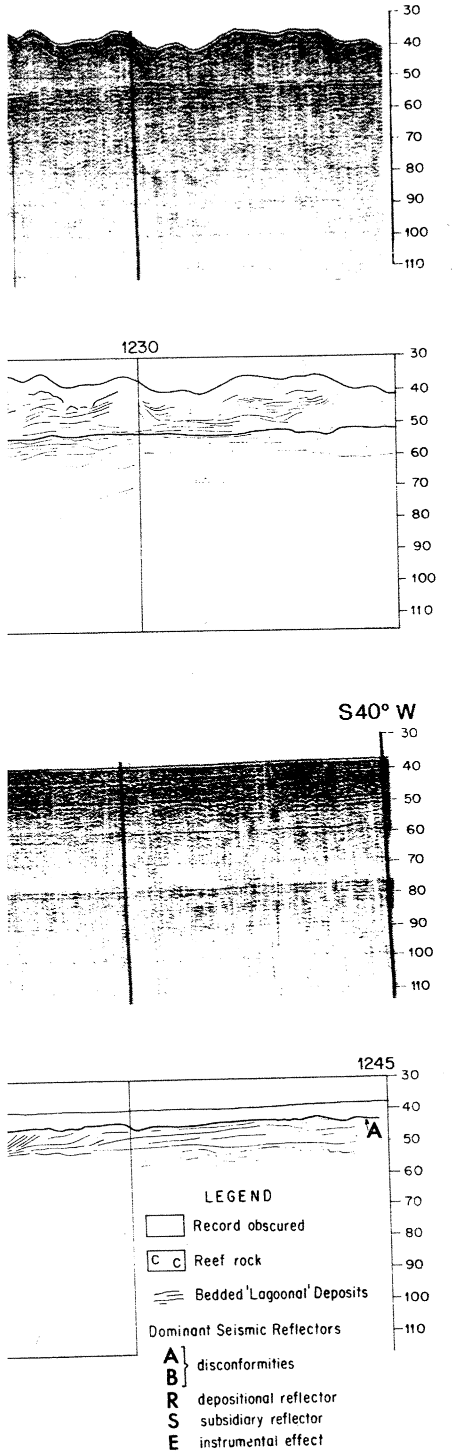


Figure 5. For description see opposite.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES


E
internal erosion surface


1240
sea bed sediments — 'Impure Carbonate Facies'



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

terrigenous, may relate to different transportation modes (Visher 1969). The coarse fraction of R133 and R154, *Halimeda* debris, is a reflexion of an ecological situation and the point of inflexion therefore may not imply a differentiation of grain size populations due to transportation modes, but may relate to grain size differences due to different grades of *in situ* post-mortem contributions, and to some extent represents a lag deposit. Similar factors may prevail in R163 where coral stick gravel is a lag deposit. However, some mixing has occurred in this particular case.

The points of inflexion on the curve representing sample R128 separate, on the one hand, carbonate gravels and carbonate and terrigenous sands, and on the other hand differentiate carbonate sands and terrigenous sands from the dominating terrigenous blue/green mud. In this case there may be, indeed, coincidence between these points of inflexion and the separation of discrete grain size populations moved by different transportation modes, but clearly there has been mixing of carbonate and terrigenous end-members in this inter-reef environment. The extreme skewness values (inclusive graphic skewness, Sk_{I}), see figure 3, suggest the mixing of different grain size populations under a variety of conditions.

5. Results of the seismic survey

(*a*) *Side-scan sonar records*

Side-scan sonar revealed submarine banks at a fairly uniform depth of 25 m, with intervening troughs and hollows descending to -37 m. The banks are not regular in form or size, and their smooth surfaces contrast with the rugged, rocky features of the hollows (see plate 1, figure 6). No small scale ripples were detected.

(*b*) *High resolution profiles*†

The most conspicuous feature is a prominent sub-bottom reflector ‘A’ which occurs over the entire area, extending from beyond the shoreward southwestern boundary eastwards to the shelf edge. It lies beneath bedded lagoonal deposits except near Cook’s Passage where it is coincident with a current-swept rugged surface at a depth of 45 m (figure 6, line 54). In detail the surface is irregular, probably karstified, is especially uneven where it truncates reefal limestones, and it has been channelled to a depth of 24 m (69 m below present sea level) at the lagoonal approaches to Cook’s Passage (see figure 6, line 54). Locally, there is discordance between bedding above with that below this surface (figure 5, pullout 1). Near Half-mile Opening (line 62) and on the leeward side of Carter Reef (line 61) surface ‘A’ loses (seismic) definition as it passes into a complex of reef-rock and bedded carbonate deposits. Reflector ‘A’ is clearly a major disconformity which records an important event in the geological history of this part of the continental shelf.

Another erosional seismic reflector (‘B’), approximately 4 m below ‘A’, is evident locally, e.g. near Half-mile Opening and below the leeward side of Carter Reef.

A very striking feature recorded by all the seismic profiles is the ‘bank’ forming deposit which overlies reflector ‘A’ and extends from the leeward side of the shelf edge reefs almost to the mid-shelf line of continental islands (see figure 5). This accumulation reaches a maximum thickness

† In the discussion of the continuous reflexion seismic profiles it is (reasonably) assumed that the interpreted seismic reflectors are either coincident with significant geological interfaces referred to throughout as ‘surfaces’ or with a layering (producing seismically reflective velocity contrasts) within consanguineous deposits. Certain instrumental phenomena by which some seismic interfaces appear at computed depths, consistently slightly different from those revealed by confirmatory drilling, is known to the authors, but is not in this work considered to be of significance.

of 18 m near the outer reefs and thins toward the mid-shelf area, probably accompanied by a facies change. Low-angle cross bedding is here interpreted, and there is seismic evidence also of an erosion surface within the bank deposits (reflector 'S'). It is noticeable that the bank tops are at a fairly uniform depth of −25 m, beneath the side-scan sonar tracks (plate 2, figure 6); in profile 62 and 61 (figures 5 and 6) they occur at −24 to −26 m, occasionally descending to −30 m. It is also significant that the distribution of the 'banks' coincides with the area of luxuriant *Halimeda* growth, and the surface deposits of *Halimeda* gravels and sands.

It should be noted that the apparent seismic reflector ('E') which follows the outline of the profile (figure 5) at a uniform sub-bottom depth of approximately 4 m is considered to be an instrumental effect. This partially masks the erosion surface (seismic reflector 'S'), which may correlate with the local reflector detected within the reef mass near Decca Hi-fix position 1237. The depositional seismic reflector 'R' (see figure 5) is remarkably smooth and level in contrast to the irregular surface 'A', and the comparative intensity of seismic reflector 'R', corresponding to a significant velocity contrast is interpreted as due to advanced lithification of the materials underlying surface 'R', possibly composing a nodular or concretionary layer.

Other significant features shown by the profiles are well developed terraces at −22.5 and −30 m on the leeward side of Carter Reef (see line 61, figure 6), and evidence of ancient buried channels filled with acoustically more transparent deposits (probably poorly sorted with a high component of fines) than those of overlying 'banks' (e.g. line 69, figure 6). The similarity, in terms of internal structure and acoustic properties, between accumulations above and below reflector 'A' suggest that a similar environment and range of sedimentary facies prevailed before and after the formation of surface 'A'. Reef-rock extends beneath Half-mile Opening (figure 5), which indicates the former existence of a more continuous shelf edge reef at this site.

(c) *The geological significance of the features recorded in the seismic profiles*

The major event recorded in these profiles is represented by the seismic reflector interpreted as disconformity 'A'. This surface was produced when a marine regression exposed the entire continental shelf to subaerial weathering and erosion, allowing it to become karstified. A further lowering of the sea level resulted in the channelling of the shelf to the new base level, coincident with the formation of a continental slope terrace at −70 m. At this time the exposed part of the shelf edge reefs must have formed a limestone cliff which descended steeply to the Queensland Trough.

FIGURE 6. Interpretations of segments of high-resolution boomer profiles of the back-reef area near Carter Reef.

Line 61 extends from Carter Reef in a southwesterly direction, and is viewed from the northwest. It shows two terraces on the leeward side of Carter Reef, and two disconformities which can be traced into Carter Reef. Disconformity 'A' lies at approximately −45 m, and occurs over the entire area. Above this level the bedded deposits of the *Halimeda* covered 'banks' reach a thickness of 21 m. Disconformity 'B', lying 5 m below A, is of local occurrence. It crosses both bedded and unbedded (reefal) deposits.

Line 54 trends parallel with the shelf edge and crosses the approaches to Cook's Passage. This cross section is viewed from the southwest and shows disconformity 'A' exposed as a 'rocky', non-depositional seabed composed of both bedded deposits and reef-rock. The exposed part of 'A' lies at a depth of 45 m, and has been channelled to a depth of 69 m.

Line 69 shows a cross section of the back-reef area along a line running parallel with the shelf edge, and is viewed from the southwest. Disconformity 'A' occurs between the younger bedded deposits of the *Halimeda* covered banks, and the underlying bedded deposits and reef-rock. Where the older accumulations have been channelled, 'A' descends to a depth of 66 m below sea level. The channel was filled by acoustically more transparent sediments before the formation of the bank deposits which are continued over the buried channel as a layer which is approximately 9 m in thickness.

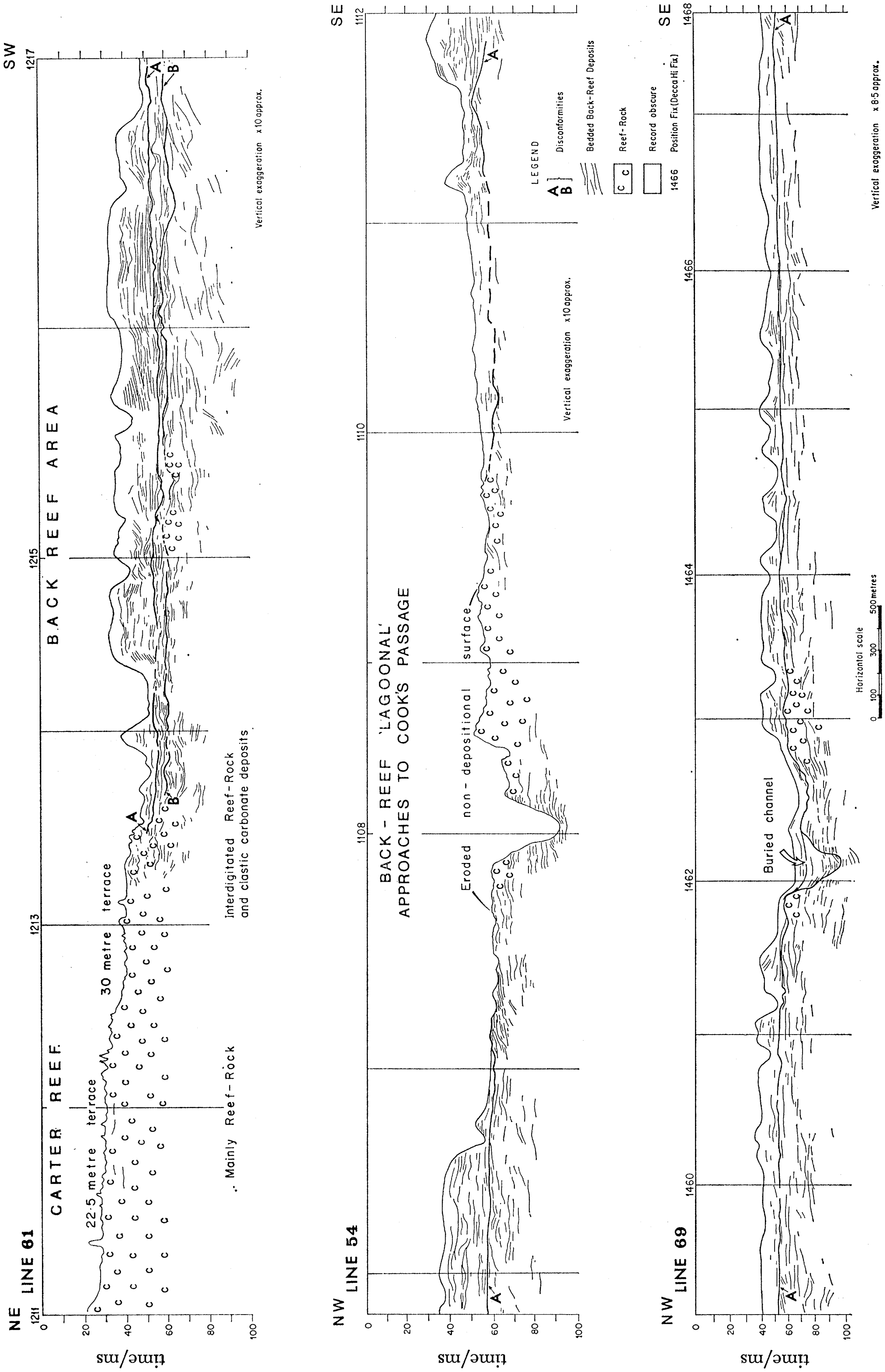


FIGURE 6. For description see opposite.

The subsequent rise of sea level and consequent reduction of stream velocities caused the stream channels to become partly filled with poorly sorted sediment containing an appreciable component of fines. As the transgression continued reefs regenerated at the shelf edge and were re-established at sites on the continental shelf. Rapid sediment accumulation stimulated by luxuriant *Halimeda* growth in the back-reef area is suggested. The uniform level of 'bank-tops' may indicate a sea level control of sediment accumulation in a tidal environment, which prevailed before elevation of sea level brought about modification of the environment and of sediment accumulation patterns.

Periods of still-stand, or possible temporary lowering of sea level, are indicated by the Carter Reef terraces, and by the erosion surfaces present within the banks and reef masses of the back-reef area, although erosion by tidal currents could have been responsible for some of the dissection which has remained a feature of the back-reef 'bank' area. The final rise of sea level was probably rapid, so that some small reefs were unable to maintain an equivalent upward growth rate, and, due probably to the same cause, shelf edge passages were maintained or became established.

The indicated approximate thickness of reef rock overlying disconformity 'A' at Half-mile Opening is 10 m (see figure 5). However, reefs are acoustically difficult to penetrate and the reflector 'A' could not be traced completely to the shelf edge, neither could it be traced far into the lee side of Carter Reef (figure 6). Indeed, there is a suspicion in the latter case (line 61) that horizon 'A' may rise within the reef mass, and that only a veneer represents post-disconformity 'A' reef growth.

6. Conclusions

Sediment characteristics and distribution patterns are determined by a complex interaction between mainland and continental island provenance, and ecological controls which determine reef development and promote conditions favourable to the maintenance of luxuriant *Halimeda* growth over much of the outer shelf. Dispersal of most end-members is restricted, and separation of discrete grain size populations according to different transportation modes is observed in most sediment subfacies. Mixing of end-members appears to be an important process in determining the nature of some inter-reef sediments, while others (*Halimeda* gravels, coral–algal reef-top deposits) may represent lag deposits, dependant for their grain size characteristics, upon *in situ* post-mortem contributions and 'currents of removal'. Strongly iron-stained grains occur in sediments near the continental islands. Their distribution does not appear to be related to particular bathymetric features, and the stained allochems are of types compatible with present ecological conditions. Therefore they are probably not relict grains. The seismic records suggest that the Holocene sedimentation pattern is a repetition of an ancient trend.

A sequence of events is indicated by the reflexion seismic profiles involving a major phase of regression resulting in the exposure of the outer shelf which probably became karstified, and subsequently channelled owing to a further fall in sea level. This was followed by a transgression during which stream channels became partly filled with sediment, reefs became re-established on the shelf, and the accumulation of the back-reef, bank-forming sediment began. Subsequent phases of the transgression may have been rapid, drowning some of the smaller shelf-reefs.

However, to try to assign absolute dates to the disconformity and to the terraces merely by comparison with eustatic curves would be presumptuous, especially since tectonic effects in this area have not been fully explored. Furthermore, it is possible that exhumed or relict surfaces which are apparent in the seismic profiles may be a source of confusion to researchers attempting to establish a chronology of sea level changes based on the recognition of a sequence of marine terraces.

An outline of the results of the investigations of the shelf in the Lizard Island area has been presented in this paper, but examination of the exact relation of surface 'A' to the continental islands, the mainland, and the large platform reefs, and an assessment of the significance of other disconformities, are continuing.

The detailed sequence of events and the full implications of the thickness and distribution of reefal and non-reefal facies in time and space may become apparent when detailed analyses of the seismic records from adjacent parts of the shelf investigated during the 1973 Expedition have been completed. Nevertheless, submarine drilling and isotope dating of features revealed by the seismic reflexion profiles presented here are desirable and would solve some of the problems concerning the geological history of the Great Barrier Reef Province.

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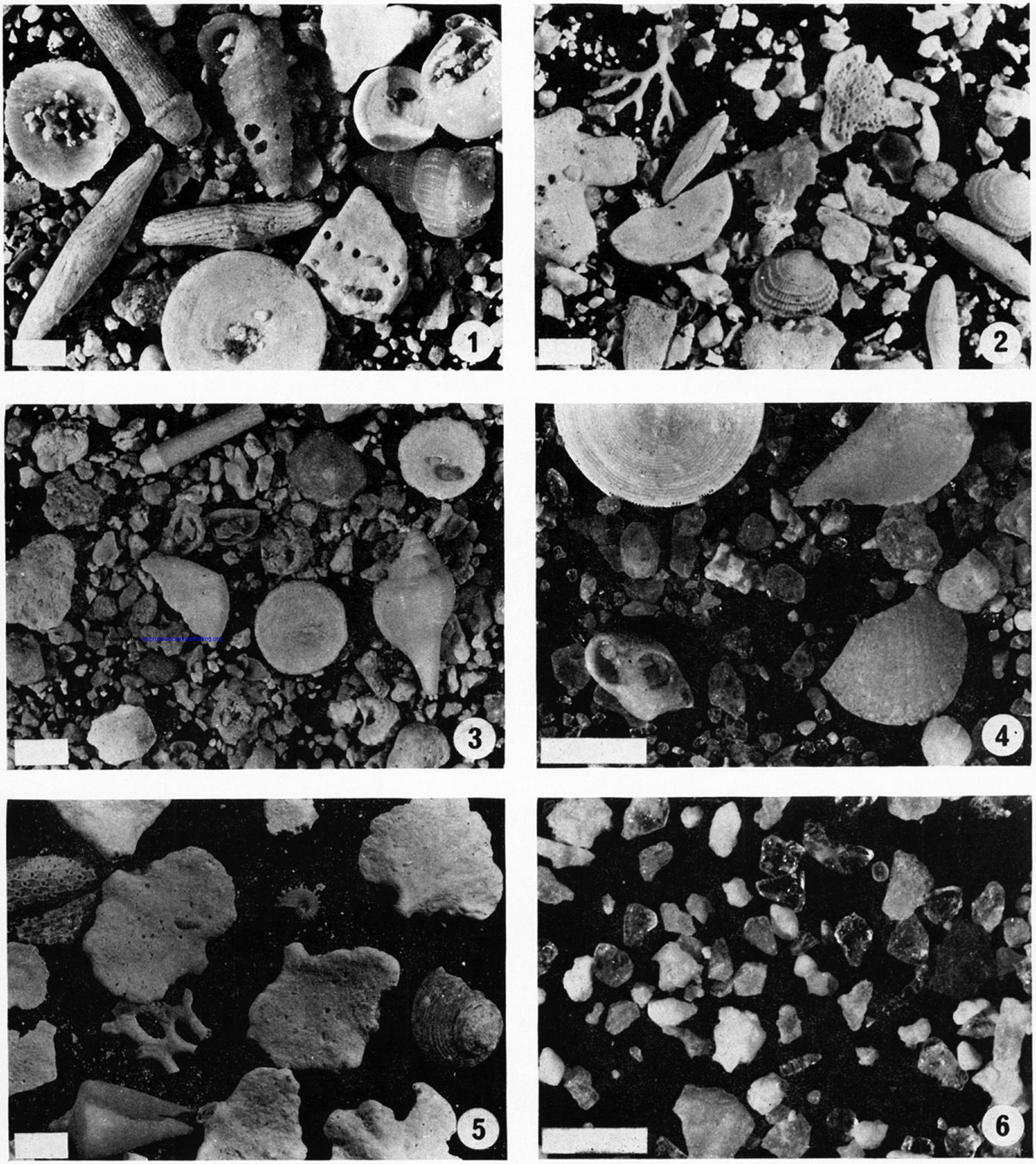

PLATE 1. For description see opposite.

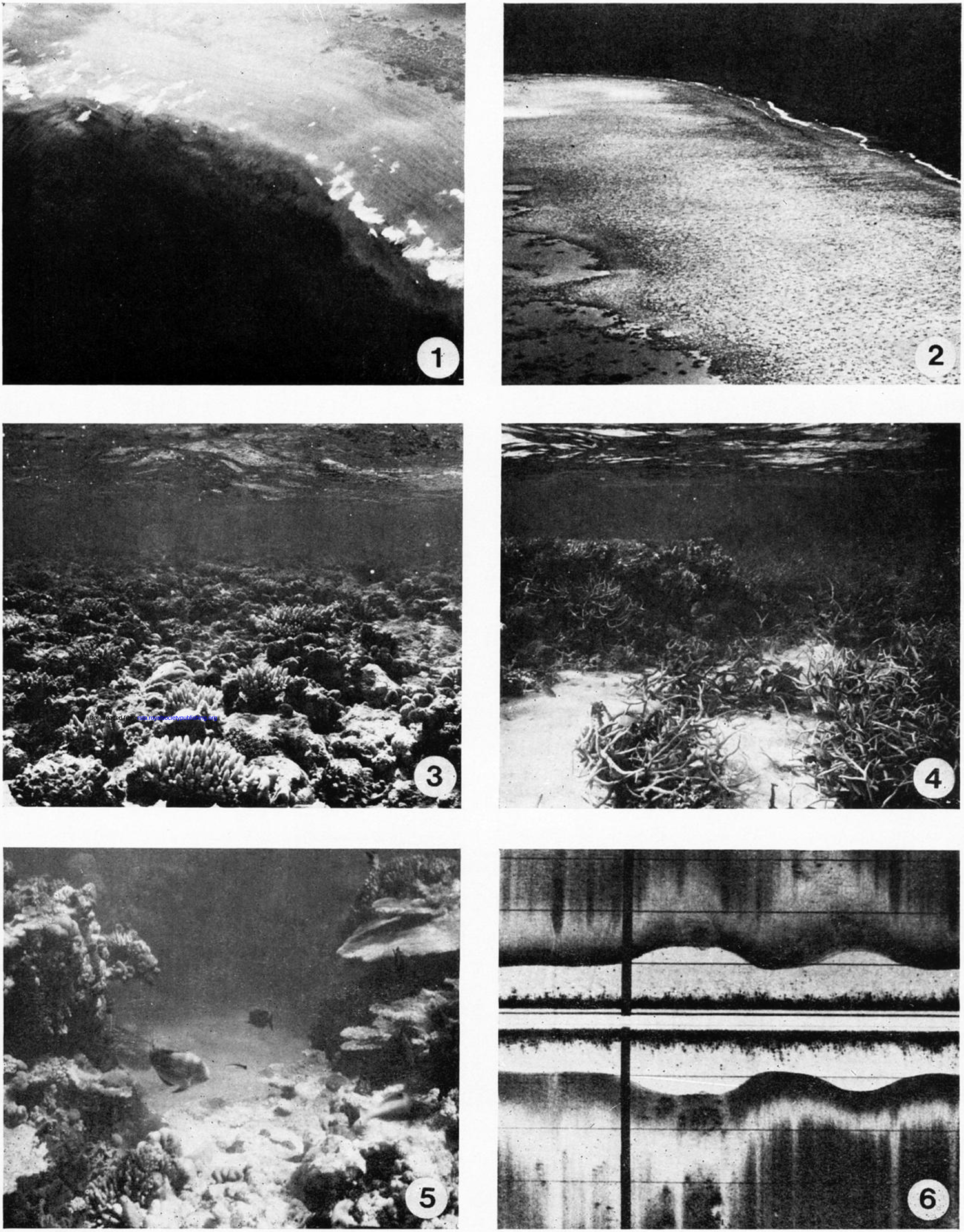

Plate 2. For description see opposite.

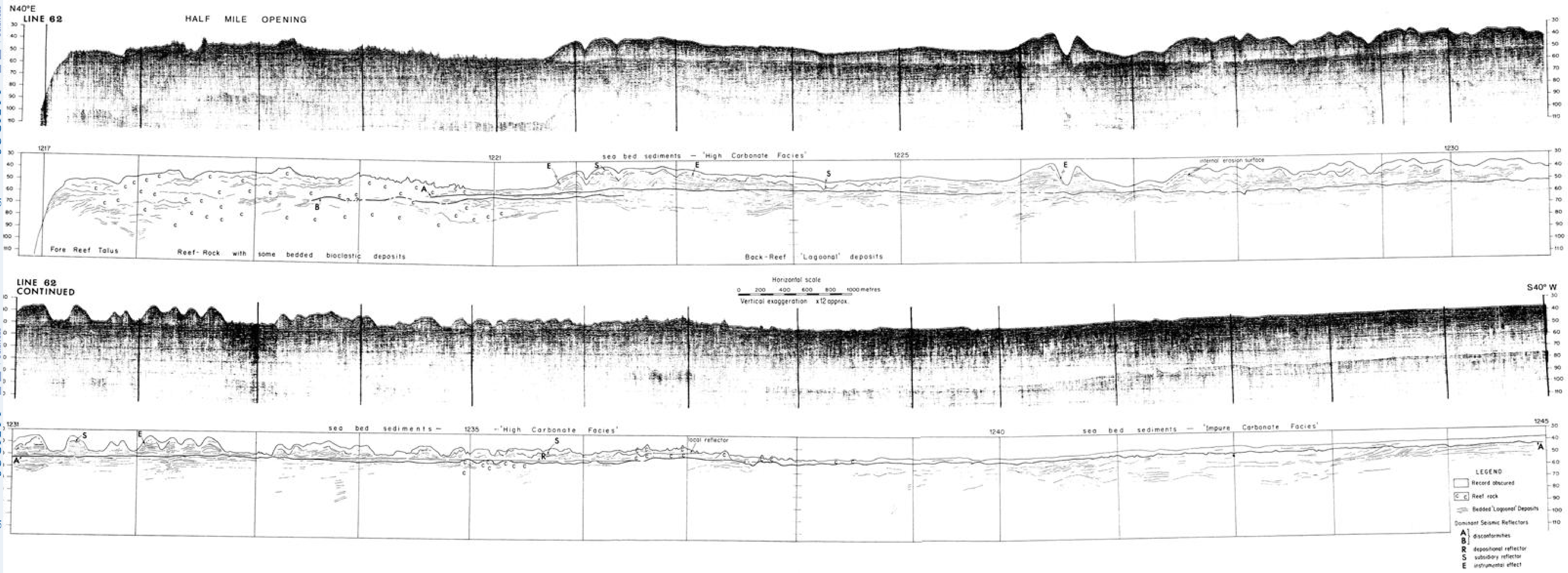

FIGURE 5. For description see opposite.