DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN 170

Sedimentology and Holocene History of a Tropical Estuary (Broad Sound, Queensland)

P. J. COOK & W. MAYO

AUSTRALIAN GOVERNMENT PUBLISHING SERVICE
CANBERRA 1977

DEPARTMENT OF NATIONAL DEVELOPMENT

MINISTER: THE HON. K. E. NEWMAN, M.P.

SECRETARY: A. J. WOODS

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

DIRECTOR: L. C. NOAKES, O.B.E.

ASSISTANT DIRECTOR, GEOLOGICAL BRANCH: J. N. CASEY

ABSTRACT

Broad Sound is situated at the confluence of four large estuaries. Freshwater inflow is restricted to the summer months. The Sound and its attendant estuaries are characterized by shallow water, a large tidal range (10 m), and strong tidal currents. In the shallow marine environment (the most seaward) pre-Holocene relict calcareous gravels are common. Calcareous sands, commonly occurring as sand ridges capped by megaripples, predominate in the open intertidal environment. Muds are most abundant in the mangrove swamp, mangrove channel, and supratidal flat environments, the muds become less calcareous and more saline in a landward direction. Textural studies revealed that grainsize parameters can be used to divide the sediments into environmentally significant groups; they also indicated that most of the sediments are brought into the estuaries during times of summer floods, and redistributed by tidal currents during the remainder of the year. The petrology and mineralogy of the sediments are consistent with some relative seaward movement of terrigenous sediment and landward movement of calcareous sediment. The relict nature of some of the sediments is revealed by their mineralogy, in particular their lack of less stable carbonates and heavy minerals. There is a seaward trend of increasing maturity in both the heavy-mineral and light-mineral assemblages. Drilling and radiocarbon dating have shown that most of the sediments are of late Holocene age. It appears from the Broad Sound evidence that sea level stabilized about 6000 years ago. Since that time there has been a marked seaward progradation of the shoreline producing a 'fining upward' regressive sequence. Regression appears to have been more rapid on the east side of the Sound, possibly a result of some late Holocene uplift. The Broad Sound study is valuable because it provides not only a regressive model for environmental interpretation in ancient sediments, but also a yardstick against which environmental changes in tropical estuaries can be measured.

Published for the Bureau of Mineral Resources, Geology and Geophysics
by The Australian Government Publishing Service

ISBN 0 642 02844 3

MANUSCRIPT RECEIVED: NOVEMBER 1974

REVISED MANUSCRIPT RECEIVED: NOVEMBER 1975

ISSUED: JUNE 1978

Printed by Brown Prior Anderson Pty Ltd 5 Evans Street Burwood 3125

Errata - BMR Bulletin 170

P. v

Table 2 is on page 48, not page 46.

P. 54

Figure 1 of Plate 18 has been printed upside down.

P. 103

In line 2, below sub-heading 'Mean-standard deviation plot', for 'removed' read 'reversed'.

P. 111

In last paragraph of left-hand column, fourth line, for 'these' read 'such'. The last sentence of this paragraph was printed in error and should be deleted.

P. 132

The caption for Figure 69 should read 'Degree of sphericity of terrigenous sand grains'.

CONTENTS

TABLES

ILLUSTRATIONS

PLATES

FIGURES

SUMMARY

Broad Sound is a vertically mixed tropical ephemeral estuarine complex on the central Queensland coast. It is characterized by shallow water, a large tidal range (10 m), and strong tidal currents (up to 4 knots) which produce elongate sand ridges in many areas. A five-fold environmental classification based on morphology and elevation is used. These environments are termed shallow marine, open intertidal, mangrove channel, mangrove swamp, and supratidal flat.

The shallow marine environment is entirely subtidal; sediments range from sands (particularly on the west side of the Sound) in areas flanking the intertidal sand ridges, to gravels (with significant mud and sand) in the more seaward portion of the Sound. The gravels, which predominate in the shallow marine environment, are composed mainly of calcareous nodules and calcitic shells overlying a hard indurated pavement, much of which is believed to be relict pre-Holocene or early Holocene sediments. The relict sediments are thought to have formed under subaerial conditions in the pre/early Holocene, and have subsequently been winnowed to produce a lag gravel. Many of the calcareous nodules forming this gravel are probably of pedogenic origin but some are calcareous intraclasts.

The open intertidal environment, which lies within the intertidal zone, interdigitates to seaward with the shallow marine environment. A few relict gravels are present in the intertidal zone; high in the intertidal zone are some coarse beach deposits, cemented in places to form beachrock. The sandy facies dominates the open intertidal environment. The sands are medium to fine-grained, well sorted, and average about 40 percent $CaCO_3$, mainly in the form of whole and fragmentary shells. There is a seaward trend of increasing grainsize in the open intertidal sands. Features of these sands include the presence of abundant mud-balls, intraformational breccias (resulting from the break-up of fine mud and sand laminae), and cross-beds. There is extensive bioturbation, particularly by crabs. Current ripples, oscillation ripples, and interference ripples are common. Megaripples, generally showing an ebb-orientation, are a particularly prominent feature of these sands; they are generally oriented at right angles to the axis of the large sand ridges and have an amplitude of up to 1.5 m and a wavelength of up to 30 m. Flanking the sand facies of the open intertidal environment is a narrow mud and sandy mud facies which is particularly well developed in areas where there is active erosion of the adjacent mangrove swamp environment and a consequent ready supply of mud. The surface of this mud zone is generally covered with a thin veneer of algae; the sediments are finely laminate and have a marked seaward depositional dip ranging from 4° to 10°. The muds are invariably strongly reducing.

Mangrove channels are mainly situated within the intertidal zone though they extend into the supratidal zone in places. They characteristically have steep v-shaped profiles with slumping commonly taking place on the banks. Sediments are generally muds and sandy muds, though in a few places the channels have incised down into the indurated surface and are floored by relict gravels.

The mangrove swamp environment, which ranges from high in the intertidal zone into the supratidal zone occurs either as a narrow belt flanking the mangrove channel, or as a wide area up to several kilometres across. The sediments of this environment are in general slightly calcareous muds, though sandy muds and sands are locally present on the seaward side of the environment. The sediments are grey and fetid on the seaward edge of the environment but become increasingly biotubated, mottled, and oxidized in a landward direction. Stratification is absent owing to infaunal and root activity.

On the landward side of the mangrove swamp environment there are supratidal flats which are subject to marine inundation only during spring tides or exceptional storm tides. The sediments of this environment are predominantly fine muds, though on their landward edge patches of locally derived sand and gravel are washed onto the flats during the summer wet season. Conditions on the supratidal flats are generally hypersaline, and gypsum crystals are common. Algal fibres are important sediment binders producing finely, though irregularly, laminate muds. The muds are only slightly calcareous, containing on average about 4 percent $CaCO_3$. Despite the low carbonate content of the muds, dolomite nodules have formed on these flats within the last 3000 years in response to the hypersaline conditions. Further accretion and progradation finally result in the removal of the supratidal flats from the marine regime. They are then colonized by grasses to form coastal grassland, which ultimately are overlain by fluvial sands and gravels.

Detailed studies of grainsize parameters revealed a marked seaward increase in grainsize of both the total sediment and the non-carbonate fraction. Skewness and kurtosis were found to be of little value in distinguishing between environments, but mean and standard deviation produced a significant separation of several sample groups, which were also recognizable by Q-mode factor analysis. These groups are referred to as the unsorted unit (found mainly in the shallow marine environment and comprising multimodal gravel-sand-mud), a pre-sorting unit comprising sand and mud from the upper reaches of the estuaries and the mangrove channels, a high-energy sorted unit composed mainly of sands of the open intertidal and shallow marine environment, and a low-energy sorted unit made up of muds of the mangrove swamps and supratidal flat environments. Most of the present-day input of terrigenous

sediment is believed to be brought into Broad Sound during summer floods, consequently the sediment remaining in the fluvial channels that enter the Sound may not be representative of the sediment carried into Broad Sound during major floods. During the remainder of the year, tidal currents are responsible for sorting this sediment into the two end-members, sand and mud populations.

The mineralogy and petrology of the sediments in general support present-day seaward movement of most of the terrigenous sediment. It has made it possible to delineate those areas of the Sound most subject to fluvial influences. Much of the carbonate fraction is swept south into the Sound from the open shelf. Variations in carbonate mineralogy depend in part on changes in the biota and the abundance of carbonate nodules. The sediments in general contain approximately equal amounts of high-Mg and low-Mg calcite; aragonite is sparse and decreases seaward. Diagenesis appears to have modified to some extent the carbonate mineralogy, with high-Mg calcite being least abundant in those sediments most subject to subaerial weathering. The dolomite nodules of the Charon Point area were found to range from $Ca_{0.65}Mg_{0.35}CO_3$ to $Ca_{0.59}Mg_{0.41}CO_3$; they show no ordering peaks. An important feature of the Broad Sound dolomites is that unlike previously-recorded occurrences of Holocene dolomites, they have formed in essentially non-calcareous terrigenous muds. The terrigenous sand fraction of Broad Sound sediments is composed predominantly of quartz; there is a marked seaward decrease in the abundance of feldspar. There is also a marked seaward trend of increasing maturity in the heavy-mineral assemblage. Whether this is due to progressive loss of seaward-moving immature grains or progressive dilution of the seaward-moving immature fraction by landward-moving mature grains is uncertain. In general, the heavy-mineral content of Broad Sound sediments is low, because of extensive dilution by biogenic calcareous material. In the mud fraction, kaolinite, illite, and montmorillonite (plus mixed-layer clays) are present in approximately equal amounts. There appears to be some degradation of montmorillonite to illite or mixed-layer illite-montmorillonite as a result of the high salinity condition prevailing in the supratidal flat environment. Illite-montmorillonite clay is also abundant in the sediments of the mangrove channel environment, indicating that much of the mud in this environment has been derived from the supratidal flats.

Studies of the Holocene succession of the Broad Sound region were undertaken using offshore seismic profiling, and offshore and onshore drilling. These investigations have shown that there is an indurated layer, believed to be a pre-Holocene or early Holocene soil profile, underlying most of Broad Sound and dipping gently to the north. Overlying this is a sequence of late Holocene sands 10 m thick in the offshore area. Onshore, the late Holocene sequence, which ranges in age from 6000 years B.P. to modern, is somewhat thinner (about 4-5 m). It consists of about 2 m of open intertidal sands with some muddy sands, overlain by an average of 1.5 m of mangrove swamp muds containing abundant wood fragments, which is in turn overlain by about 0.7 m of olive laminate muds of the supratidal flat environment. In places this is overlain by a non-marine sequence of thin soils and fluvial sands and gravels. Radiocarbon dating of both wood fragments and shell material indicates that the Broad Sound shoreline has prograded rapidly seawards over the past 6000 years. In the Torilla Plains area the average rate of progradation is 1.7 km per 1000 years. On the west side of Broad Sound in the chenier plain region the maximum rate of progradation is 1.2 km per 1000 years. There is strong evidence from the Broad Sound region that sea level stabilized at about the present-day level approximately 6000 years ago, and that the shoreline has been prograding since that time. During this period, there was a gradual increase in the tidal range in Broad Sound, but on the east side of the Sound (Torilla Peninsula) there is also evidence of uplift with a maximum rate of 1.1 m per 1000 years. As a consequence progradation was more rapid, and the Holocene sequence is thinner on the east side of Broad Sound than on the west side.

Some of the implications of the Broad Sound study are examined. Although some sedimentary (and geochemical) features of Broad Sound are similar to the Middle Cambrian sediments of the Georgina Basin and some processes are likely to be comparable, the tropical estuarine environment exemplified by Broad Sound does not appear to be a good analogy for the overall Cambrian depositional environment. Nevertheless the Broad Sound sequence is important as it supplies an excellent model of a regressive 'fining-upwards' sequence, and is likely to be of wide application for environmental reconstruction in ancient sediments. The Broad Sound study is also important as a source of information on a tropical estuarine system which has undergone little or no modification by man. Consequently it will be useful as a yardstick for measuring environmental changes which are occurring in other estuarine environments as a result of human activity.

INTRODUCTION

As a result of stratigraphic, petrographic, and geochemical studies of the Middle Cambrian phosphate deposits of northwest Queensland in 1969, de Keyser & Cook (1972) concluded that the phosphorites were probably deposited in bays or estuaries. Little was known about the distribution or mode of concentration of phosphorus in estuarine sediments and consequently the Bureau of Mineral Resources (BMR) decided to undertake its own research into this topic in order to gain a better understanding of ancient sedimentary processes. Broad Sound on the central Queensland coast (Fig. 1), a tropical estuary, and Mallacoota Inlet, a temperate estuary in eastern Victoria were selected for study. They were chosen to provide two climatically different estuaries lacking any significant phosphorus input from domestic, agricultural, or industrial effluent. A study of Mallacoota Inlet was undertaken primarily by Reinson (in press) in the Department of Geology at the Australian National University, with BMR assistance, and will not be considered here.

It was apparent that in order to understand mechanisms controlling the distribution of phosphorus it was desirable to study not only the phosphate levels in sediments and water but also to consider such features as water movements, grainsize, heavy minerals, clay mineralogy, biogenic activity, and the Quaternary history of the area, as well as the behaviour of the numerous major and trace elements which are likely to have influenced the distribution of phosphorus in any way. Consequently it was decided to undertake a comprehensive study of Broad Sound. This Bulletin is primarily concerned with the physical and biogenic processes prevailing in Broad Sound. A second Bulletin will deal with geochemical processes operative in both the estuary and the catchment (Cook & Mayo, in prep.). It should, however, be remembered that at times there is no clear division into physical and chemical processes in the estuarine environment, for frequently one process is strongly influenced by the other.

Two field seasons were undertaken: June to October 1970, and May to August 1971. In 1970 P. J. Cook (party leader) and W. Mayo undertook sediment and water sampling over the entire estuary and adjacent catchment areas as well as bathymetric and seismic surveys. S. E. Smith carried out some water sampling and was responsible for analyses made at the Charon Point base camp. P. M. Angus carried out detailed geochemical sampling of the Styx River catchment. In 1971 P. J. Cook and W. Mayo carried out further sediment sampling and seismic profiling, measured Eh and pH in various depositional environments, and determined the Holocene succession by auger drilling. W. A. Burgis supervised a program of diamond drilling in the Torilla Plains area. In the inter-field-season period and subsequently, all these geoscientists were involved in laboratory studies. All sample preparation, most of the textural analyses, and some of the chemical laboratory work on the samples were undertaken by K. J. Armstrong and D. E. Hunter.

Acknowledgements

The writers wish to express their appreciation to K. J. Armstrong and D. E. Hunter for their field and laboratory work throughout the Broad Sound project. The assistance of F. L. Stevenson, G. Burgis, A. Lewis, and C. Madden in the field is acknowledged. The considerable amount of X-ray diffraction work carried out by G. Berryman represented an important contribution to the Broad Sound work. Mr G. Oke (Captain of the M. V. *Bali Hai)* and Mr C. B. Hope (Captain of the M. V. *Offshore Driller II)* and their crews, and also the staff of Laser Electronics Pty Ltd were helpful with various phases of the investigations. The hospitality of Mr & Mrs G. Burrill of 'Bald Hills' and Mr & Mrs A. Mace of 'Torilla' was appreciated by all members of the 1970 and 1971 field parties.

Unpublished information on the Broad Sound area was kindly supplied by Commander A. Vaughan of Australian Hydrographic Services, The Broken Hill Proprietary Co. Ltd, and R. Planalp of Target Exploration.

Dr B. G. Thom and Dr R. J. McLean of the Australian National University offered helpful comments on the manuscript.

Climate

The climate of the region around Broad Sound was examined in depth by the Department of National Development (1965) and is not considered in detail here. The climate of the adjacent area of Shoalwater Bay has been dealt with by McAlpine (1972). The Broad Sound area has a subhumid tropical climate with a marked concentration of rainfall in the summer months. The main climatic features are summarized in Figure

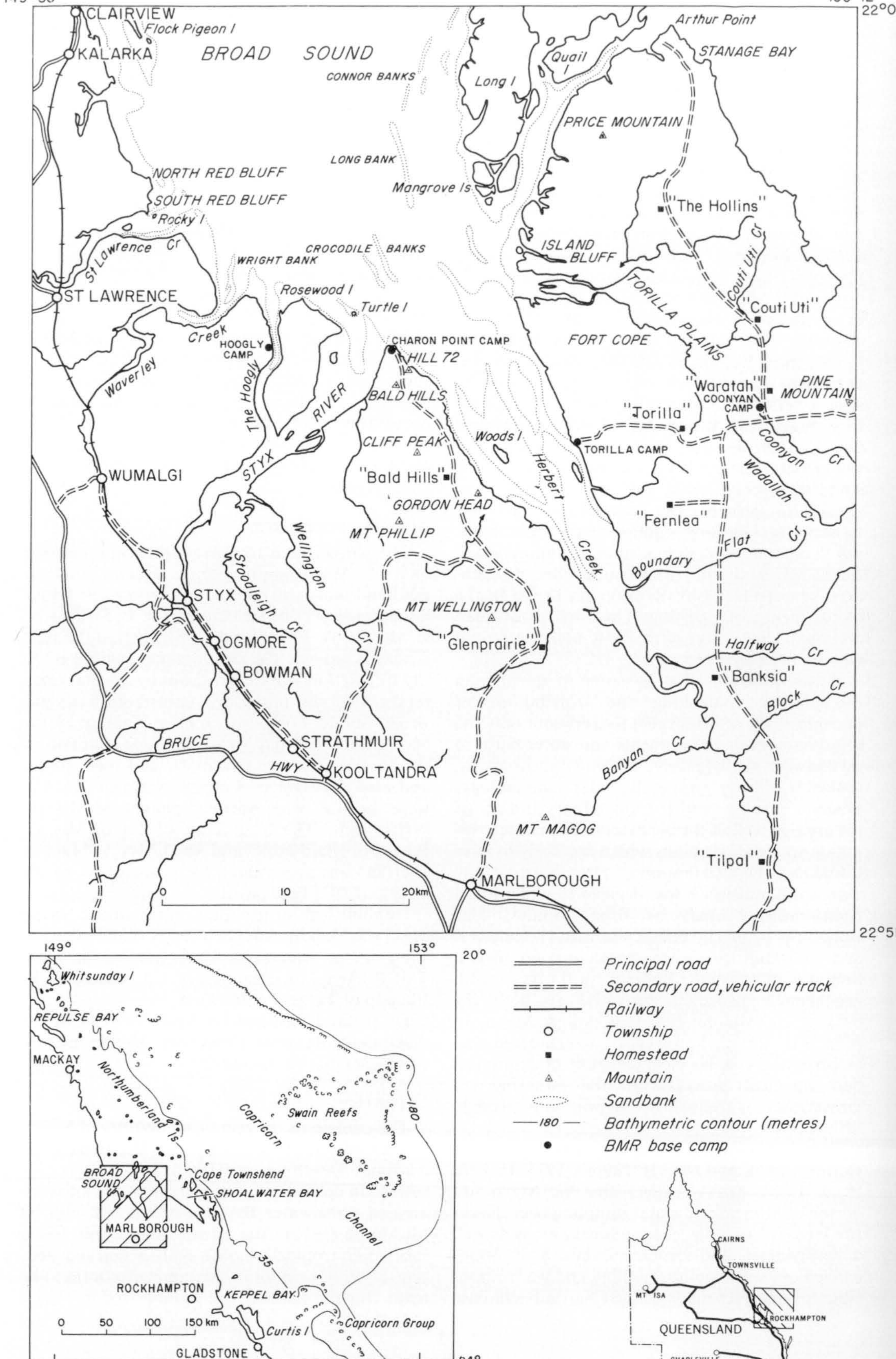


Figure 1. Locality map.

F55/A12/51

2. The average mean temperature ranges from 27° in January to 17°C in July. Temperatures in excess of 40°C or below 0°C are seldom if ever attained on the coast, but temperatures are more extreme inland. The average rainfall in the coastal region is about 1000 mm, most of which falls from November to March (Fig. 2). The average annual rate of evaporation at St Lawrence is about 1400 mm, consequently there is a substantial annual excess of evaporation over precipitation. Only during January and February does precipitation exceed evaporation, and runoff is thus greatly reduced during most of the year. An important feature of the rainfall pattern is that much of the rain falls during thunderstorms or tropical cyclones, resulting in wide rainfall variation from year to year. As much as 75 mm (3 inches) of rain in half an hour is reported to have fallen in Kunwarara near Marlborough (Department of National Development, 1965). Rainfall of this intensity produces severe flooding in parts of the area.

Persistent light winds are experienced in the Broad Sound area throughout the year. The strength and direction of the prevailing winds are shown in Figure 3. During the spring and summer months the dominant wind direction is from the northeast. As a result of the wind fetch, the area from Charon Point to the mouth of St Lawrence Creek is subjected to strong wave action in a northeasterly sea. In the autumn and winter months the wind is mainly from the southeast to southwest. The long southeasterly fetch can produce a heavy southeasterly sea, but because of the configuration of the coast, this has little erosive action on the coastline. Summer cyclonic storms with wind velocities in excess of 160 km per hour (100 miles per hour) affect the Broad Sound area at times. A cyclone passed through the region during the interval between the 1970 and 1971 field seasons. Many large eucalypt trees were blown over or snapped by this storm, but it appeared that the winds did not severely affect the mangroves of the intertidal and supratidal zones.

Field Methods

A total of eight months was spent on field work in the Broad Sound area in 1970 and 1971. Numerous logistic difficulties were experienced because of the remoteness of the area and the large tidal range. For instance, it was necessary to spend two weeks building a causeway across the intertidal muds at Charon Point (Fig. 1) before any offshore operations could be undertaken. In 1970 a comparatively large camp established at Charon Point, from which all field operations were undertaken. In 1971 it was more convenient to set up several small camps during the field season; all onshore operations were carried out

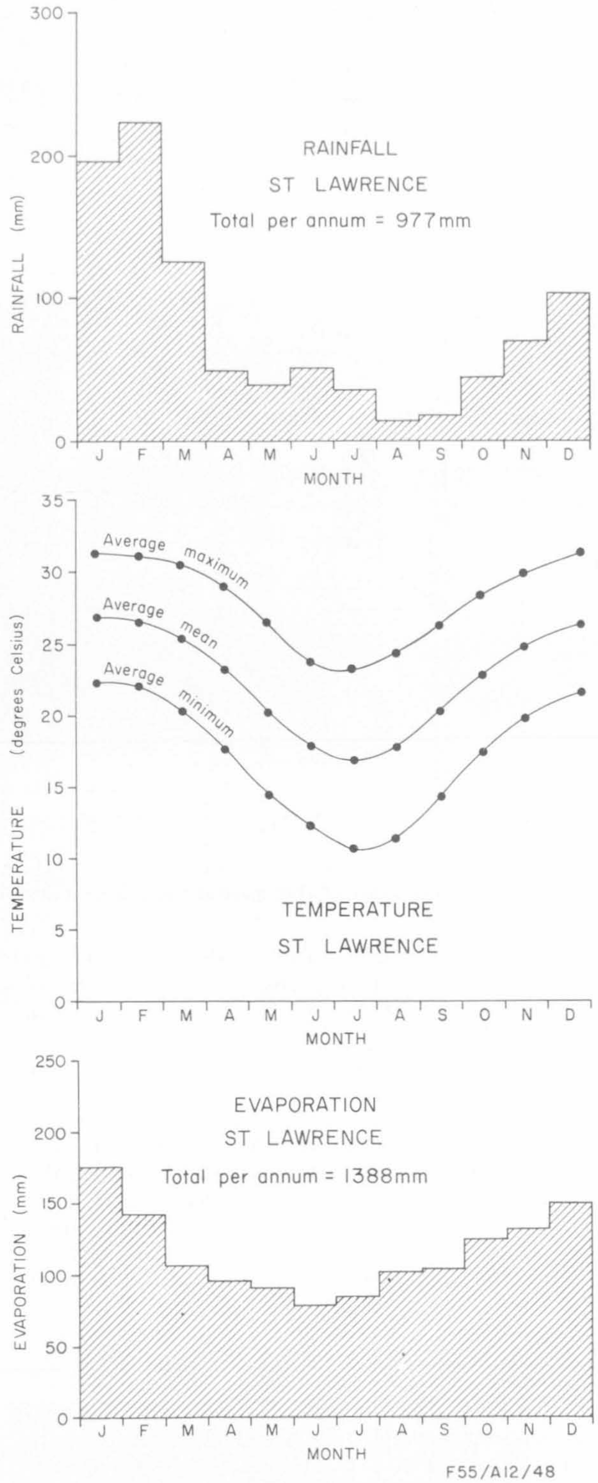


Figure 2. Climatic data for the Broad Sound (St Lawrence) area adapted from the Department of National Development (1965).

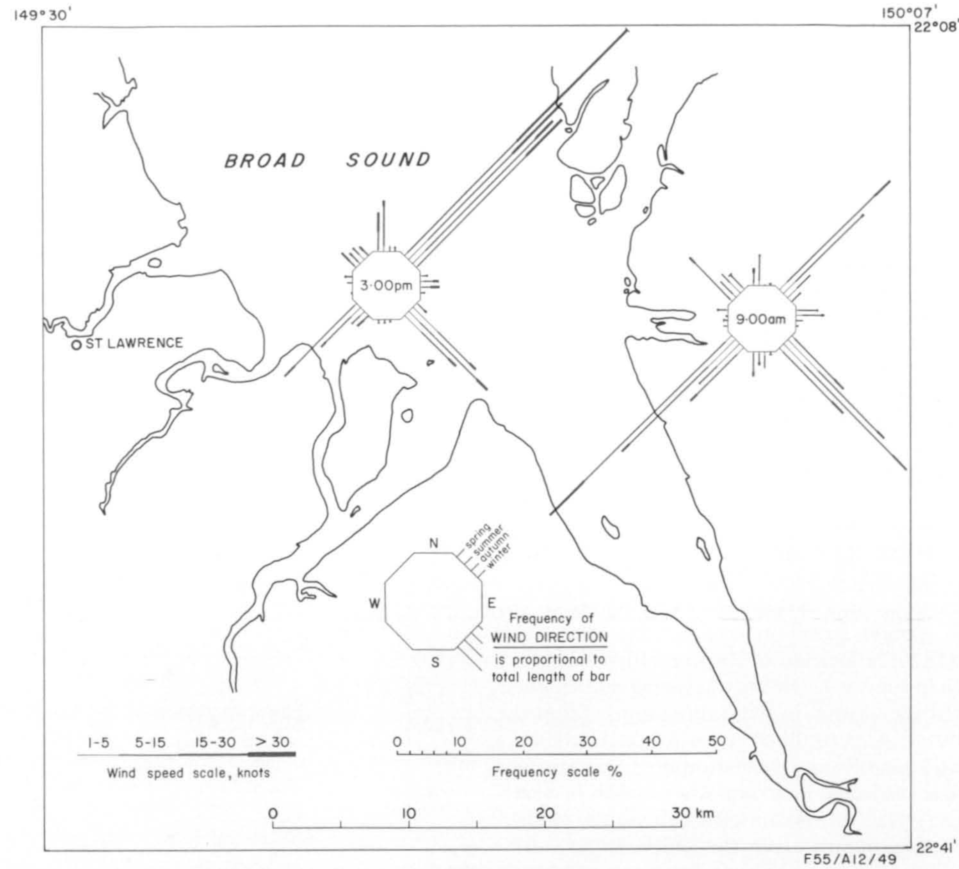


Figure 3. Frequency of wind speed and direction for the Broad Sound (St Lawrence) area at 9.00 a.m. and 3.00 p.m.

using four-wheel-drive vehicles; offshore operations were undertaken from a variety of vessels ranging from 4 to 40 m long. A 4-m aluminium dinghy and a 5-m inflatable rubber dinghy were used for nearshore work; the aluminium dinghy, though robust, was rather small and unstable; the inflatable craft was both stable and sufficiently large to work from conveniently, though it was rather fragile. The deeper-water work was generally undertaken from the M.V. *Bali Hai,* a 14-m steel-hulled vessel chartered by BMR; this was satisfactory to work from because of its comparatively shallow draught (2 m), its ample covered working area at the stern, and its ability to accommodate 6 passengers. Late in the 1970 field season the M.V. *San Pedro Strait,* an oil-rig supply vessel with an overall length of about 40 m, was used briefly to enable seismic and heavy coring equipment to be used. In 1971 the 20-m M.V. *Offshore Driller II,* was used for contract offshore seismic and drilling operations. In 1970 an aircraft was chartered for oblique aerial photography.

SAMPLING

A map previously compiled from aerial photographs indicated the distribution of the various inferred sedimentary environments. Using this interpretative map it was possible to estimate the number of localities to be sampled from each environment, given the sampling system, and the seaward limit of the sampling which was taken as an east-west line from the southern tip of Long Island (Fig. 1).

Unbiased sampling of the estuary was considered essential and, as a pilot study had not been carried out, sampling at the intersections of a square grid was selected to uniformly sample the whole study area, as well as individual environments. Comparison of variables would then be possible between separate environments and the whole estuary. Where necessary, environments not adequately sampled with the selected grid could be sampled separately with any random sampling technique and results could still be compared with those from the total area. The only possible problem with such a grid might be that cyclical variation of any of the measured variables on the same scale as the selected grid size would result in biased results for the variable. Cyclical changes of this type would be exceptional and were not expected at Broad Sound; consequently this problem was ignored.

Various sizes of grids were placed over the environment map to vary the number of localities in each of the four main inferred sedimentary environments as interpreted from the aerial photographs, with the aim of obtaining a minimum of 50 samples in each environment. The mangrove swamp environment covers the smallest area. With the grid set at 1.9 km there were 59 sampling localities in the mangrove swamp environment, 72 in the supratidal flat environment, 97 in the open intertidal environment, and 91 in the shallow marine environment. Therefore, with this grid size, sampling of the environment covering the smallest area would be adequate, and further subdivision of the other three environments would be possible.

The only remaining decision was whether the selected grid should be randomly orientated over the estuary. This problem was solved when just before leaving for the field 1:100 000 topographic maps of Broad Sound with a 1-km grid became available. For convenience, this grid at 2-km spacing was used without affecting the randomness of the sampling.

Owing to errors in the original depositional environment map and to changes in the size of the final sampling grid, the total number of sampling localities in the mangrove swamp environment was only 27. Numerous sampling points interpreted as supratidal flats subsequently proved to be coastal grasslands and consequently were not sampled, but an adequate number of localities (68) was sampled. A total of 70 localities were sampled in the shallow marine environment and 105 in the open intertidal (Fig. 4). In addition to the grid samples it was decided whilst in the field to sample the mangrove channel environment separately; it was sampled at 2-km intervals by dividing up the total length of all the major channels, to give 34 sampling localities.

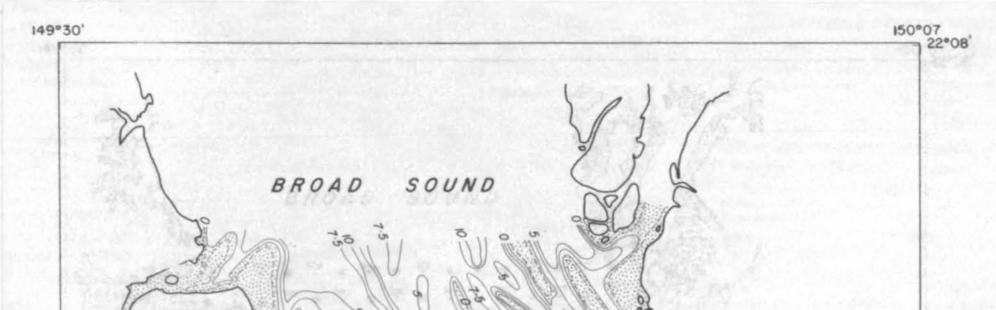


Figure 4. Sample localities, sample numbers, and buoy positions in the Broad Sound area.

Extra samples were also taken along the centre of the Styx River, The Hoogly, and the Waverley and St Lawrence Creeks at points of intersection with the 1-km grid lines (Fig. 4).

When measuring each variable an analytical error may be expected. This analytical error reflects the precision, but not the accuracy, of the analytical technique. Given no analytical error, the value for a variable measured on repeat samples from the same locality would be expected to change (sampling error) because of many factors, the most important being positioning error and local changes in the variable. Consequently, the combination of the analytical and the sampling errors could be large enough to mask an overall variation in a particular environment. To test the sampling error, triplicate sampling was carried out at approximately every tenth locality sampled in each field environment.

The grid was sampled using a simple cone dredge in subaqueous environments. In subaerial environments, the sample was obtained by first clearing any surface litter; digging a hole about 30 cm square, and then quartering the sample until a suitable specimen size was obtained.

A grab sampler (Pl. 1, fig. 1) was generally found to be unsatisfactory. Coring was attempted at every alternate grid-sampling site. This was achieved at subaerial locations by driving an open plastic tube with a diameter about 7.5 cm into the sediment. At subaqueous sites, a small 30-kg gravity corer was used; this technique was found to be satisfactory in muds, penetrating to a depth of 45 cm but a penetration of only 10 cm or less was achieved in sandy or gravelly sediments. A 300-kg gravity corer was also used at a few localities, but again penetration was unsatisfactory, and a maximum core length of only 1 m being obtained. Attempts were made during 1970 to obtain better subsurface information using a vibratory coring device but this too was unsuccessful. In 1971 Offshore Drilling and Research drilled 28 offshore holes for BMR. Using a vibratory, air-lift water-jet drilling device penetrations of 10 m into the sediment were achieved. Onshore, subsurface information was obtained to depths of 7 m by hand augering. In the Torilla Plains area a diamond drilling program using a Failing 1000 rig provided subsurface information down to a maximum depth of 60 m, although most drill holes were less than 10 m deep. This onshore drilling program is reported in detail by Burgis (1975).

Position Fixing

Onshore and upper-estuary sampling points were fixed by use of the 1:86 000 aerial photographs and the 1:100 000 topographic maps. The more seaward points sampled in the 1970 program were fixed from the shore by theodolite. The scheme adopted was that theodolite stations were set up on two of the following sites: (a) Charon Point, (b) Turtle Island, (c) Rosewood Island, (d) Island Bluff, and (e) North Red Bluff (Fig. 1). Transceivers were used to direct the ship to every alternate sampling point, where a marker buoy was then positioned. Intervening points were subsequently fixed during the course of sampling by the ship's observer visually lining up sets of buoys (Fig. 4). This scheme worked well, positioning was accurate to within ± 20 m, and it was possible to reoccupy sampling points during subsequent bathymetric, coring, and seismic programs with ease. Despite the strong currents, few buoys were lost during the field season. During the 1971 seismic program, an alternative method of position fixing involving laser navigation was used. This consisted of setting up a shore station from which the laser beam was directed on an appropriate bearing. The ship then sailed either towards or away from this station, keeping on the laser beam at all times. Positions along the laser line were obtained every two minutes using sextant cut-off angles determined on prominent landmarks.

Previous Investigations

Previous geological investigations in the Broad Sound area have been concerned primarily with the Palaeozoic and Mesozoic rocks. Malone, Olgers, & Kirkegaard (1969) dealt briefly with the Cainozoic of the St Lawrence 1:250 000 Sheet area; Kirkegaard, Shaw, & Murray (1970) showed the distribution of Cainozoic sediments in the Port Clinton 1:250 000 Sheet area adjacent to Broad Sound. Both publications referred extensively to earlier reports on the Broad Sound area.

The only onshore work on Quaternary sediments before the present investigation was by Jardine (1928) who briefly examined the Holocene marine sequence in the Torilla Plains area. Offshore investigations have been undertaken by the United Geophysical Company (Roosjen, 1966) who carried out a seismic survey at the northern end of Broad Sound for Ampol Exploration Ltd. Maxwell (1968) sampled the bottom sediments at a few localities at the northern end of the Sound and briefly discussed the tidal range of the area.

A number of reports on various phases of the present investigations have already been written. These include a report by Burgis (1975) on the Cainozoic stratigraphy of the Torilla Plains area, an account of the clay mineralogy of the Quaternary sediments of Broad Sound by Gibson

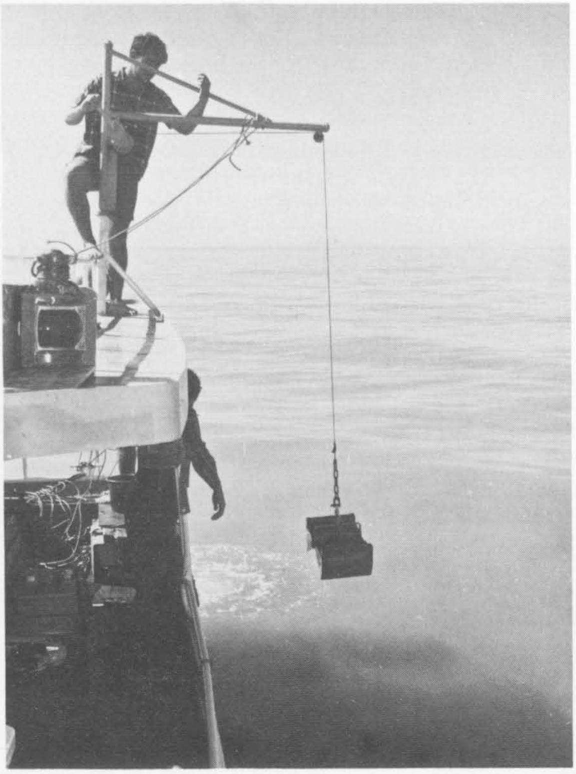


Plate 1, fig. 1. Grab sampler being lowered from the M.V. *Bali Hai*. (GA/4187)

Plate 1, fig. 2. Removing a sediment sample from the cone dredge. (GA/3965)

B

(1972), a discussion by Mayo (1972) on grainsize analysis techniques (and associated parameter computation) for use with the Broad Sound sediments, and a report on the significance of grainsize parameters in Broad Sound sediments (Mayo, 1974). In addition, Cook & Polach (1973a) reported on the significance of a Holocene chenier sequence in the Styx River and Waverley Creek areas, and also the discovery of Holocene dolomites (1973b). The geochemistry of the dolomites is considered in more detail by Cook (1973). The geochemistry of Broad Sound and its associated drainage is the subject of a separate Bulletin (Cook & Mayo, in prep.).

Regional Geology

The Broad Sound region is structurally and stratigraphically complex. It lies on the eastern edge of the Lower Palaeozoic Tasman Geosyncline and the predominantly Upper Palaeozoic Yarrol Basin, and is adjacent to the Mesozoic Styx Basin.

The oldest rocks exposed in the region (Fig. 5) are believed to be the Lower Palaeozoic schist, gneiss, marble, and phyllite of the 'Coastal Block' (Kirkegaard et al., 1970), which flank the Torilla Plains and are up to 20 000 m thick. Devonian sediments, and acid volcanics crop out in the northern part of the region and are well exposed on Long Island. The serpentinites of the Marlborough area are of uncertain age; they are believed to be Lower Palaeozoic but may have been block-faulted into their present position in the Lower Permian.

Deposition in the Yarrol Basin began in the Upper Devonian and continued until the Upper Permian. During this time, a thick volcanic and sedimentary sequence was deposited in the western half of the Broad Sound area where volcanogenic sediments such as the Carmila Beds are well developed. In the ranges to the east of Broad Sound, this sequence is more than 4000 m thick. Yarrol Basin sedimentation was terminated by severe folding and faulting in the late Upper Permian, when granite and granodiorite were emplaced in the southeast corner of the Broad Sound area. Faulting and igneous activity may have continued well into the Mesozoic; many of the major structural features such as the Broad Sound Fault were probably established in the Mesozoic.

The Cretaceous Styx Coal Measures were deposited in a small downfaulted basin on the west side of Broad Sound. They are predominantly freshwater sediments with minor coal, and have a maximum thickness of 400 to 500 m.

The Cainozoic stratigraphy of much of the Broad Sound region is poorly understood. Thick sequences of poorly lithified colluvial conglomerate and breccia of probable Tertiary age flank the ranges on the west side of Broad Sound. Isolated patches of Tertiary volcanics are preserved in the ranges east of Broad Sound. The undifferentiated Cainozoic deposits on the east side comprise sand, sandstone, and conglomeratic sandstone, all showing varying degrees of lateritic weathering. Many of these deposits are believed to be Tertiary but some, particularly the unconsolidated pale brown sand flanking parts of Torilla Plains, are probably Quaternary and perhaps Holocene.[1]

Fluvial deposits are locally developed in the upper reaches of all the river valleys, but it is only in the valley of Herbert Creek that they are extensive. Many of these deposits are Holocene, but some may be considerably older. Holocene marine mud and sand are well developed around the periphery of Broad Sound. Though comparatively thin (maximum thickness is about 10 m), these deposits cover an area of about 1000 km^2. The Holocene marine sequence is discussed at length in this Bulletin.

[1] The Pleistocene-Holocene boundary is generally taken as 10 000 years B.P., based on the waning of a relatively small ice sheet in northern Europe. This event has little relevance to the rest of the world in general, and to Australia in particular. Much more significant events would appear to be the onset of the post-glacial transgression at about 22 000 years B.P. and the more recent stabilization of sea level (variously placed from about 6000 to 3000 years B.P.). However, in order to conform with accepted usage, the Pleistocene/Holocene boundary is taken here as 10 000 years B.P. Early Holocene is taken as 10 000 to 6000 years B.P., and late Holocene as 6000 years B.P. to the present.

PHYSIOGRAPHY

Onshore Physiography

The geomorphology of the Torilla Plains area was studied by Burgis (1975), and Galloway (1972) described the geomorphology of the Shoalwater Bay area to the east. The present writers made geomorphic observations in the coastal plains area. Elsewhere, detailed information is not available and consequently only broad divisions are shown (Fig. 6); apart from the coastal plains area, these divisions are based on airphoto interpretation and limited field observations.

1. Coastal plains

This topographic unit comprises the low-relief plains bordering Broad Sound. It ranges in width from less than 1 km in areas adjacent to a steeply sloping hinterland (Pl.2, fig. 1) to 10 km flanking Waverley Creek (Pl.2, fig. 2) and more than 20

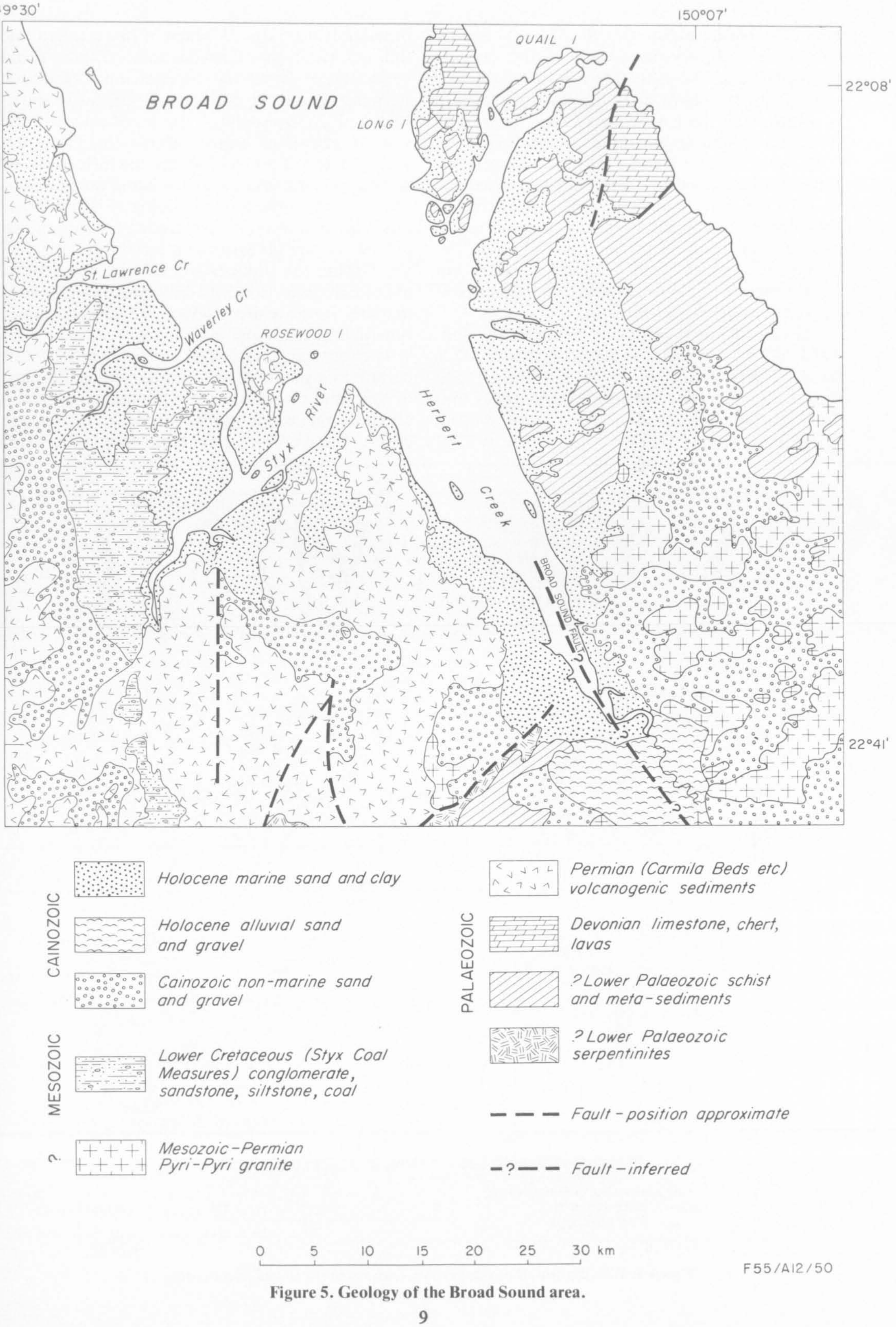


Figure 5. Geology of the Broad Sound area.

km in the Torilla Plains area (Pl.3, fig. 1, fig. 2). Gradients are everywhere very gentle, ranging from an estimated 1 in 1000 to 1 in 10 000 (Pl.4).

The coastal plains may be subdivided into two sub-units, the mangrove swamps/supratidal flats, and the coastal grasslands.

The swamps and flats lie within the supratidal zone (see later) and are subaerially exposed for most of the time. They nevertheless are areas of active marine sedimentation and are subject to marine inundation during high spring tides. The mangrove swamp and supratidal flat environments of this topographic unit will be considered at length in this Bulletin.

The coastal grasslands occur immediately landward of the supratidal swamps and flats (Pl.5, fig. 1). The two units commonly interfinger, with supratidal channels commonly extending far into the coastal grasslands. An anastomosing drainage system is characteristic of the coastal grasslands (Pl.5 fig. 2). Much of this topographic unit lies within the extratidal zone, (Table 1), and consequently is subject to occasional flooding, particularly during cyclones. Possibly owing to localized uplift, some of the inner areas of the coastal grassland extend above the extratidal zone, i.e. out of reach of all marine influences. In addition, many areas are now being taken out of the extratidal zone by the building of dams across tidal channels in order to exclude seawater and so extend the coastal areas suitable for grazing cattle. During the summer wet season, the coastal grasslands are flooded with freshwater, particularly in those areas which are now dammed; or with brackish water elsewhere.

The coastal grasslands are everywhere underlain by a sequence of intertidal-supratidal sands and muds, with a thin soil (average thickness about 30 cm) which supports a thick couch grass cover. There is strong evidence that the coastal

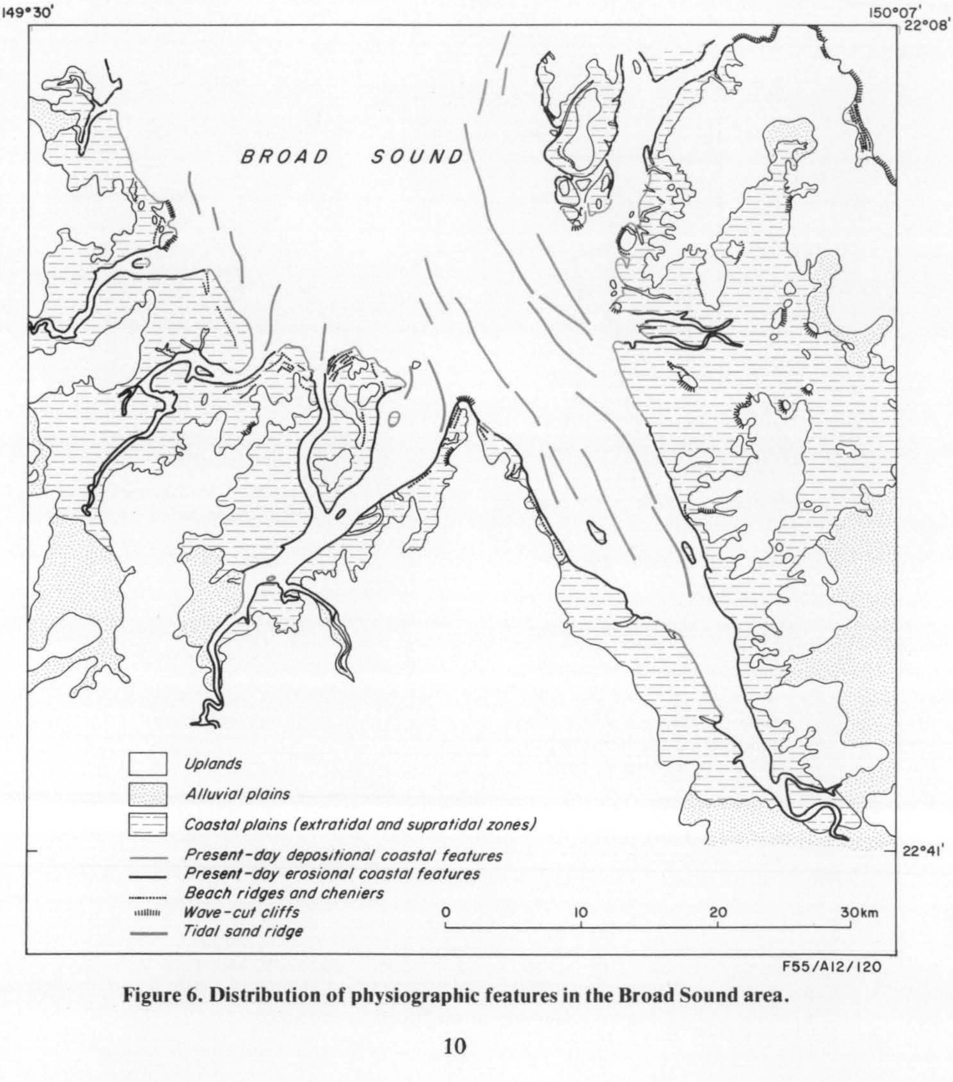


Figure 6. Distribution of physiographic features in the Broad Sound area.

Plate 2, fig. 1. Narrow coastal plains south of Charon Point; looking south. IM — intertidal muds; M — mangrove; S — supratidal flats; P — Mount Phillip (393 m). (GA/4076)

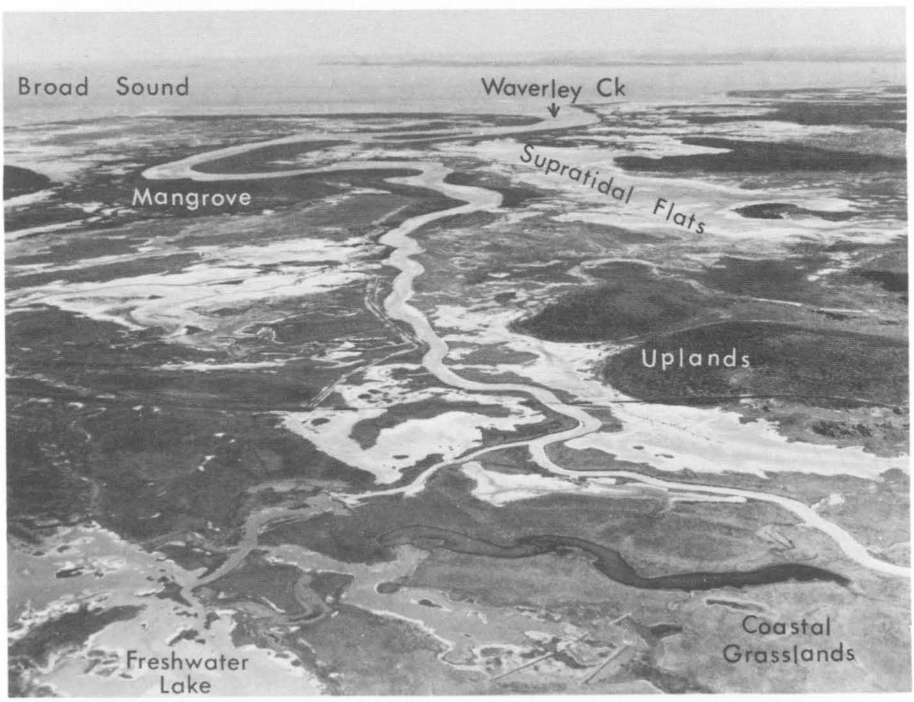


Plate 2, fig. 2. Wide coastal plain flanking Waverley Creek, on the west side of Broad Sound; looking east. (GA/4146)

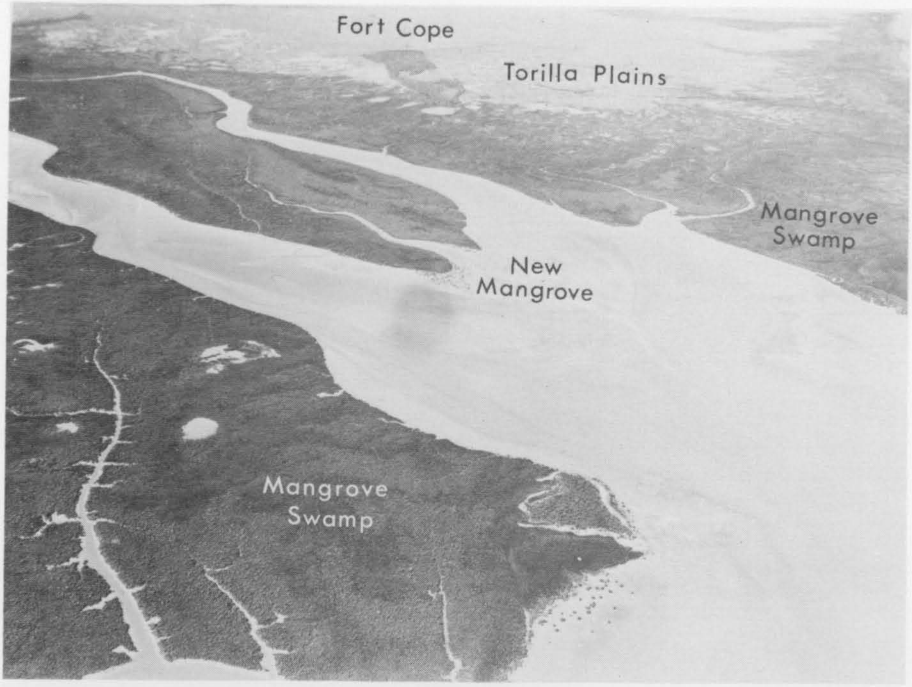


Plate 3, fig. 1. Wide coastal plains on the east side of Broad Sound; looking southeast. (GA/4128)

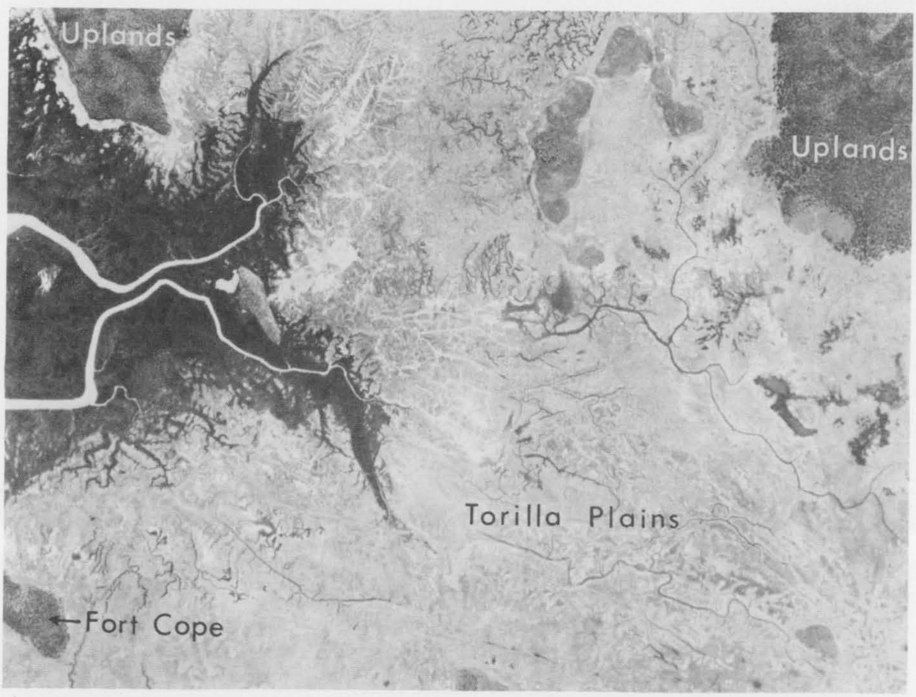


Plate 3, fig. 2. Vertical aerial photograph of Torilla Plains from an altitude of 7500 m. (GA/7832)

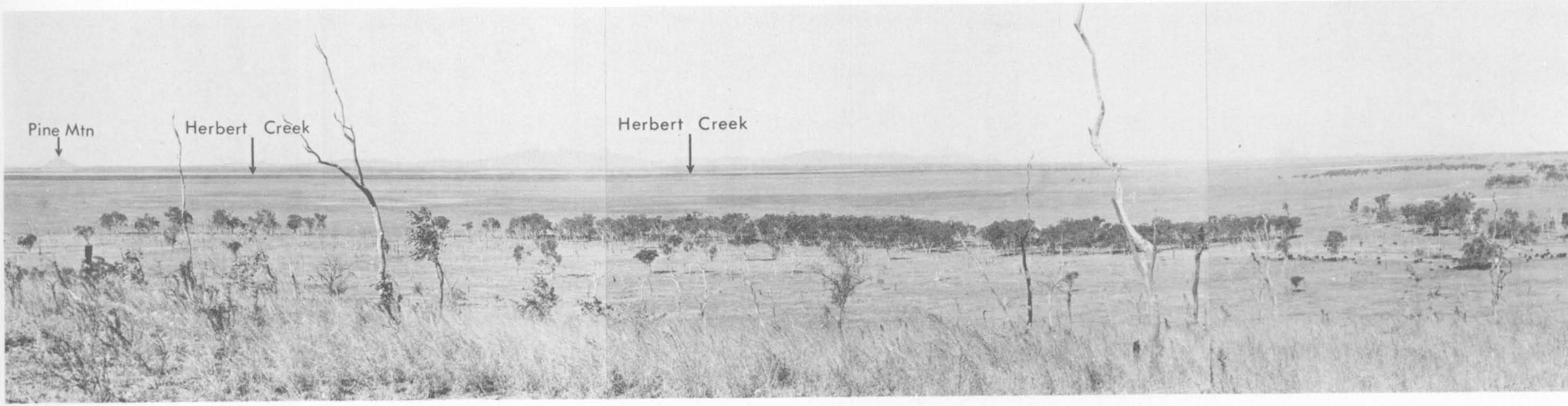


Plate 4. Looking due east over the Glenprairie coastal plains, on the west side of Herbert Creek. (M/1090)

TABLE 1. TIDAL ZONE NOMENCLATURE USED FOR BROAD SOUND
Storm tidal level (12 m)
EXTRATIDAL
High-water springs (11 m)
SUPRATIDAL
High-water mean (10 m)
INTERTIDAL
Low-water mean (1 m)
INFRATIDAL
Low-water springs (0 m)
SUBTIDAL

grasslands are a comparatively young feature which have developed in the past 6000 years or less owing to the seaward growth of the coastal plain in response to the depositional progradation of the intertidal-supratidal deposits. This topic is discussed later. Topographic remnants of this progradation include the wave-cut cliffs occurring up to several km inland in the Torilla Plains area (Pl.6, fig. 1). Old beach ridges are also a feature of the coastal grassland (Pl.6, fig. 2). Though they rise only 1 to 2 m above the surrounding grasslands they are nevertheless prominent topographic features because they support a thick tree cover, in contrast to the treeless coastal grasslands.

The anastomosing drainage pattern characteristic of the coastal grassland (Pl.5, fig. 2) is thought to be the effect of the downward incision of a low-relief drainage pattern consequent on uplift (see later). Examples of stream capture, flow inversion, and abandoned meanders are common. Lagoons occur in some areas where freshwater may persist throughout the dry season. As a result of the extensive water cover and the deep incision of the drainage channels, vehicular travel over the coastal grasslands is always difficult, and frequently impossible.

2. Alluvial plains

Extensive low-relief areas of alluvial deposits are present southeast of the Torilla Plains, west of the Styx River, and flanking Herbert Creek (Fig. 6). These deposits range from fine sands to coarse gravels and vary in thickness from a few metres to tens of metres. In many areas their form is sheet-like, but they have a fan-like morphology in places. Unlike the coastal plains the alluvial plains are quite heavily timbered in places. A poorly developed dendritic drainage pattern is superimposed on the alluvial plains in some areas.

Alluvial plain deposits are of varying origins and ages. Thick coarse-grained alluvial sheet deposits are probably the oldest unconsolidated sediments, and range up to 30 m or more thick (Pl.7, fig. 1) and are indurated in places. They antedate Holocene marine sediments of the Torilla Plains area, which they underlie in Port Clinton No. 5 drillhole (Burgis, 1975), and they could be Pleistocene or older. Overlying the late Holocene marine deposits is a second sequence of alluvial deposits; around the margins of the coastal plain are several alluvial fans up to 2 km long and 0.5 km wide (Pl.7, fig. 2) with prominent levee development.

Alluvial deposits also flank the larger watercourses; some are fairly extensive, and those flanking Herbert Creek are up to 3 km wide (Pl.8, fig.1). The drainage pattern in these areas is characterized by large, well developed meanders and cut-off meanders (Pl.8, fig. 2). The age of the flood plains is uncertain; the surface of most coincides with present-day sea level. As sea level is believed to have attained present level about 6000 years ago (see later) it is probable that many flood plains are late Holocene features. Their underlying deposits may be much older, but no subsurface information is available. Conversely, in places the flood plain flanking Herbert Creek is now being covered by modern alluvial fan deposits (Pl. 9, fig. 1).

3. Uplands

This general term is used for a variety of topographic forms. Uplands on the east side of Broad Sound are composed of low rounded hills underlain predominantly by Lower Palaeozoic metamorphic rocks which have been extensively lateritized. The maximum altitude in this area is about 375 m, but most hills rise to less than 100 m above the surrounding plain. The uplands are generally heavily timbered; the drainage pattern is poorly defined in most areas. A characteristic feature is a series of circular or sub-circular depressions (Pl. 9, fig. 2) ranging in altitude from sea level to tens of metres above sea level, which Burgis (1974) has compared to teardrop lakes developed in lateritic soils of Tabasco, Mexico (West, Psuty, & Thom, 1969) and the baixas of Brazil (Vann, 1963). They are believed to have formed by the sapping of the laterite profile by groundwater.

On the west side of Broad Sound, the main ranges show much greater relief than those of the east, reaching a maximum altitude of 500 m and with ranges commonly attaining heights in excess of 400 m. A lower range runs northeast towards Charon Point, where uplands abut the intertidal zone. The rocks underlying the eastern ranges are predominantly Upper Palaeozoic (Fig. 5), locally mantled by younger colluvial deposits. The lower ranges between Waverley Creek and The Hoogly are composed of flat-lying Mesozoic sediments, which give rise to low mesas adjacent to the coastal plains flanking The Hoogly and Waverley Creek.

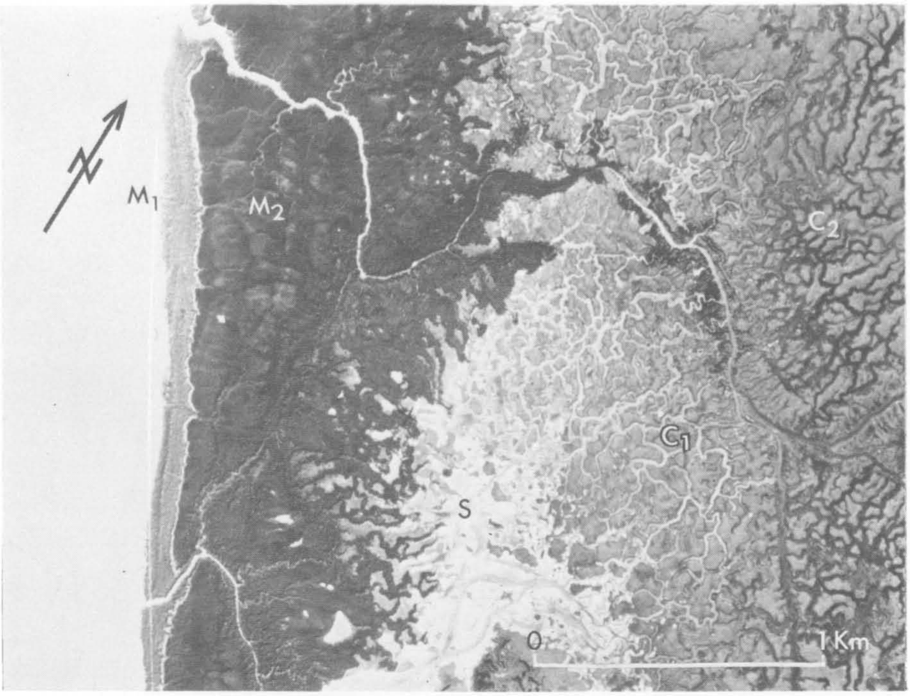


Plate 5, fig. 1. Vertical aerial photograph (altitude 3600 m) of the coastal plains on the east side of Herbert Creek. M_1 — recent mangrove growth; M_2 — thick, older, well established mangrove swamp; S — supratidal flats; C_1 — coastal grasslands with supratidal channels; C_2 — coastal grasslands with freshwater channels. (GA/5906)

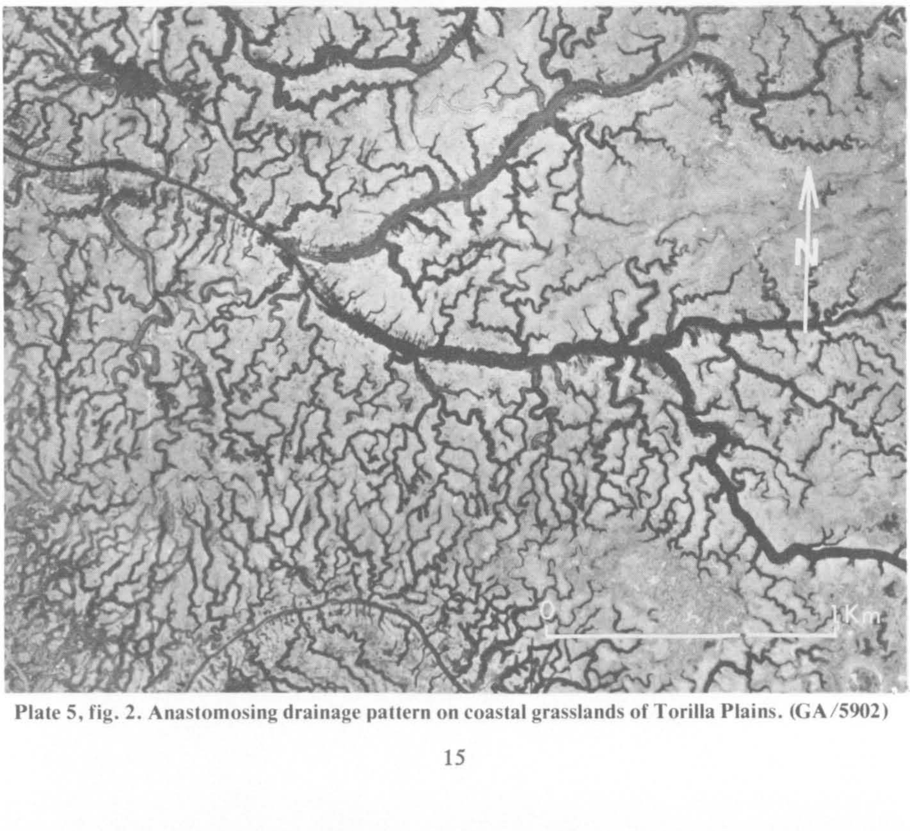


Plate 5, fig. 2. Anastomosing drainage pattern on coastal grasslands of Torilla Plains. (GA/5902)

Plate 6, fig. 1. Holocene wave-cut cliff in lower Palaeozoic metasediments; Torilla Plains. (GA/7863)

Plate 6, fig. 2. Vertical aerial photograph (altitude 3600 m) of the Holocene 'island' of Fort Cope, now surrounded by coastal grasslands. (GA/5902)

Plate 7, fig. 1. Pre-Holocene alluvial conglomerate in the Styx River catchment. (M/1138)

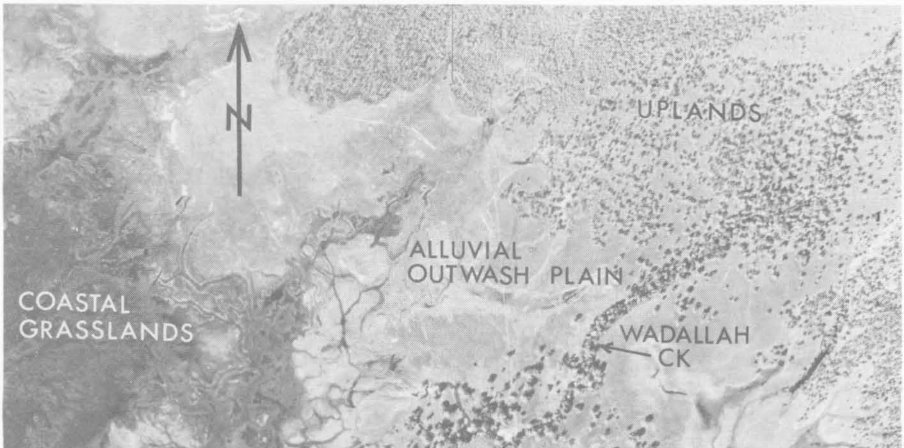


Plate 7, fig. 2. Vertical aerial photograph (altitude 3600 m) of late Holocene alluvial deposits prograding across the coastal plain on the southeast side of Torilla Plains. (GA/5904)

Plate 8, fig. 1. The broad alluviated valley of the upper part of Herbert Creek, looking south. (GA/4095)

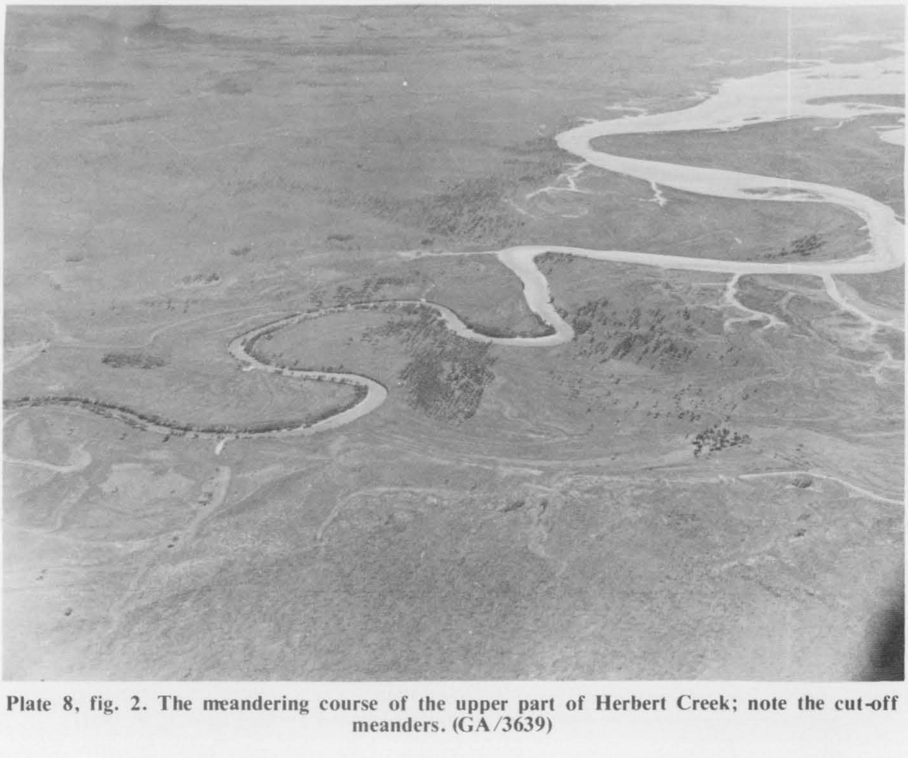


Plate 8, fig. 2. The meandering course of the upper part of Herbert Creek; note the cut-off meanders. (GA/3639)

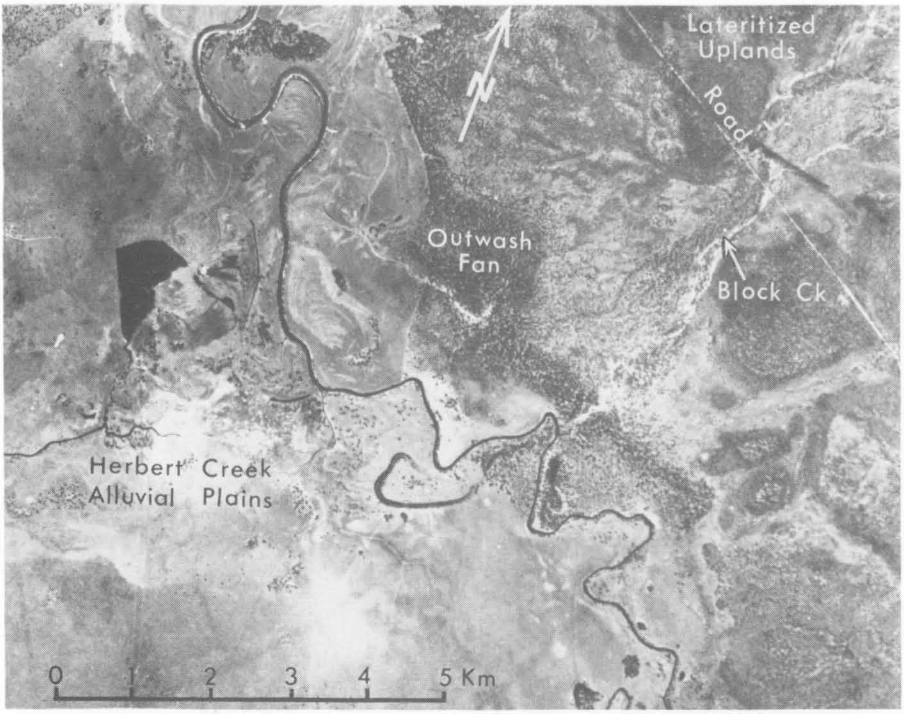


Plate 9, fig. 1. Vertical aerial photograph (altitude 7500 m) of a late Holocene alluvial outwash fan migrating across older Herbert Creek alluvial deposits. (GA/7835)

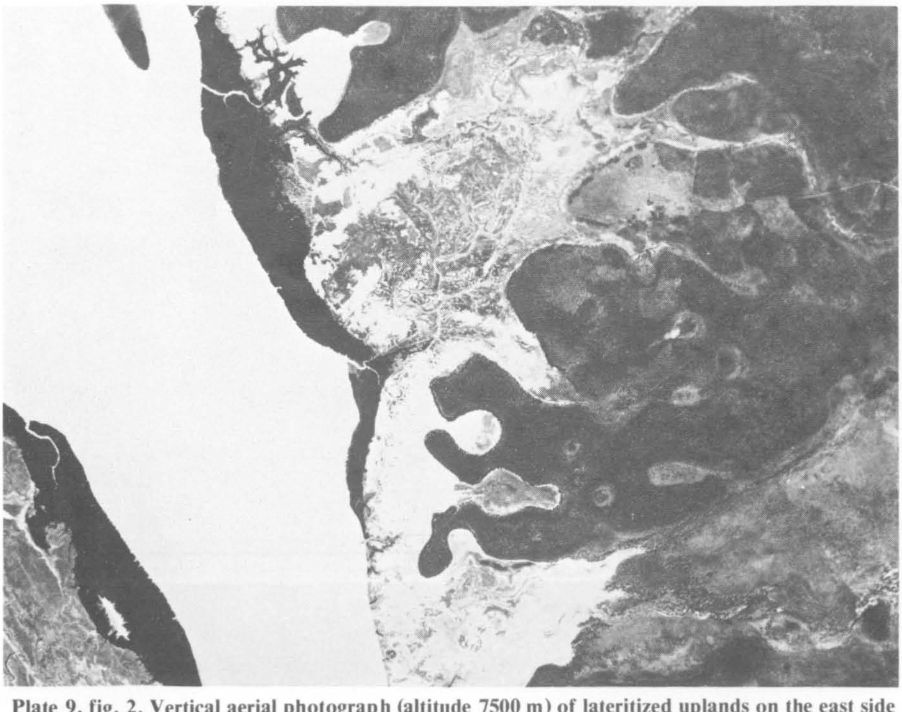


Plate 9, fig. 2. Vertical aerial photograph (altitude 7500 m) of lateritized uplands on the east side of Herbert Creek showing the characteristic circular depressions. (GA/7834)

Plate 10, fig. 1. Looking south down Herbert Creek from the typical funnel-shaped estuary mouth. (GB/4096)

Plate 10, fig. 2. Upper part of the Herbert Creek estuary looking north, showing the meandering form of the tidal channels. (GA/4177)

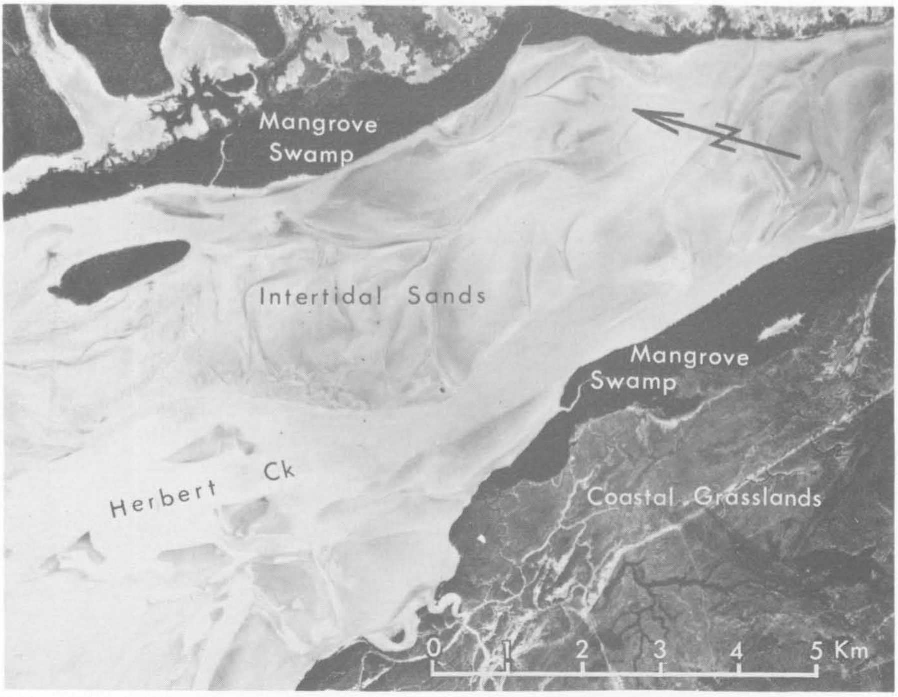


Plate 11, fig. 1. Vertical aerial photograph of part of Herbert Creek (altitude 7500 m) showing the meandering form of tidal channels in the open intertidal sands. (GA/7828)

Plate 11, fig. 2. Elongate intertidal sand bodies in Herbert Creek; looking east. Megaripples are visible in the foreground. (GA/3643)

COASTAL MORPHOLOGY

Estuary shape

It is evident from Figure 6 that all major estuaries entering Broad Sound have the classical funnel-shape (Pl. 10, fig. 1), a feature shown by many estuaries with a large tidal range. Wright, Coleman, & Thom (1973) have demonstrated that the shape of an estuary mouth is primarily a function of the size of the standing wave induced by the tidal regime. They have shown that this relation holds for the estuary of the Ord River in Western Australia, as well as for a number of others. The funnel-shape therefore is essentially the configuration which equilibrates the forces of tidal erosion and depositional progradation. Having now attained this comparatively stable configuration, the funnel-shape of the four major estuaries in Broad Sound should persist in the immediate future unless there is a marked change in the tidal range, the rate of sedimentation, or the rate of uplift.

Sea cliffs

The presence of wave-cut cliffs up to several kilometers inland has been mentioned previously. Cliffs are comparatively rare along the present-day shoreline, particularly in the southern part of the study area (Fig. 6). This is primarily because of the absence of wave-resistant bedrock abutting the coast, except at Charon Point where there are low cliffs composed of Upper Palaeozoic Carmila Beds. Cliffs are more abundant in the northern half of Broad Sound, being prominent at Island Bluff, North and South Red Bluffs, and at the southern end of Long Island. The increase in the extent of cliffed coastline to the north is probably the result of decreasing Holocene sedimentation, so that in the northern areas uplands are not separated from the modern coastline by extensive coastal plains as is the case to the south.

Erosional-depositional coastal features

A low scarp up to 1 m high is commonly found

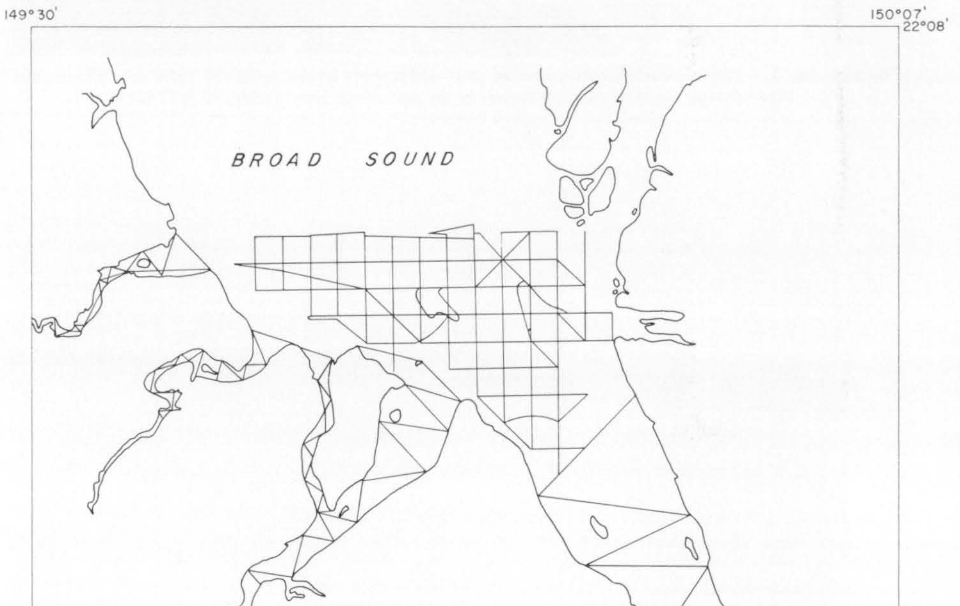


Figure 7. Echo-sounder traverse lines undertaken during 1970 and 1971. The echo-sounder was also run during all seismic traverses (see Figure 88).

on the seaward side of the mangrove swamps, situated approximately at the boundary of the intertidal-supratidal zones. This erosional feature which results both from wave-cutting and slumping following repeated wetting and drying, is widespread around much of the coast (Fig. 6) but is particularly common in the upper and middle reaches of the four major estuaries. Depositional features are evident in some areas, notably at the mouths of the estuaries. Deposition is indicated by the lack of the wave-cut cliff, and commonly by the presence of young pioneering mangrove seaward of the more established mangrove swamp (Pl. 5, fig. 1; Pl. 10, fig. 1). The penecontemporaneous occurrence of erosional and depositional features in adjacent areas is indicative of a present-day phase of sedimentary cannibalism, the Holocene sediments eroded from the upstream regions possibly providing much of the sediment for the actively prograding downstream areas.

Offshore Topography

Before the present survey, no detailed bathymetric surveys had been undertaken in the southern end of Broad Sound. In 1970 and 1971 numerous echo-sounder traverses were made in the area (Fig. 7) and a detailed bathymetric map was prepared (Fig. 8). Features evident from this map are the irregular sea-bottom and the abundant elongate northwest-trending ridges and channels (also shown in Fig. 6). Many of these topographic features are shown schematically in Figure 9, which also shows the concentration of sand-ridges on the east side of Broad Sound, the featureless sea-bottom on the west side, the numerous steep-sided ridges, and the comparatively steep margin flanking the mangrove swamps (though this slope is somewhat oversteepened in Fig. 9 owing to the vertical exaggeration). In a few places, notably near the mouths of the estuaries, outcropping Palaeozoic bedrock produces a rugged bottom topography (Fig. 10). Although Broad Sound is comparatively close to the Great Barrier Reef (Fig. 1) there are no living coral reefs in the study area and few living corals. Small patches of living coral were found only at the southern end of

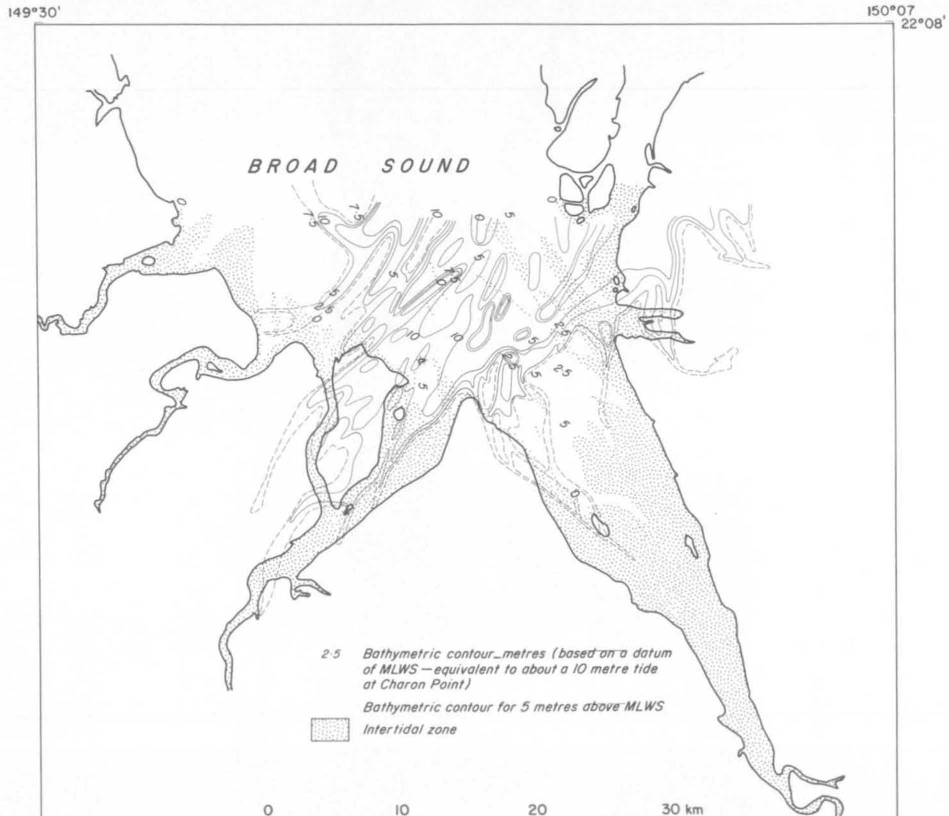


Figure 8. Bathymetry of the southern half of Broad Sound.

C

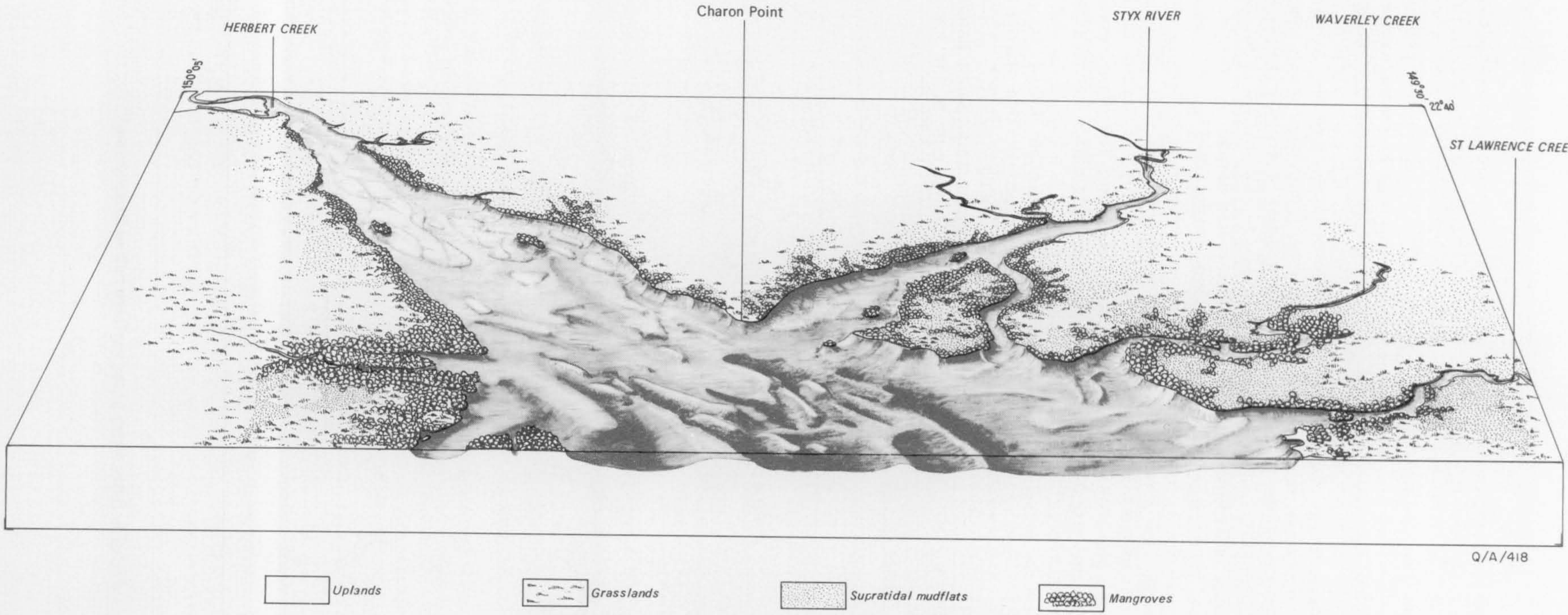


Figure 9. Bottom topography of the southern half of Broad Sound.

Long Island area. A jagged bottom profile at the northern limit of the study area is believed to be pre-Holocene reef, and small patches of pre-Holocene reefal material were found at the mouth of the Styx River.

Channels

In response to the strong currents, tidal channels have developed in many areas. Many channels extend far into the mangrove swamps and in some places into the mudflats. These channels are discussed later. In the upper parts of the estuaries the tidal drainage pattern may be compared superficially to a low-energy braided stream system (Pl. 10, fig. 2; Pl. 11, fig. 1). Farther downstream the channels are less abundant but better defined. On the east side of Broad Sound the channels are flanked by sand ridges. On the west side of the Sound the channels have a well defined U-shaped profile (Fig. 11) which contrasts with the comparatively flat shallow-marine plains of this area. The western channels are best developed near the estuary mouths; they are up to 8 m deep but generally no more than 100 to 200 m wide. In places around outcropping bedrock, scour channels (Fig. 12) may be locally well defined but commonly have little lateral extent. Although some channels are possibly pre-Holocene, most are believed to be Holocene features resulting from the erosion of bottom sediments by tidal currents, possibly assisted at times by freshwater run-off from the estuaries. Undoubted pre-Holocene channels detected on the west side of the Sound by seismic profiling are discussed later.

Sand banks and ridges

Elongate sand bodies of fine to medium-grained sand-size material are a prominent topographic feature of Broad Sound. In the upper reaches of the estuaries the sand bodies are wide, flat-topped sand banks flanked by steep narrow channels. Farther downstream these gradually give way to more discrete elongate sand bodies, and in the northern and eastern portions of the Sound to prominent sand ridges up to 10 km long, 1 km wide, and 10 m high (Fig. 13). The elongate form is apparent at low water from the shape of many of the intertidal sand bodies (Pl. 13, fig. 2.).

The downstream change from sand banks to sand ridges is illustrated by the three echograms of Figure 14. It is apparent from these profiles that these sand bodies are not entirely homogenous as reflection multiples are discontinuous and preferentially located on the edges of banks and ridges. The presence of multiples suggests that in these areas the sediment is either coarser-grained, or alternatively the grain packing differs from the dominant packing type.

Both the intertidal and subtidal sand ridges are everywhere oriented approximately parallel to the tidal currents. Maxwell (1968) considered that the Broad Sound sand ridges are aeolian because of their parallelism with the prominent aeolian dune fields of the Port Clinton area to the southeast. The writers believe that this parallelism is entirely fortuitous, for the ridges appear to be solely the result of tidal processes. At the northern end of Broad Sound, where the tidal currents have a north to northeasterly direction, the sand ridges also have a northeasterly orientation; in addition, radiocarbon dating (see later) has shown that some of the ridges are of late Holocene age, and consequently of subaqueous origin.

Linear sand bodies of the Broad Sound type have been described by Off (1963) from a number of localities. Off also observed the parallelism of these ridges to the tidal currents, and contrasted them with sand waves oriented perpendicular to the current. Small-scale sand waves (megaripples, Pl.11, fig. 2) are a prominent feature of many of the Broad Sound sand ridges which are discussed in some detail later. Off (op. cit.) considered that 'ridges appear to be present wherever tidal current volocities range between 1 and 5 knots and a supply of sediment is available'. The Broad

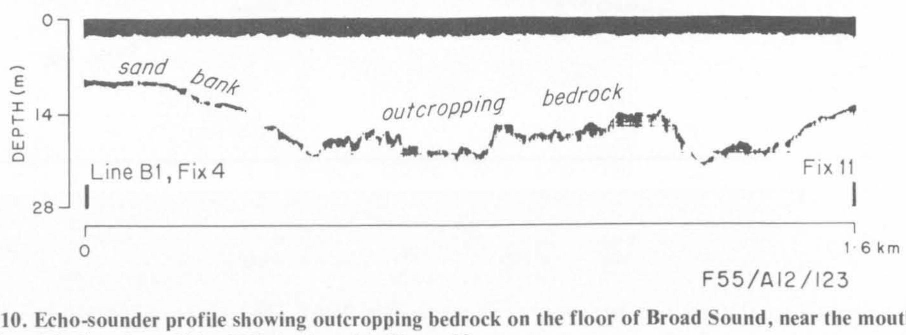


Figure 10. Echo-sounder profile showing outcropping bedrock on the floor of Broad Sound, near the mouth of the Styx River. The location of Line B1 is indicated in Figure 88.

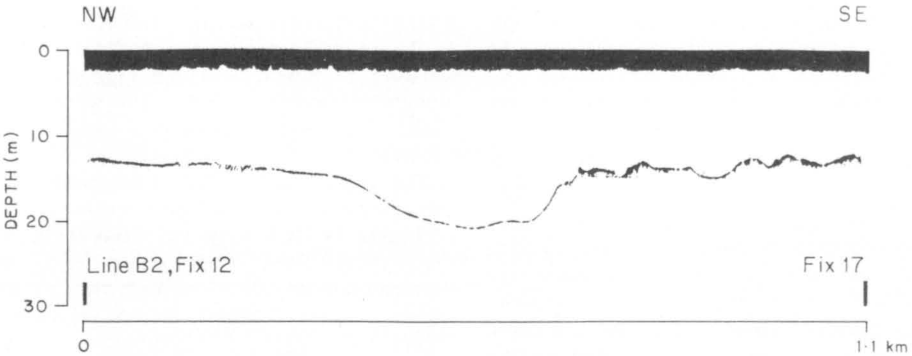


Figure 11. Echo-sounder profile showing a late Holocene channel in the sea-floor on the west side of Broad Sound. The location of line B2 is indicated in Figure 88.

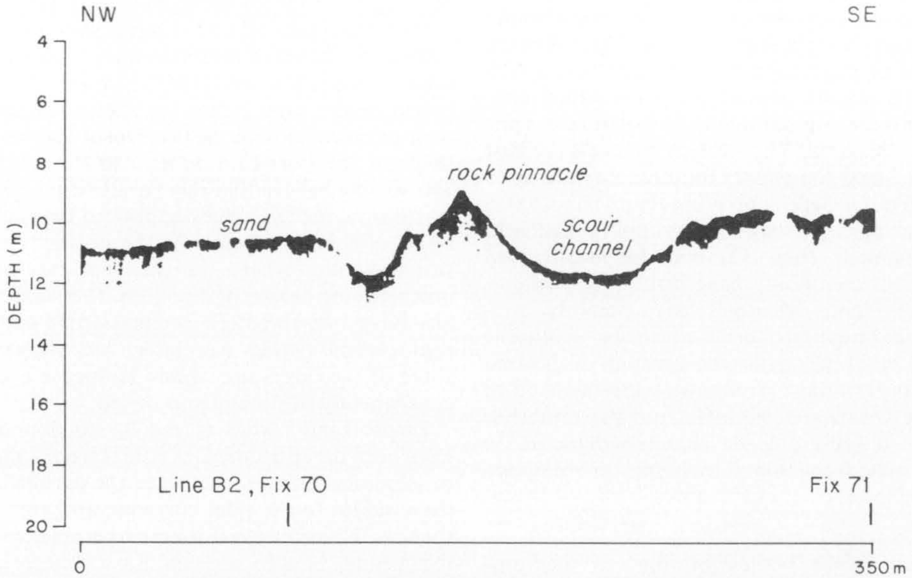


Figure 12. Echo-sounder profile showing scouring around a rock pinnacle. The location of line B2 is indicated in Figure 88.

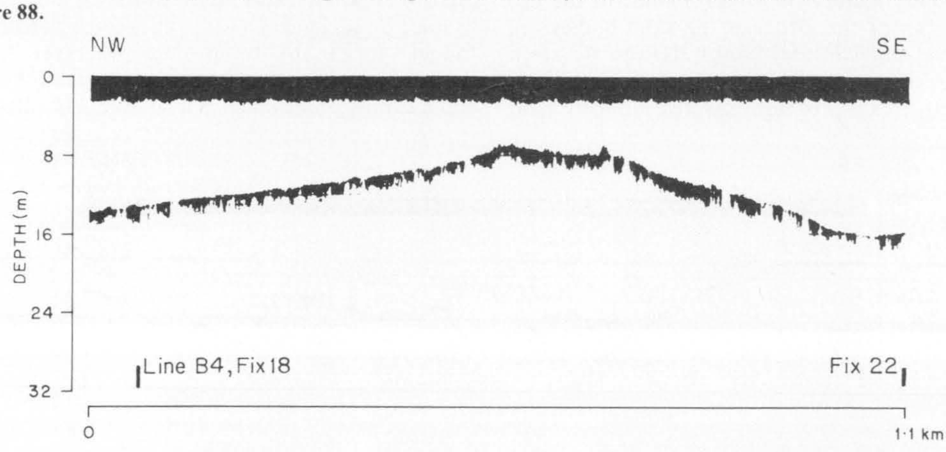


Figure 13. Echo-sounder profile across the southern end of Crocodile Banks. The location of line B4 is indicated in Figure 88.

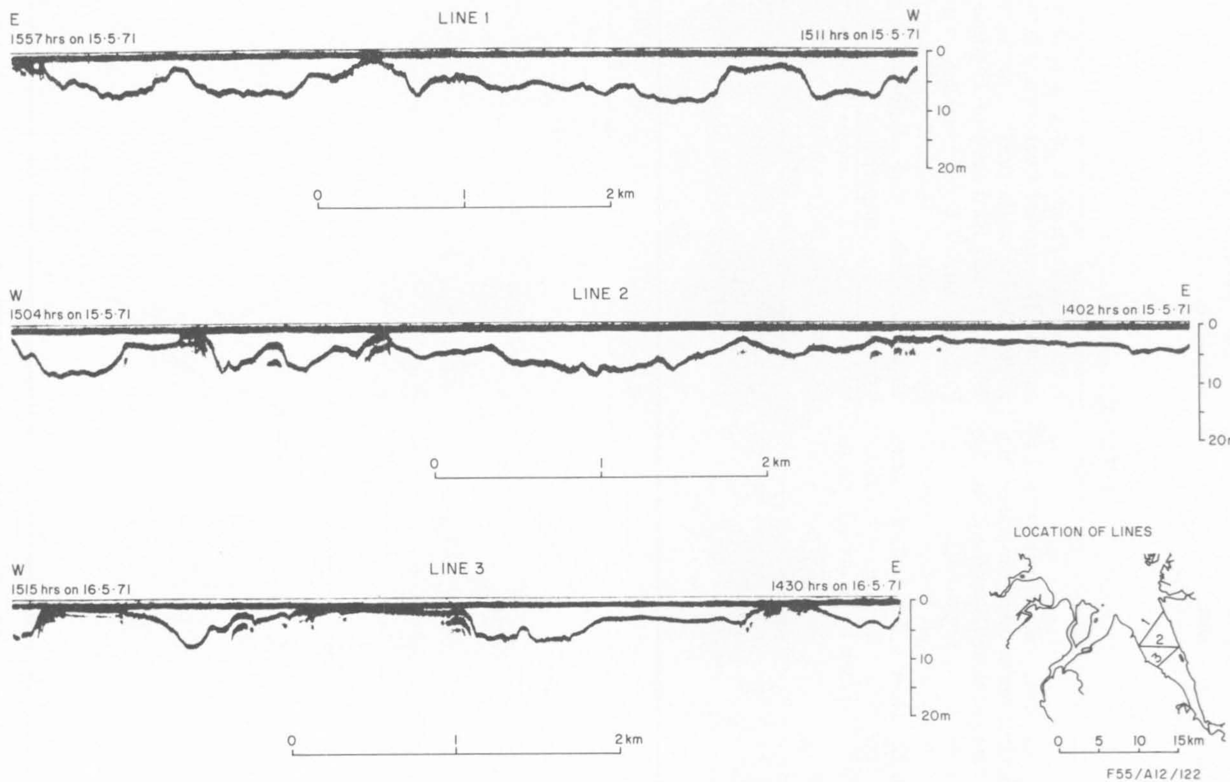


Figure 14. Echo-sounder profiles across sand bodies at the northern end of Herbert Creek.

Sound environment seems to meet both conditions. He suggested that the elongate sand ridges form by the setting up of eddy currents which in turn result in bands of lower current velocity in which the ridges can form; once formed they tend to be self-perpetuating by acting as nuclei for the accumulation of additional sediment. Observations made on the Broad Sound ridges neither support nor refute this hypothesis.

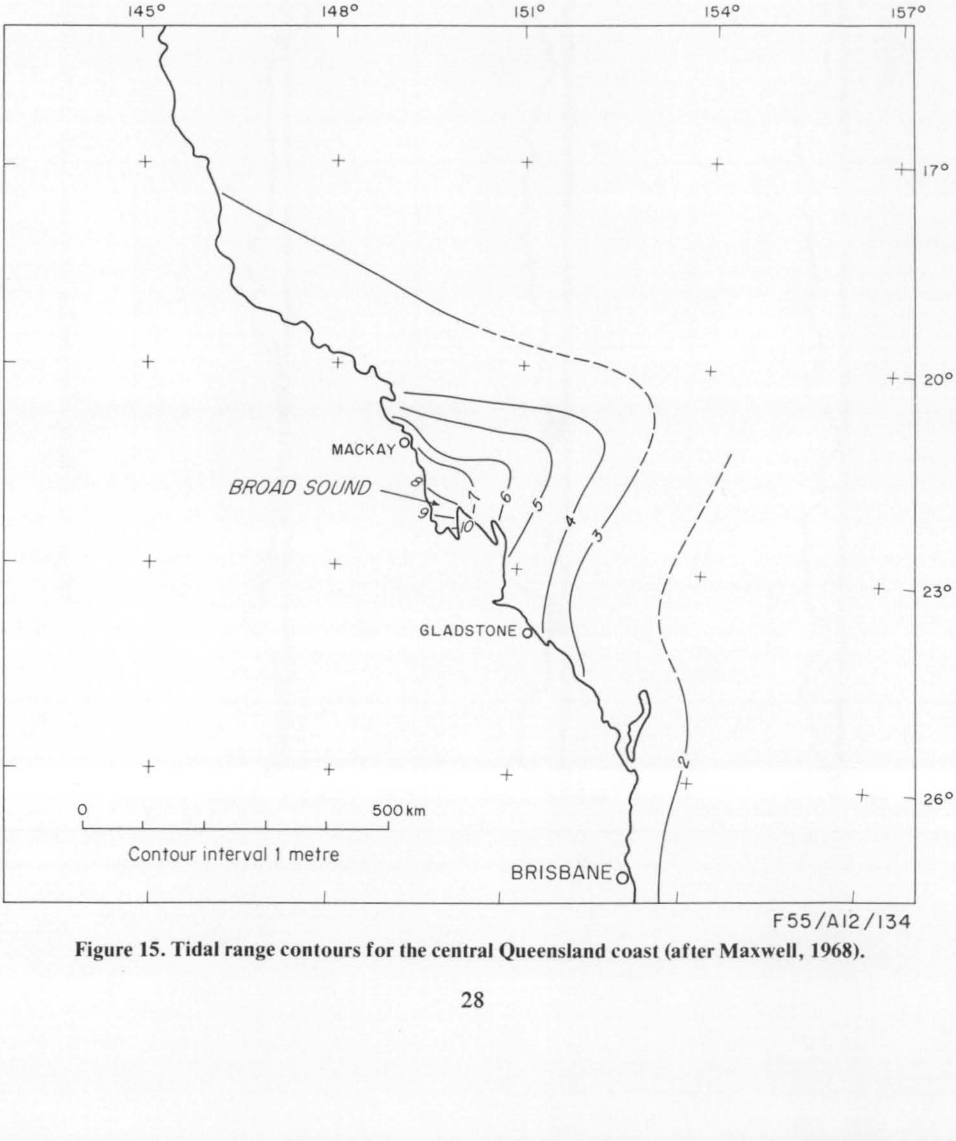
Stratigraphic evidence (including C^{14} dating) suggests that the Broad Sound ridges are migrating longitudinally and the ridges are regarded as the leading edge of a prograding intertidal-subtidal sand body which is moving slowly northwards over the pre-Holocene surface in a manner perhaps analogous to the subaerial migration of seif dune fields.

HYDROLOGY

TIDES

Tides and tidal currents play a dominant role in the establishment of present-day sedimentary and geomorphic patterns at Broad Sound and for this reason will be considered in some detail.

Broad Sound has the highest tidal range in eastern Australia, reaching a maximum spring range of about 10 m. The tidal range distribution near Broad Sound is shown in Figure 15, but no accurate tidal information is available for Broad Sound. The nearest tidal station is at Mackay, about 150 km to the north. The Admiralty Tide Tables record a tidal delay of 25 minutes at Flock Pigeon Island (at the northern end of Broad Sound), compared to Mackay. The writers found an average tidal delay of about 45 minutes at Charon Point compared to Mackay. The delay was in excess of an hour in the upper reaches of



F55/A12/134

Figure 15. Tidal range contours for the central Queensland coast (after Maxwell, 1968).

Herbert Creek and the Styx River. The delay and also the amplitude were, however, highly variable, being influenced to a considerable extent by the direction and velocity of the prevailing wind; highwater can be as much as two hours behind Mackay when a strong southeasterly wind is blowing.

The Broad Sound tides are semi-diurnal, the tide generally ebbing for longer than it floods. The degree of asymmetry of tidal curve is variable and depends on such factors as the tidal range at the time, the prevailing wind, and the degree of restriction of an area. At Charon Point the ebb tide runs for about half an hour longer than the flood. The difference is about an hour in Herbert Creek and near the mouth of The Hoogly. The 'Australia Pilot' (Hydrographic Department, 1962, p. 126) stated: 'In the entrances to St Lawrence and Waverley creeks, the tide rises very fast, the incoming stream running for about 3½ hours and the outgoing stream from about 8½ hours; the winds considerably affect the tides, northerly winds generally retarding and lessening, and southeasterly winds accelerating and increasing the rise'. No such marked asymmetry was noted during 1970 and 1971. Although there is some doubt about the degree of asymmetry in particular areas, over the study area in general the ebb tide runs for about 6.5 hours and the flood tide for about 5.5 hours.

The difference in tidal range between Broad Sound and the standard station of Mackay is quite marked. The Admiralty Tide Tables (Vol. 3, p. 352) recorded 7.9 m at Flock Pigeon Island, with a 5.5-m spring tide at Mackay. The difference increases to the south, with spring tides of up to 10.8 m in Herbert Creek. A chart to correct for the tidal range at Broad Sound given a known tidal range at Mackay is given in Figure 16. The curves are based on tidal readings taken at Charon Point in 1970 and 1971 using calibrated tidal poles. The larger tidal range results in an extensive tidal zone and strong tidal currents. It also results in a tidal bore (or in some instances a series of tidal bores) with a height of up to 0.6 m (Maxwell, 1968, fig. 45) in the upper reaches of Herbert Creek.

The reason for the high tidal range in the Broad Sound area is uncertain. The funnel-shape of Broad Sound undoubtedly accentuates the tidal amplitude, although it could be argued that the funnel-shape is the result rather than the cause of the high tidal range. However, it is evident from Figure 15 that the entire coast from Port Clinton to Mackay is a region with a high tidal range. Easton (1970, 46) stated: 'Tides near Mackay are influenced by the offshore break in the Great Barrier Reef and the presence of Broad Sound. Being at the junction of two different zones, the times of high and low tides differ more in this region.' Both Easton (1970) and the 'Australian Pilot' (Hydrographic Department, 1962) pointed out that within about 100 km of Broad Sound the tidal streams on the rising tide converge on the Sound, and on the falling tide diverge from it.

TIDAL ZONES

There is no generally accepted scheme for tidal zone nomenclature, possibly because no single scheme is universally applicable. Consequently, as it was considered necessary to define tidal zones at Broad Sound, it was also desirable to name these zones. The scheme adopted in Table 1 was found to be useful because of the close relation between physiographic features and depositional environments and the tidal cycle. The meanings of most of the terms used are largely self-evident; the prefixes are considered to be etymologically correct.

The subtidal zone extends from low-water springs down, and is never subaerially exposed. The infratidal zone is only rarely subaerially exposed, perhaps only three to four times a lunar month during spring tides. It is defined as the tidal zone between low-water mean and low-water springs levels. It is a difficult portion of tidal cycle to determine in the field because of the lack of accurate information at Broad Sound. The intertidal zone is defined as that portion of the tidal cycle between low-water and high-water mean tidal levels. It is vertically the most extensive of the zones; sediments within this zone are subaerially exposed every semi-diurnal tide. The supratidal zone is taken as that portion of the tidal cycle between the high-water mean and high-water springs levels. It could perhaps be argued that the prefix 'supra' (meaning 'above') cannot be applied here because the zone is below the high-water springs level. However, the prefix as applied here conforms with that commonly followed in geological literature (e.g. Lucia, 1972), and refers to normal tides and not spring tides i.e. above normal tidal level or supra (normal) tidal. This same philosophy holds for the prefix 'infra' in infra (normal) tidal.

The term extratidal is applied to the zone between the high-water springs level and the level reached by exceptional storm or cyclonic tides. This is a difficult zone to define in the field because no such storm tides were observed by the writers; however, it is estimated that such storm tides can reach up to 1 m above the high-water springs level. This water level may be elevated during the wet season by freshwater inflow which may result in an extensive brackish extratidal zone.

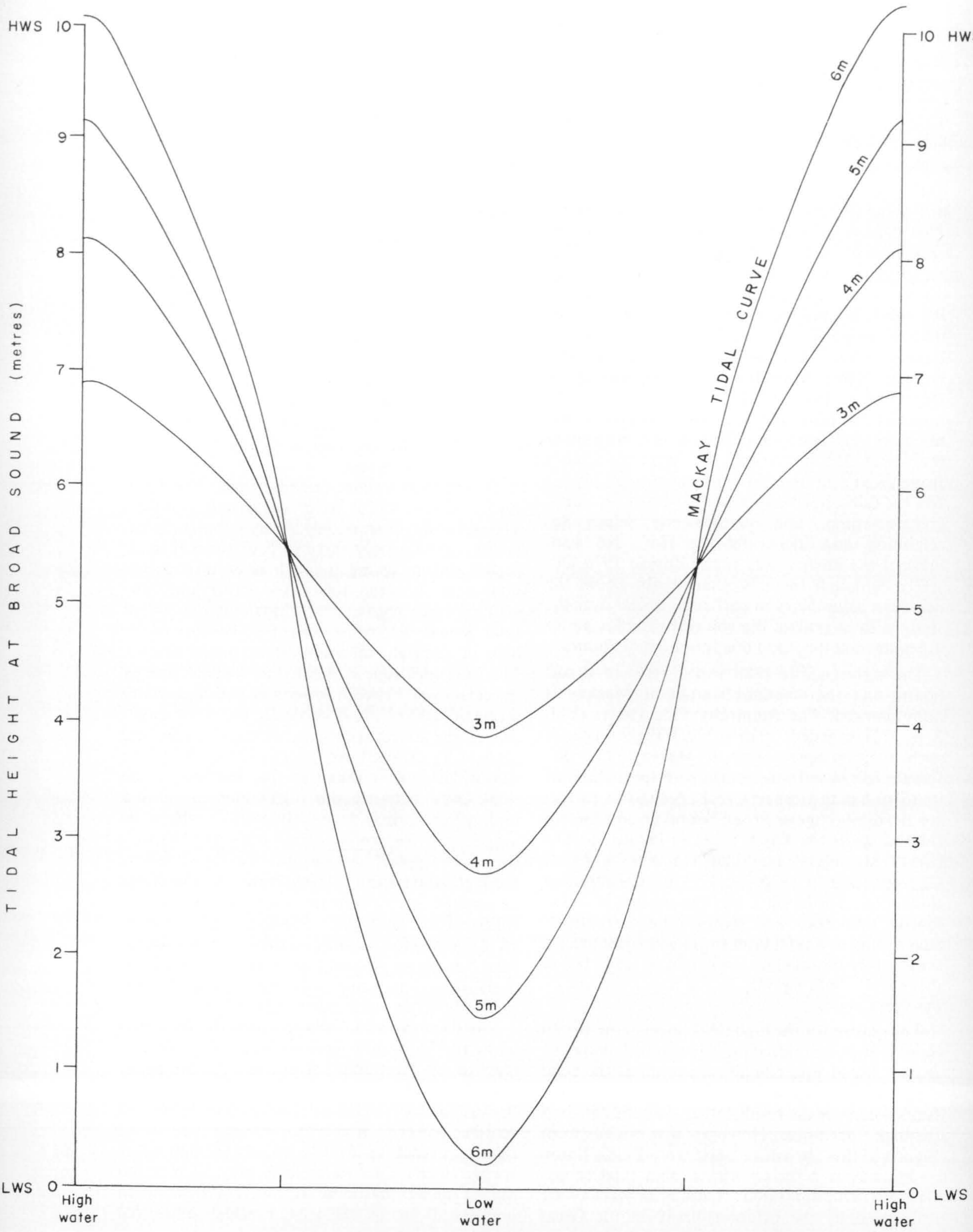


Figure 16. Translation of known Mackay tidal curves into Broad Sound tides.

TIDAL CURRENTS

As a direct result of the high tidal range, tidal currents are strong in Broad Sound; the 'Australia Pilot' (Hydrographic Department, 1962) recorded current velocities of up to 6 knots. The 'Australia Pilot' also noted that the tidal stream sets between south and east into Broad Sound and ebbs between north and east out of it. The impression was gained from the earlier arrival of the tidal peak on the east side of the Sound, and from the orientation of sand bodies that the flood tide tends to enter along the east side of Broad Sound and ebb along the west side, thus producing a net clockwise motion of currents and sediments. It might also be expected from theoretical consideration that this is the direction of flow which would be induced by the Coriolis Force.

Current observations were made over a number of tidal cycles at various locations during 1971 in order to determine the magnitude and behaviour of Broad Sound currents. The maximum current measured was 1.2 m/s (approximately 3 knots). Direction and magnitude of tidal currents as given in the 'Australia Pilot' (op. cit.), and Admiralty Chart No. Aus. 822, and determinations made in the field are given in Figure 17. General observations which may be made are that at any location the ebb and flood currents may have markedly different velocities and also that the current velocity decreases with depth.

A typical current velocity curve, determined near Turtle Island, is shown in Figure 18; the effect of current diminution closer to the bottom is not evident because of the depth of water ranging from 8 to 16 m and the current meter could not be submerged below a depth of about 5 m. The tendency of the flood current to set about south-southeast and the ebb current to set about due north is evident from Figure 18.

Current velocities determined in The Hoogly show clearly the general tendency of decreasing velocity towards the bottom (Fig. 19). One feature to be noted is that for a brief period after high water, the bottom current has a higher velocity than the surface current, presumably an indication that the bottom waters begin to ebb before the surface waters. A further series of

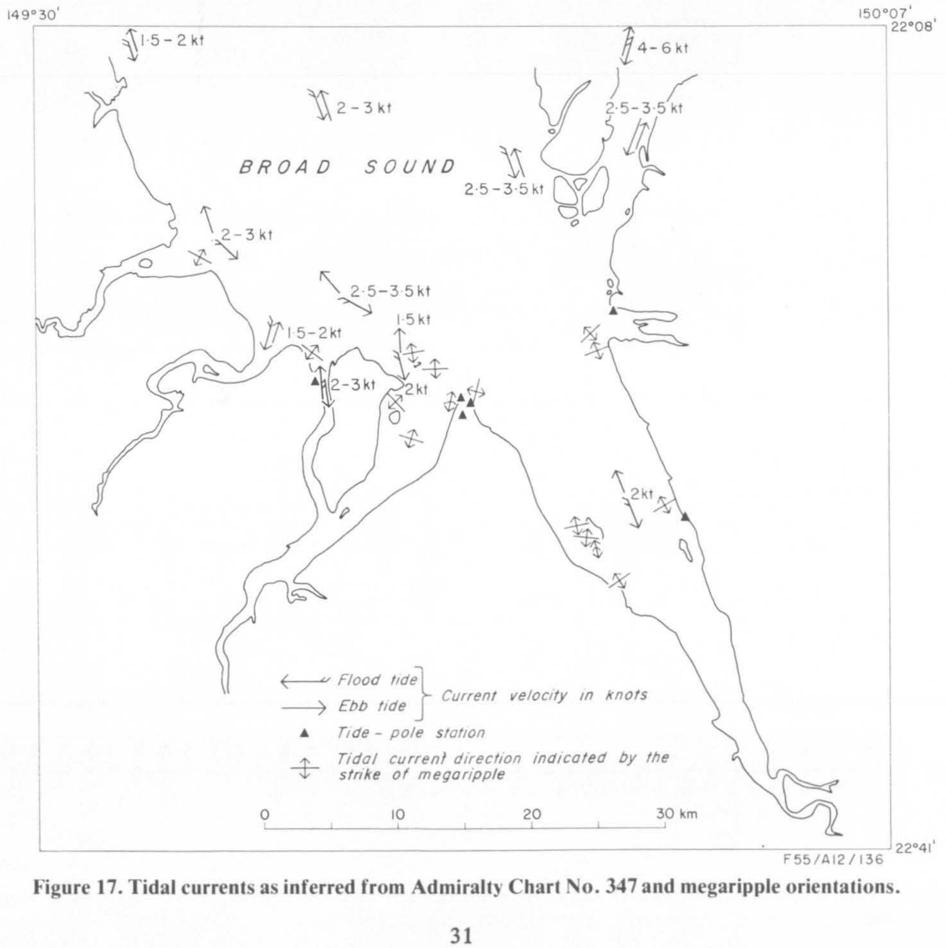


Figure 17. Tidal currents as inferred from Admiralty Chart No. 347 and megaripple orientations.

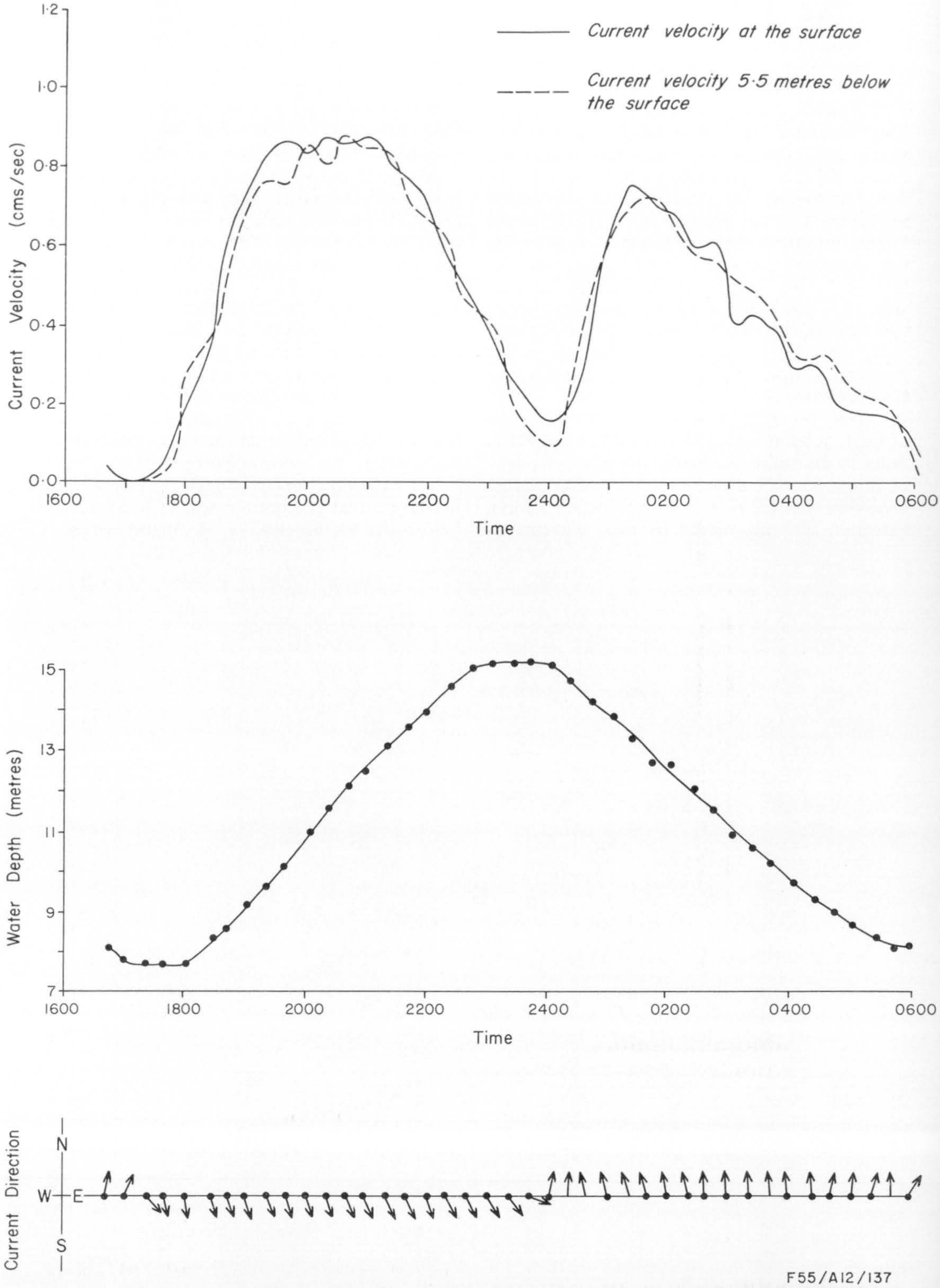


Figure 18. Tidal amplitude and current velocity over a tidal cycle 1600 on 22 June 1971 to 0600 on 23 June 1971, Turtle Island.

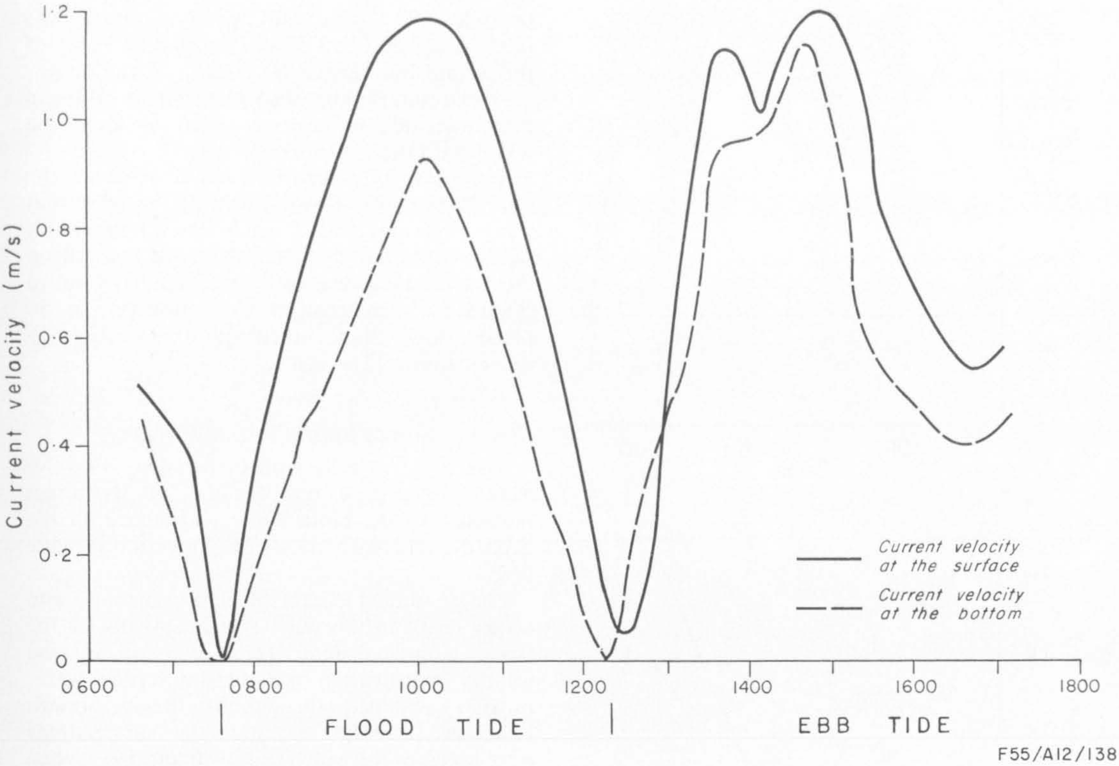


Figure 19. Current velocities determined over a tidal cycle 0600 to 1800 on 25 May 1971, in the main channel of The Hoogly.

current velocity determinations were made over megaripples in the central part of Herbert Creek (Fig. 20). Minimum current velocities occur in the bottom waters (Fig. 21), presumably the effect of friction at the sediment-water interface. One feature of all the velocity curves is that the period of slack water at high or low water lasts for only a half-hour or less. This results in the waters at the southern end of Broad Sound invariably being turbid and always carrying a substantial suspended load. The combination of extreme turbidity and high energy has a marked effect on sediment distribution and generally results in hostile conditions for the biota.

Wave Activity

No quantitative data are available on wave frequency, amplitude, or wavelength. General observations during the 1970 and 1971 field seasons suggest that there is considerable wave activity in Broad Sound. Major wave activity was noted when a northeasterly or southeasterly wind

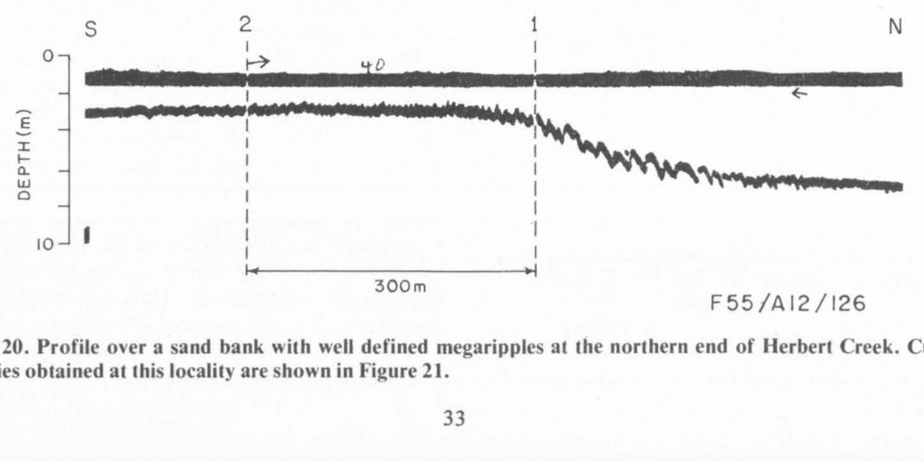


Figure 20. Profile over a sand bank with well defined megaripples at the northern end of Herbert Creek. Current velocities obtained at this locality are shown in Figure 21.

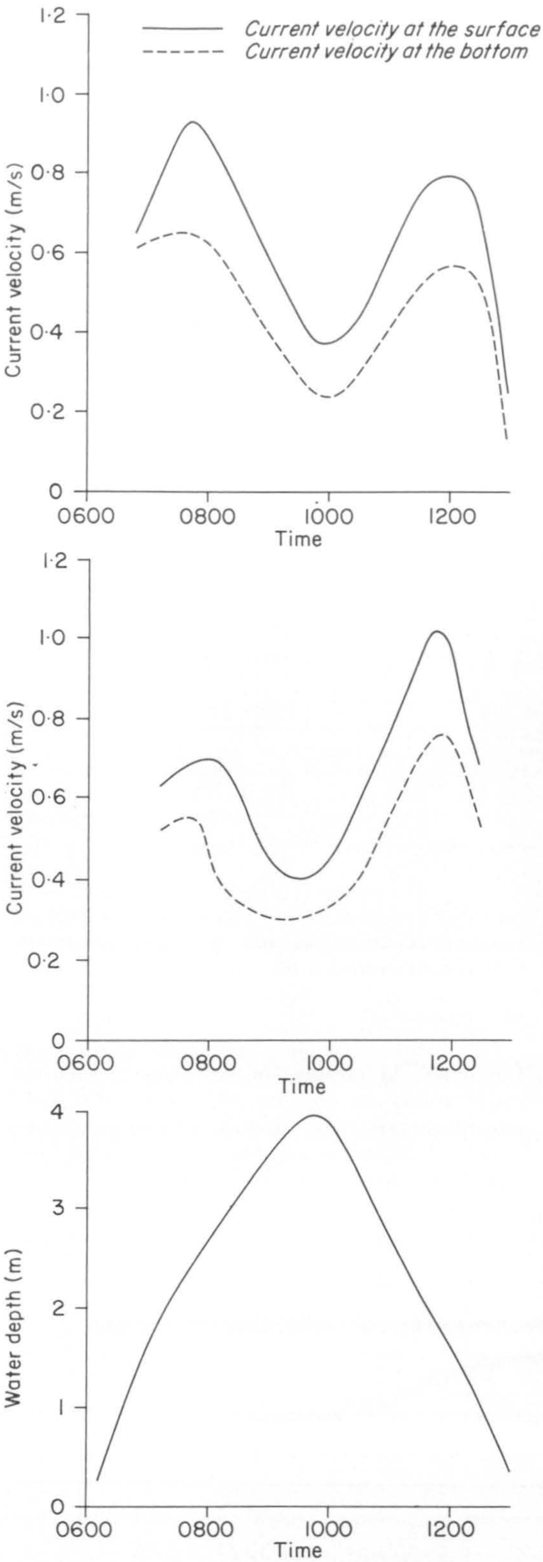


Figure 21. Current velocities over the sand bank shown in Figure 20. Localities 1 and 2 are indicated in Figure 20.

prevailed. The maximum wave amplitude was in the order of 1 to 1.5 m in the southern part of the Sound but ranged up to 2 m at the deeper northern end. Because the southern part of Broad Sound is shallow and restricted in area, the wavelength there is short.

Wave activity was particularly severe when the tidal current was flowing against the wind and wave direction, and at such times treacherous seas were encountered. It is estimated that during the two field seasons, seas were relatively calm to slight for 25 percent of the time, moderate for 50 percent of the time, and comparatively rough for the remaining 25 percent.

Composition of Broad Sound Waters

This topic is dealt with in detail by Cook & Mayo (in prep.), but because of its direct relevance to the biota and its influence on the depositional environments brief mention is made here.

The combined effects of tides, currents, and waves result in thorough vertical mixing of the Broad Sound waters. There was no vertical salinity stratification in numerous vertical water profiles obtained throughout Broad Sound. However, it should be noted that all readings were taken in the winters of 1970 and 1971 when there is little or no freshwater runoff. Local residents reported that at periods of extreme summer flooding The Hoogly 'runs fresh' at low water and at such times there may be limited stratification. However, because of the prevalence of high-energy conditions at Broad Sound such stratification is likely to be short-lived and of limited areal extent.

Extensive sheets of brackish water cover the coastal plain during the wet season, the result of freshwater runoff mixing with marine overflow from spring and storm tides. The area inundated by brackish water is being progressively reduced by erecting dams across the coastal plains in the Torilla Plains area, on Glenprairie station, and in areas flanking Waverley Creek, to prevent the influx of salt water.

No measurable freshening of open Broad Sound waters was observed during the winter; waters were invariably marine with salinity ranging from 36 to 38 parts per thousand total dissolved salts. In one instance after heavy rain, dilution by fresh water was observed in a mangrove channel. A more common situation, however, is for hypersaline waters to occur in the mangrove channels owing to runoff from the hypersaline supratidal flats bordering the mangrove. This is particularly apparent during spring tides when large volumes of water flood over the hypersaline sediments.

A typical salinity profile over a tidal cycle in a mangrove channel near Charon Point is shown in Figure 22 and it is apparent from this that there is a marked increase in salinity from 36 parts per thousand at high water to 46 parts per thousand at low water. Because of this hypersaline inflow, parts of Broad Sound could probably be regarded as a vertically mixed inverse estuary (following the usage of Pritchard, 1967) for at least half the year.

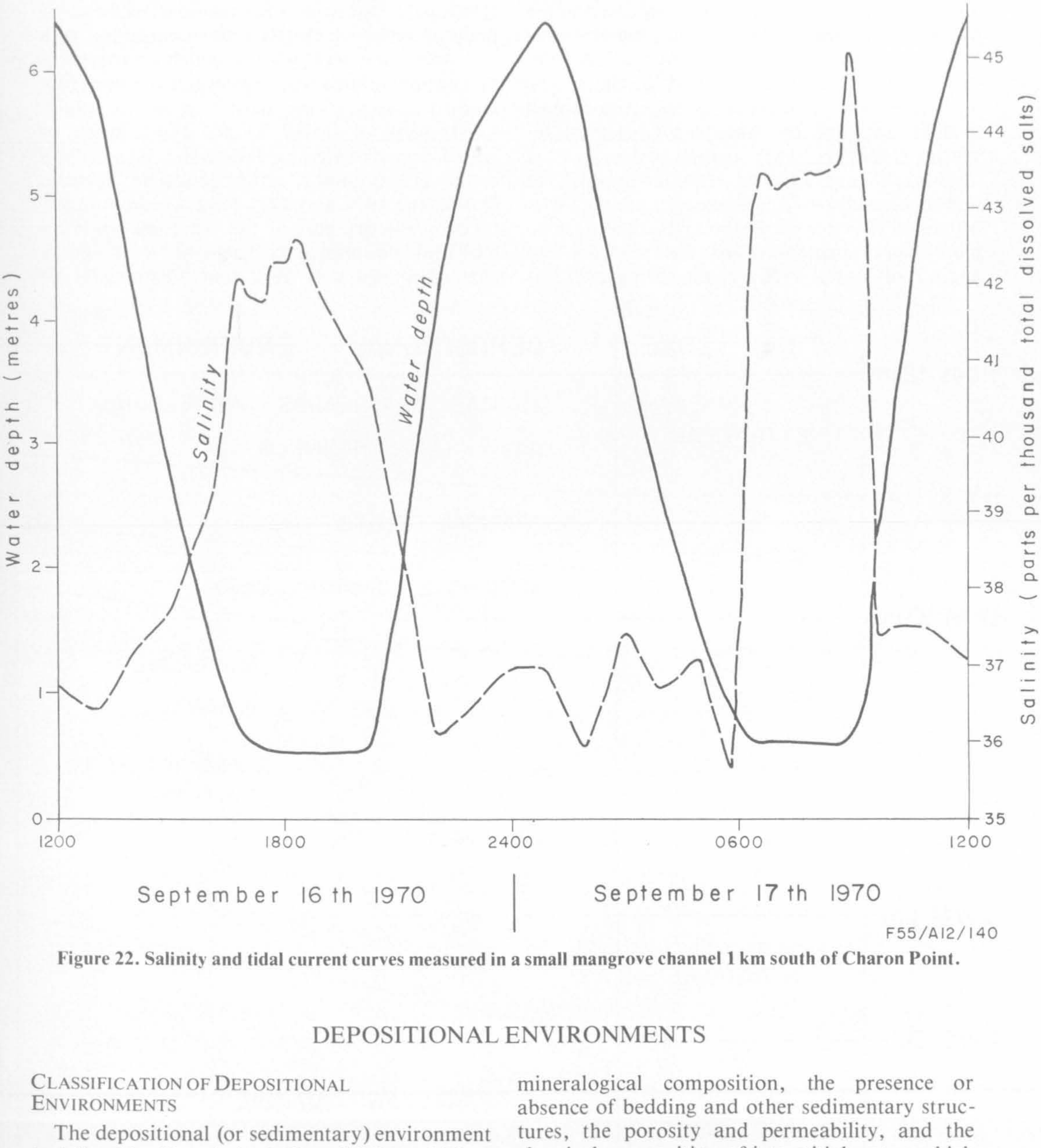


Figure 22. Salinity and tidal current curves measured in a small mangrove channel 1 km south of Charon Point.

DEPOSITIONAL ENVIRONMENTS

CLASSIFICATION OF DEPOSITIONAL ENVIRONMENTS

The depositional (or sedimentary) environment is defined by Krumbein & Sloss (1963, p. 234) as 'the complex of physical, chemical, and biological conditions under which a sediment accumulates'. These conditions influence the grain-size of sediment, their chemical and mineralogical composition, the presence or absence of bedding and other sedimentary structures, the porosity and permeability, and the chemical composition of interstitial waters which in turn influence the diagenetic changes which take place in the sediments after burial. Consequently, an understanding of processes operating within depositional environments is fundamental to our understanding of both modern and ancient sediments and therefore depositional environments will be described in some detail.

There is no universally accepted classification of sedimentary environments; terms such as transitional, littoral, near shore, bay, and marine are all applicable in varying degrees to describe the overall Broad Sound environment, but the most logical term in view of its location at the confluence of four rivers would seem to be 'estuarine'. The term estuarine has been defined in different ways: the American Geological Institute (1962, p. 167) defines estuary as a 'drainage channel adjacent to the sea in which the tide ebbs and flows. Some estuaries are the lower courses of rivers or smaller streams, others are no more than drainage ways that lead seawater into and out of coastal swamps'. On the basis of this definition the southern half of Broad Sound is regarded as an estuary. Schubel & Pritchard (1971) gave ten different definitions of an estuary, most of which would encompass Broad Sound. Perhaps the most widely accepted definition of an estuary is that given by Pritchard (1967, p.3): 'An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage'. This definition is not fully satisfactory for Broad Sound. The dilution of Broad Sound water by freshwater is mostly a comparatively minor, rather ephemeral feature. During the 1970 and 1971 field seasons (undertaken in the dry part of the year) there was no measurable dilution except in a single mangrove channel immediately after rain. Conversely, an

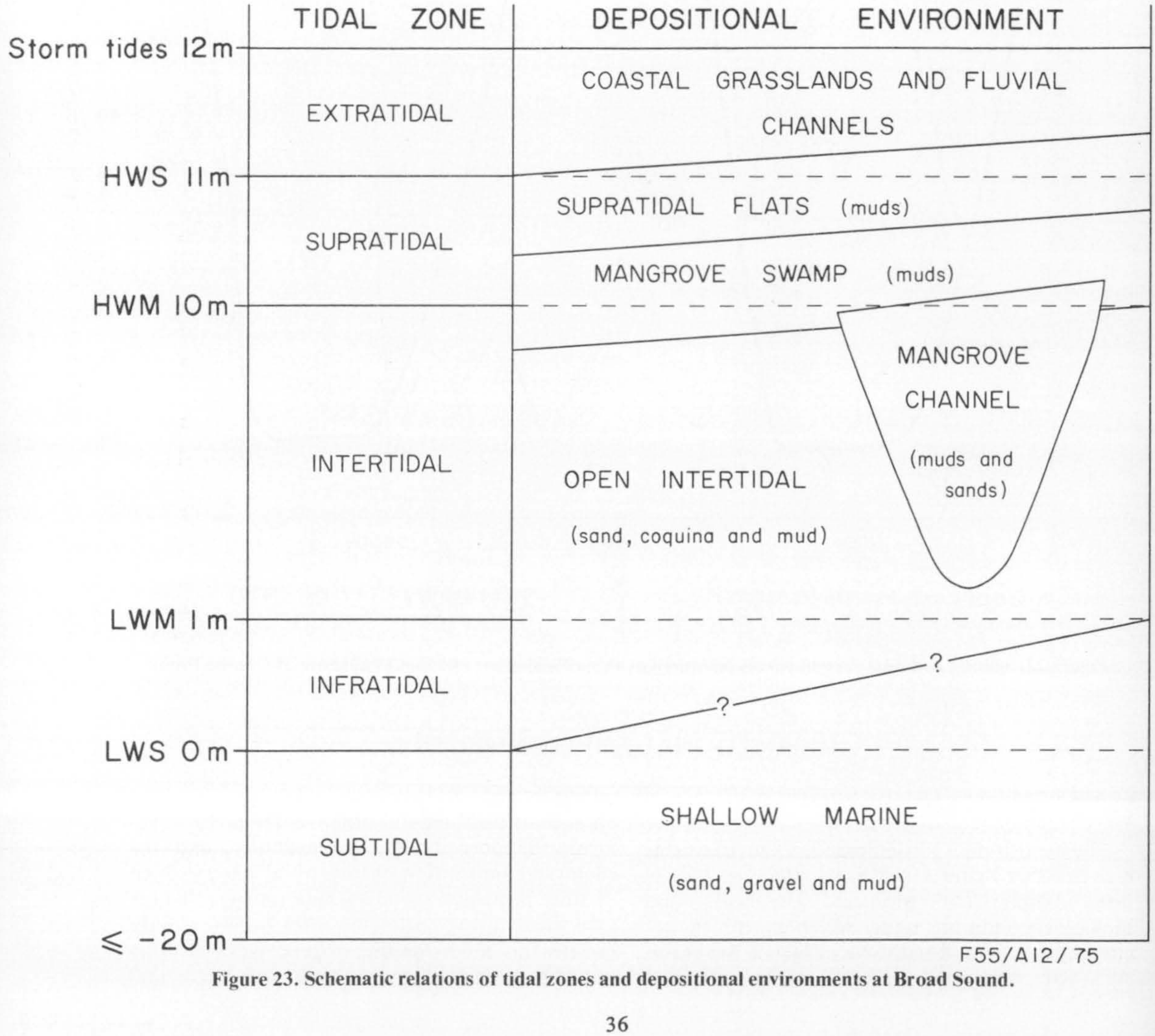


Figure 23. Schematic relations of tidal zones and depositional environments at Broad Sound.

increase in salinity as a result of runoff from the saline flats landward of the mangrove was observed on a number of occasions. Pritchard has suggested the term 'inverse estuary' where there is hypersaline inflow. However during the wet summer months, there is at times significant dilution of sea water, particularly after cyclonic storms. The seaward extent of this dilution is not known. It may extend to the funnel-shaped mouths of the four main river courses, and perhaps for several kilometres beyond, after exceptionally heavy runoff. However, the high tidal range and the associated strong tidal current probably soon disperse the freshwater runoff, resulting in a re-assertion of the marine influence. Thus, because of these features, Broad Sound perhaps cannot be regarded as typically estuarine but rather as an ephemeral estuarine complex.

To regard the depositional environment solely as 'estuarine' is rather meaningless in the Broad Sound context because of the wide range of depositional conditions found under this all-embracing term. Consequently a more detailed (and more meaningful) break-down of environments is necessary. All the important sedimentary processes in Broad Sound are the direct or indirect result of the high tidal range, and the location of an area or a body of sediment within that tidal range. Consequently the appropriate tidal term, such as open intertidal, is used for a number of environments. The other important though inter-related factor influencing the depositional conditions is the biota in Broad Sound, particularly the presence and abundance of mangrove. The environmental significance of mangrove lies in its role as a sediment trapper and binder and in its ability in areas where it is exposed to the open sea to convert a high wave-energy environment into a low-energy environment. It is in addition a diverse adaptable group of plants which extends from the intertidal zone high into the supratidal zone.

The terms used for the various depositional environments and their relative position within the tidal cycle are shown schematically in Figure 23. The derivation of the terms is self-evident, and most are either in general use or have previously used for similar environments by other workers. The use here of the term 'supratidal flat' does not conform to the usage of some in Australia, such as Logan (1971) and Thom et al. (1974), who regarded the supratidal zone as being above the level of all but exceptionally high spring or storm tides. The usage followed here is consistent with that of Shinn et al. (1965) who stated that 'the supratidal zone lies above normal high tide but can be flooded by spring or storm tides'. This terminology is also used by Lucia (1972, p. 160) who defined the supratidal zone as '. . . that area of

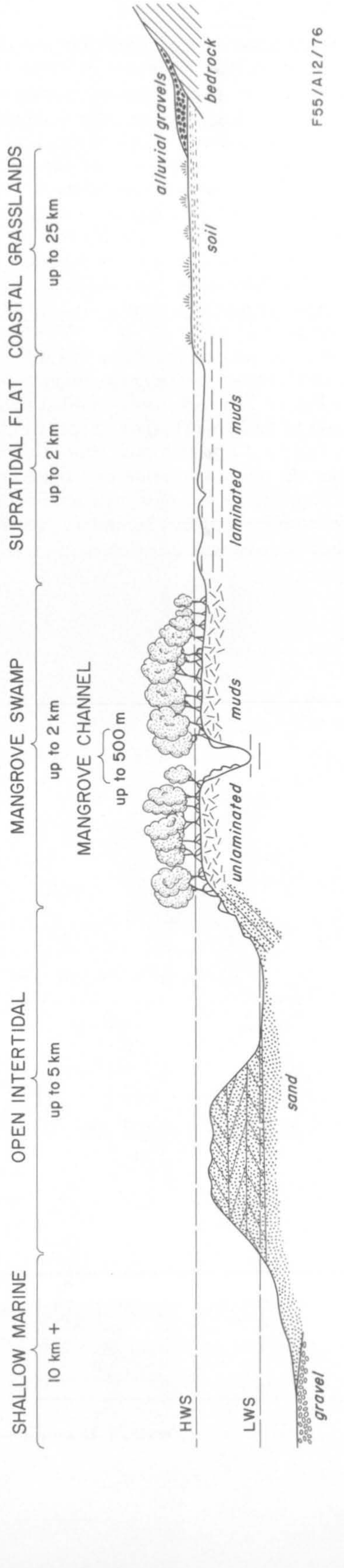


Figure 24. Schematic representation of the depositional environments at Broad Sound.

tidal flat sedimentation out of reach of the daily tides. Its elevation may be higher or lower than the mean high tide mark. This environment is covered only by spring or storm tides and lies exposed subaerially for long periods of time'.

The term 'open intertidal' is used for the environment extending seaward from the outer edge of the mangrove swamp environment to the base of the intertidal zone. This contrasts with the mangrove channel environment which also lies within the intertidal zone but which is areally restricted, and at times also chemically restricted.

The lateral relations of the various environments is shown schematically in Figure 24. The areal distribution of the environments is indicated in Figure 25 which was compiled from a combination of bathymetric data, airphoto interpretation, and field observations. From this, it is evident that the shallow marine and open intertidal environments are the most extensive depositional environments. The boundary between them cannot be fixed with any degree of certainty in the field because of the large tidal range. The boundary in Figure 25 is taken at the top of the subtidal zone as determined from the bathymetric map (Fig. 8). Both the open intertidal/mangrove swamp and the mangrove swamp/supratidal flat boundaries, though gradational over a few metres, are nevertheless readily established both in the field and from aerial photographs. The supratidal flat/coastal grassland boundary is also comparatively easy to establish in most areas, except where the mudflats extend into the extratidal zone and the boundary with the grassland is gradational. The mangrove channel environment is the most restricted of the Broad Sound depositional environments. It is, however, readily distinguishable as a separate environment with several unique processes operating within it. Although it is undoubtedly possible to divide these environments into sub-environments, such sub-environments are essentially a response to localized and generally ephemeral processes operating within the main environment. It is

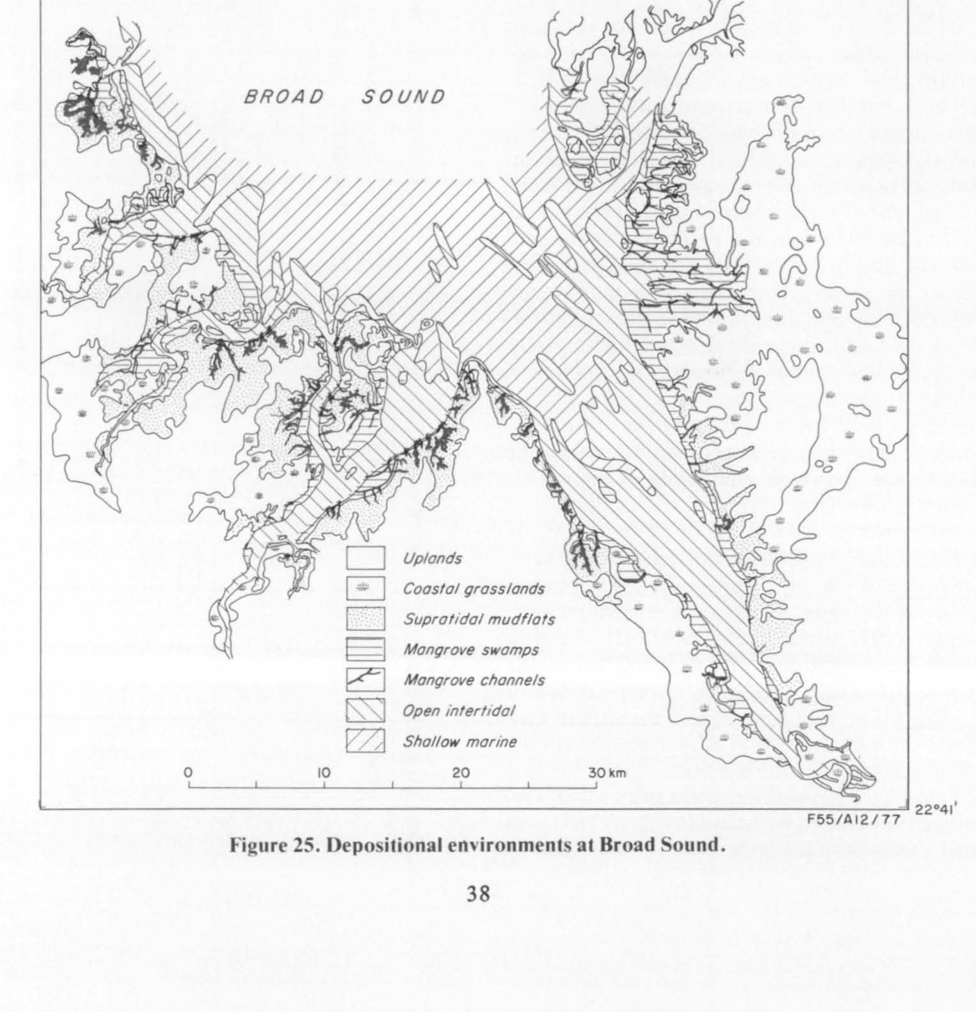
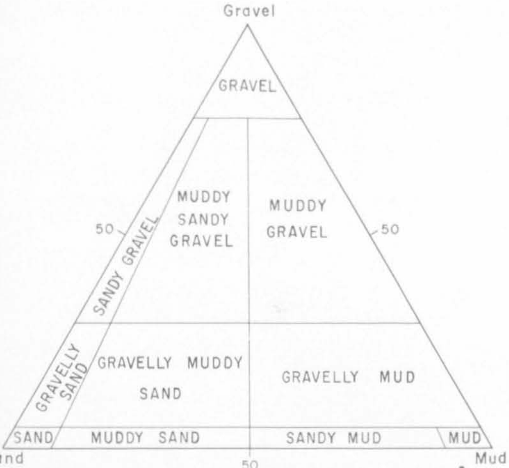
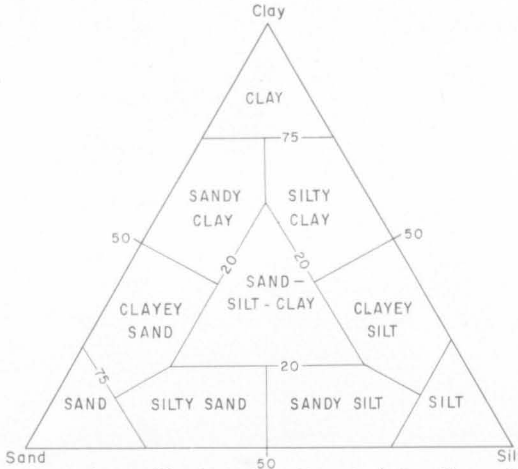


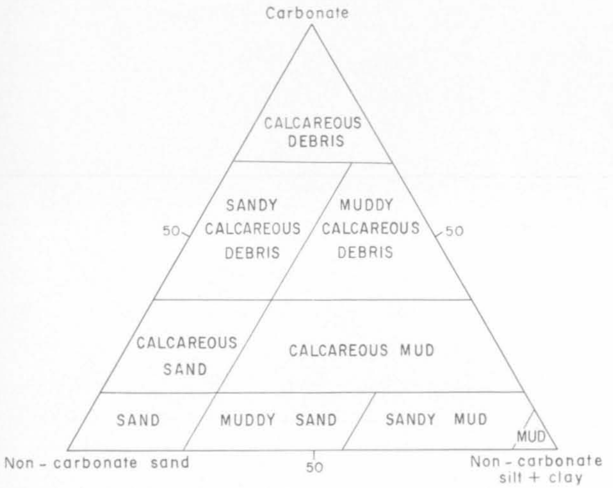
Figure 25. Depositional environments at Broad Sound.



Textural classification of sediments (after Folk, 1954)



Textural classification of sediments (after Shepard, 1954)



Nomenclatural scheme for major sediment-forming fractions in Holocene sediments. Adapted from Nelson and Bray (1970, p 51)

F55/A12/68

Figure 26. Textural classification schemes used for Broad Sound sediments.

therefore considered desirable to base all sub sequent discussion on these five major depositional environments.

SEDIMENTARY FACIES

It is apparent from earlier discussions that textural and lithological terms are not included in the environmental nomenclature scheme. It is nevertheless frequently convenient to refer to 'intertidal sands' or 'intertidal muds'. Used in this way, such terms are comparable with the concept of 'facies' as developed by Gressly (1838) or the 'lithosome' of Krumbein & Sloss (1963). The term as used here is a combination of environmental and lithologic factors. In the discussion on sedimentary environments only the gross lithologic characteristics are used, namely the relative abundance of mud, sand, gravel, and carbonate. Mineralogy and detailed textural analyses of the sediments are dealt with later. The textural classification schemes used (Fig. 26) follow those suggested by Shepard (1954), Folk (1954) and Nelson & Bray (1970). The grainsize distributions of the various depositional environments are shown in Figure 27. It is evident from this that there is considerable overlap of the

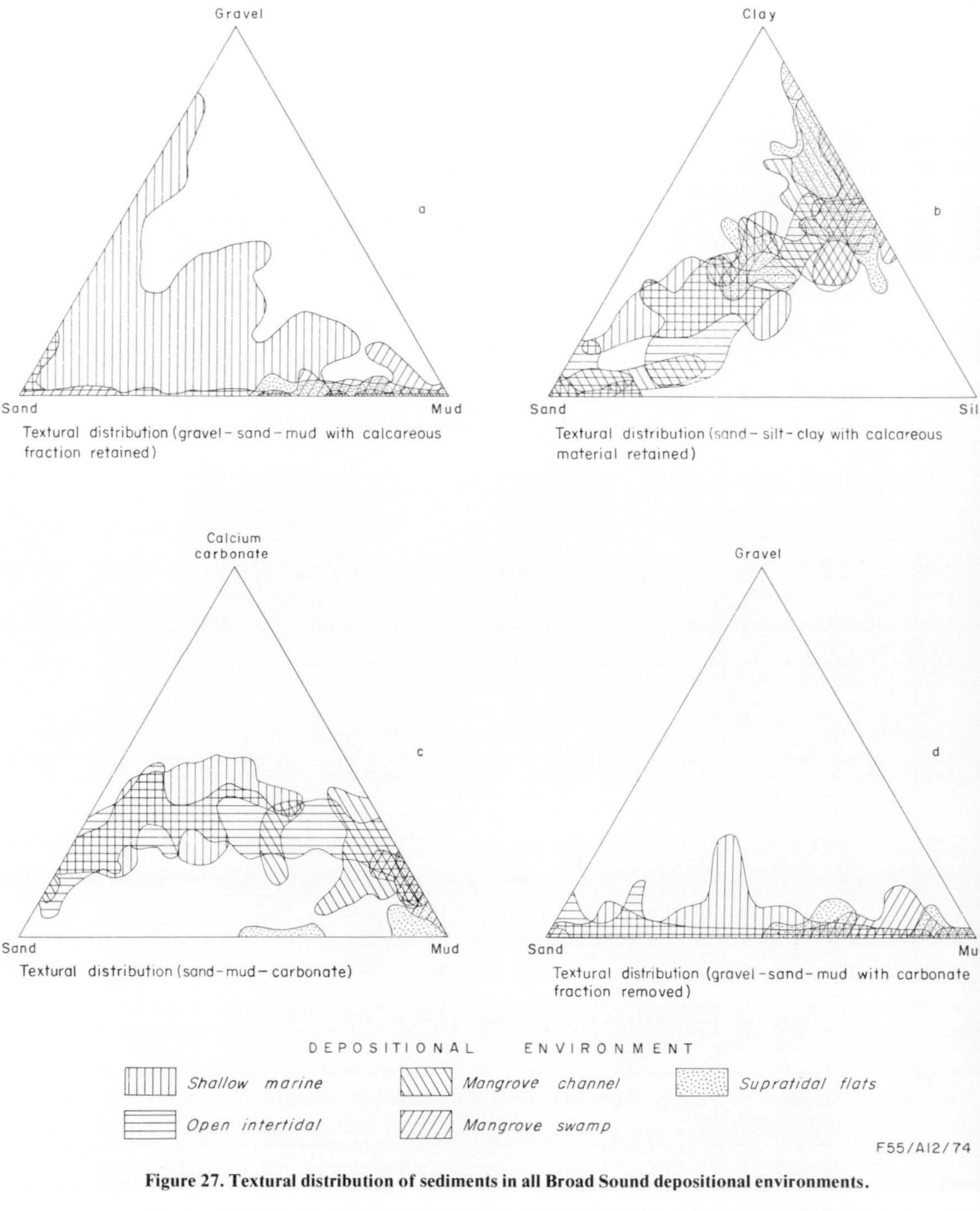


Figure 27. Textural distribution of sediments in all Broad Sound depositional environments.

various textural fields. Conversely in some instances, e.g. the mangrove swamp environment, the sediments fall into a very restricted field. Thus, the depositional environment has a marked influence on the lithology of the sediment in Broad Sound. Considering the estuarine sediments as a whole (Fig. 27a) there is evidently a complete spectrum of textures representing mixtures of sand and mud, and sand and gravel, but not mixtures of mud and gravel. Consequently muddy gravels and gravelly muds are sparsely represented. Facies variation throughout the

Broad Sound area (based on the mud-sand-gravel classification of Folk) is shown in Figure 28. From this, it is evident that the coarsest sediments occur in the most seaward environments, and the finest sediments in the most landward. This trend is even more evident in Figure 29 which shows the distribution of gravel. Most gravel is composed of carbonate material of biogenic origin but it is clear from Figure 30 that the greatest percentage of terrigenous (non-carbonate) gravel is also found to seaward. The predominance of carbonate in the gravel fraction is demonstrated by comparing the abundance of gravel in Figure 27a with that in Figure 27d (from which the carbonate has been removed by acidulation).

A feature of the sediments in all the depositional environments is the lack of 'pure' silt or 'pure' clay (using the Shepard nomenclatural system) as shown in Figure 27b. The mud fraction tends to retain approximately equal amounts of silt and clay whatever the abundance of sand. In addition, as shown in Figure 27a, there is extensive overlap of the textural fields of the various environments in Figure 27b. Using the sand-mud-carbonate classification scheme of Nelson & Bray (1970) as shown in Figure 27c it is again evident that there is considerable overlap of the various environmental fields. A trend of decreasing proportion of carbonate fraction with an increasing mud fraction is apparent. This trend is also reflected in Figure 31 where the more landward depositional environments, i.e. those with the greatest percentage of mud, are also the least calcareous.

Shallow Marine Environment

The shallow marine environment lies entirely within the subtidal zone; the maximum depth in the study area is about 10 m below the Low Water Springs level. Because this environment is never subaerially exposed, knowledge of it comes entirely from indirect observation using such means as dredging, coring, and seismic profiling. Direct observation using scuba-diving equipment was not attempted because of the extreme turbidity of the water, the numerous sharks, some sea snakes, and a few crocodiles.

Much of the shallow marine environment is

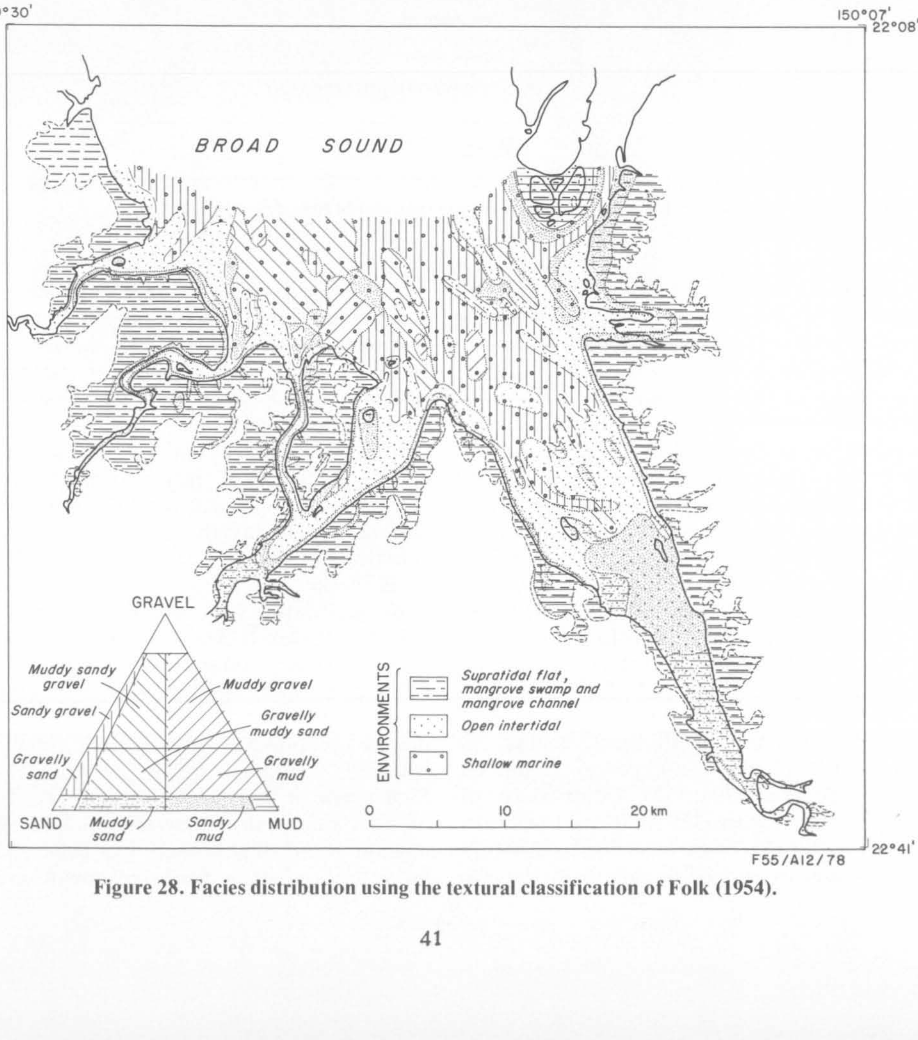


Figure 28. Facies distribution using the textural classification of Folk (1954).

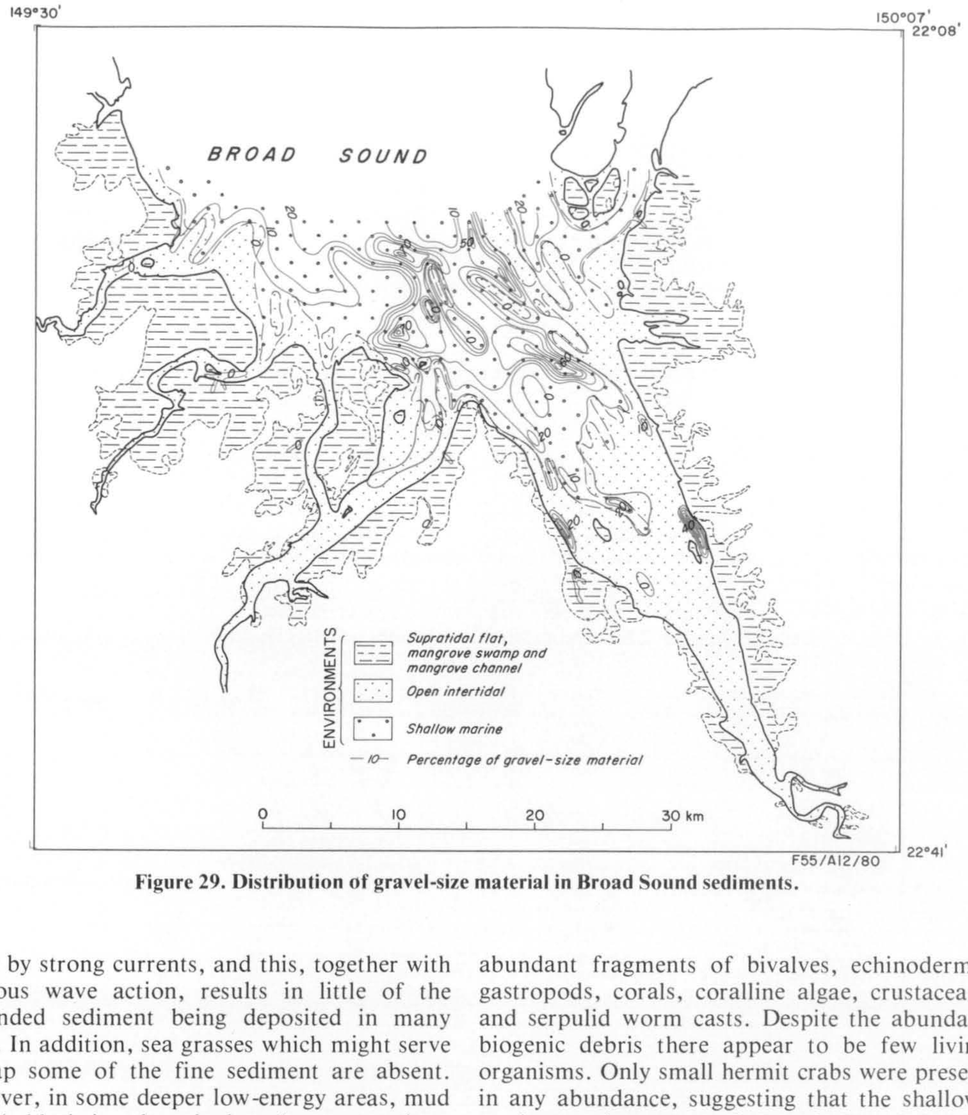


Figure 29. Distribution of gravel-size material in Broad Sound sediments.

swept by strong currents, and this, together with vigorous wave action, results in little of the suspended sediment being deposited in many areas. In addition, sea grasses which might serve to trap some of the fine sediment are absent. However, in some deeper low-energy areas, mud is probably being deposited at the present time. Plant material, ranging in size from leaves to mangrove trees several metres long, is frequently carried into the environment, particularly during spring tides, but little of this debris is incorporated in the bottom sediments. Topographically, the sea-bottom ranges from an irregular and in places jagged surface on the east side, to a flat comparatively featureless plain on the west side.

The sediments of the shallow-marine environment are the coarsest of all Broad Sound environments (Pl. 12, fig. 1) and contain abundant gravel-size material (Fig. 32). Comparison of Figure 32a with Figure 32d suggests that most gravel-size material is calcareous. Much of it is in the form of calcareous nodules and there are also abundant fragments of bivalves, echinoderms, gastropods, corals, coralline algae, crustaceans and serpulid worm casts. Despite the abundant biogenic debris there appear to be few living organisms. Only small hermit crabs were present in any abundance, suggesting that the shallow-marine environment of Broad Sound is uncongenial for most large forms of life. The calcareous nodules are commonly well rounded (Pl. 12, fig. 2) though they range in shape from spherical (Pl. 13, fig. 1) to disc-like (Pl. 13, fig. 2). Evidence from petrological data and radiocarbon age dates (see later), and geochemical evidence (Cook & Mayo, in prep.) support the view that the nodules have been subaerially weathered. Many are believed to be intra-clasts resulting from the subaerial erosion of calcareous marine sediments. Others may also be of pedogenic origin having formed within a Pleistocene or early Holocene soil profile. Some of the calcareous material dredged up was angular and freshly broken; it is believed to have been broken off a hard pavement underlying

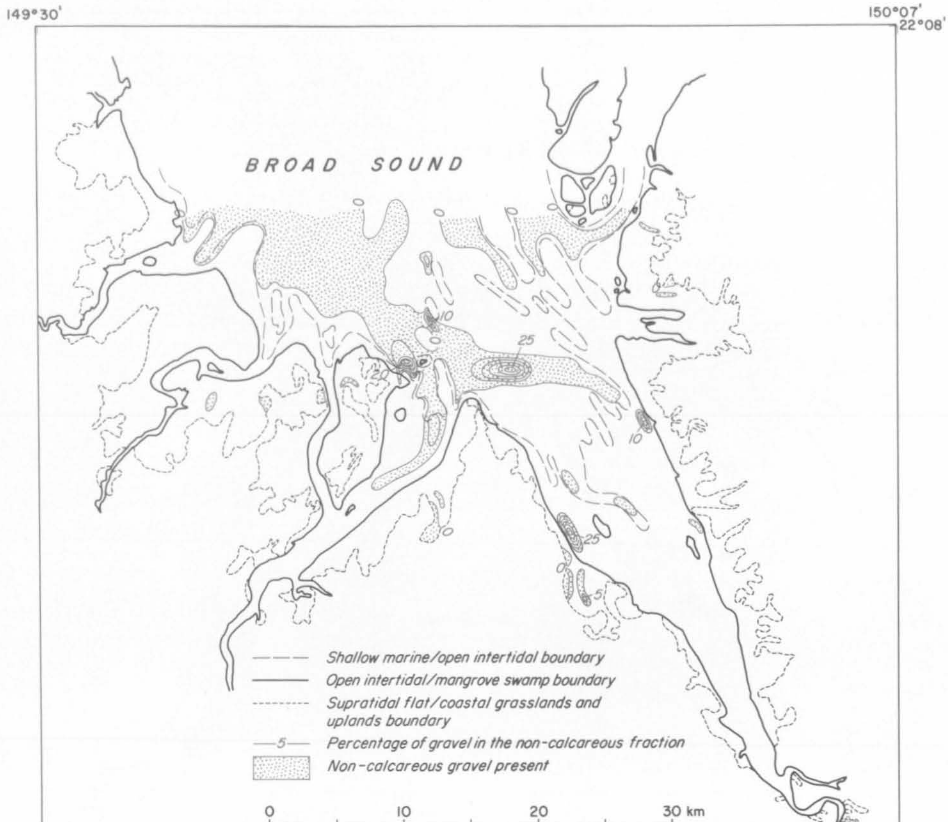


Figure 30. Distribution of terrigenous gravel-size material in Broad Sound sediments, after removal of the calcareous fraction by acidulation.

much of the area. Thus much of the sediment in the shallow-marine environment is not the product of that environment but is a residual or relict deposit of Pleistocene or early Holocene age. The processes of erosion operative within the present environment have, however, modified the texture of these relict gravels, winnowing out finer material to produce a lag deposit. Despite this winnowing, there is still abundant mud associated with the gravel; some of the mud may result from settling out of fine material from suspension in localized areas, for instance in the lee of sand ridges. In addition it is apparent from the work of Hjulstrom (1939) and Sundborg (1956) that the critical erosion velocity for mud may be the same as for gravel; thus a current which is able to erode sand may not necessarily be capable of eroding mud. Consequently, winnowing of a sediment originally composed of mud, sand, and gravel may ultimately produce a deposit composed only of mud and gravel. The grainsize distribution of these sediments (discussed later) shows clearly that there are two major classes of sediments in the shallow-marine environment: multimodal sediments composed of gravel, sand, and mud of both relict and modern origin; and unimodal sediments composed predominantly of sand. The sands are identical in composition with their intertidal counterparts. The shallow-marine sands should therefore be regarded as the leading edge of the intertidal sand bodies which are prograding into the subtidal zone.

The facies distribution map (Fig. 28) shows that the fine-grained shallow-marine sediments (muddy sandy gravels and gravelly sandy muds using the Folk classification) are more common on the west side of Broad Sound than on the east side. Figure 31 also shows that the western part of the Sound is the least calcareous area of the shallow marine environment. In addition, non-calcareous gravel-size material is more abundant in the western half of the shallow marine environment than in the east (Fig. 30). All these features

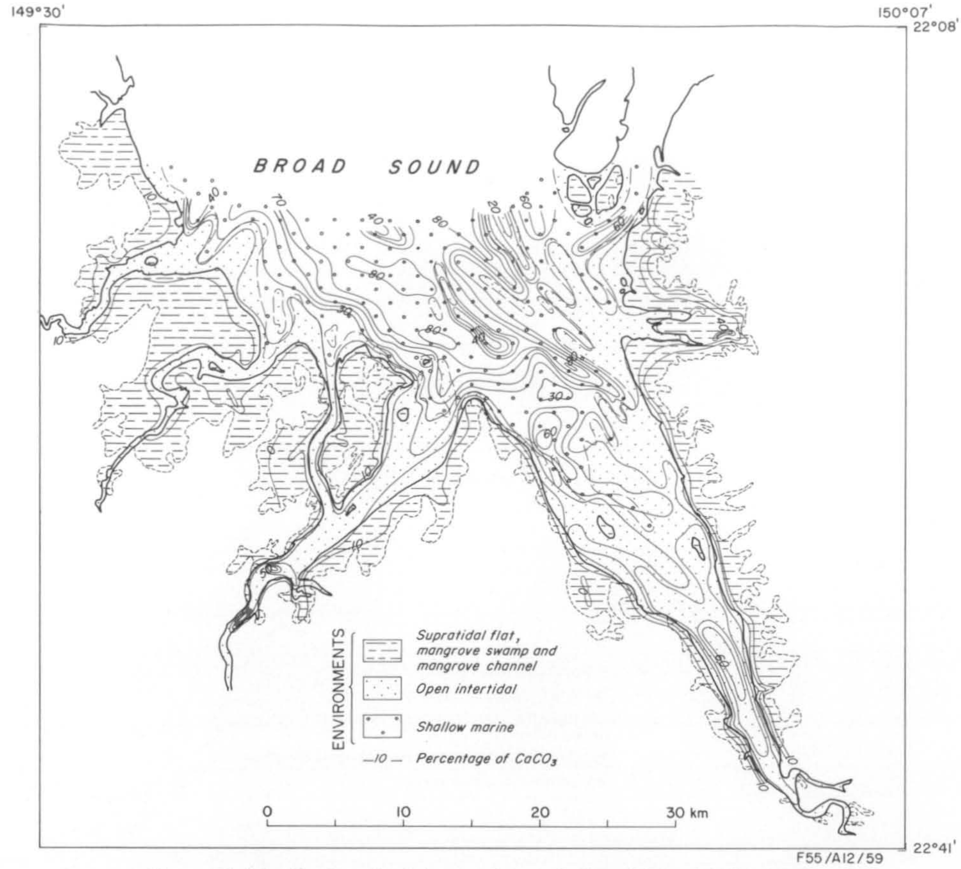


Figure 31. Distribution of calcium carbonate in Broad Sound sediments.

reflect the proximity of the Styx, Waverley, and St Lawrence estuaries transporting fine terrigenous material into the shallow marine environment during the wet season. Several gravity cores in this area encountered soft green and grey-green muds with a minimum thickness of 1 m. The coarse lag deposit was not encountered during either coring or drilling operations in this muddy facies. A further feature of the shallow-marine muds is that some samples had a definite fetid odour, suggesting reducing conditions. This is in contrast to the coarser marine sediments in which conditions generally appear to be oxidizing.

The shallow marine environmental, characterized by its coarse residual sediments, may be compared with the more open environment which predominates over much of the east Australian continental shelf. In common with many of the world's continental shelves (Emery, 1968) there is little active sedimentation at the present time, except near major estuaries. However, even in the vicinity of a major estuarine system such as Broad Sound the effect of the present cycle of Holocene sedimentation does not extend for more than a few kilometres beyond the mouths of the four main estuaries.

Open Intertidal Environment

This depositional regime lies within the intertidal zone (Fig. 23). Its lower limit, which grades into the infratidal-subtidal zone occupied by the shallow marine environment, is seldom exposed. Interdigitation is a feature of the sedimentary pattern in Broad Sound (Fig. 25). The upper limit of the open intertidal environment is marked by a sharp boundary with mangrove swamps in most areas, but it grades into the fluvial environment (in places over distances of several kilometres) in the upper reaches of the estuary. It also grades laterally into the more restricted mangrove channel environment (Fig. 25).

The average concentration of carbonate in the open intertidal environment is 31.3 percent (Table 2), the carbonate component being in the form of whole and fragmentary shells. This is in-

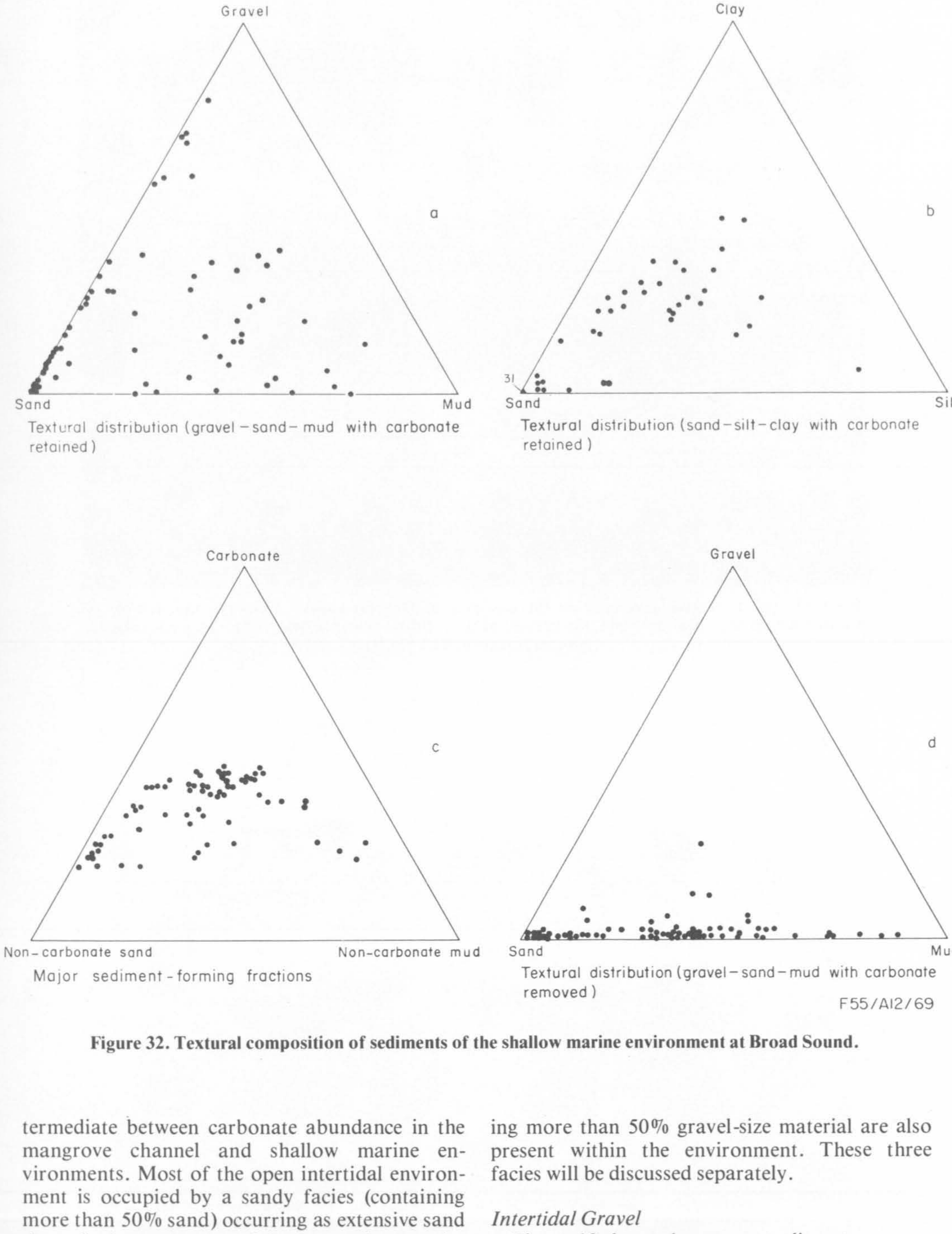


Figure 32. Textural composition of sediments of the shallow marine environment at Broad Sound.

termediate between carbonate abundance in the mangrove channel and shallow marine environments. Most of the open intertidal environment is occupied by a sandy facies (containing more than 50% sand) occurring as extensive sand sheets in the upper part of the four main estuaries and sand ridges in the lower parts (Fig. 28). A muddy facies (containing more than 50% mud-size material) is present mainly around the periphery adjacent to the mangrove swamp environment. Isolated patches of sediment containing more than 50% gravel-size material are also present within the environment. These three facies will be discussed separately.

Intertidal Gravel

Figure 33 shows that coarse sediments are rare in the open environment. This is true of both the carbonate and non-carbonate fraction (Figs. 29 and 30). Nevertheless there are local occurrences (Pl. 12, fig. 1) as a consequence of exposure of the early Holocene gravel surface which shallows

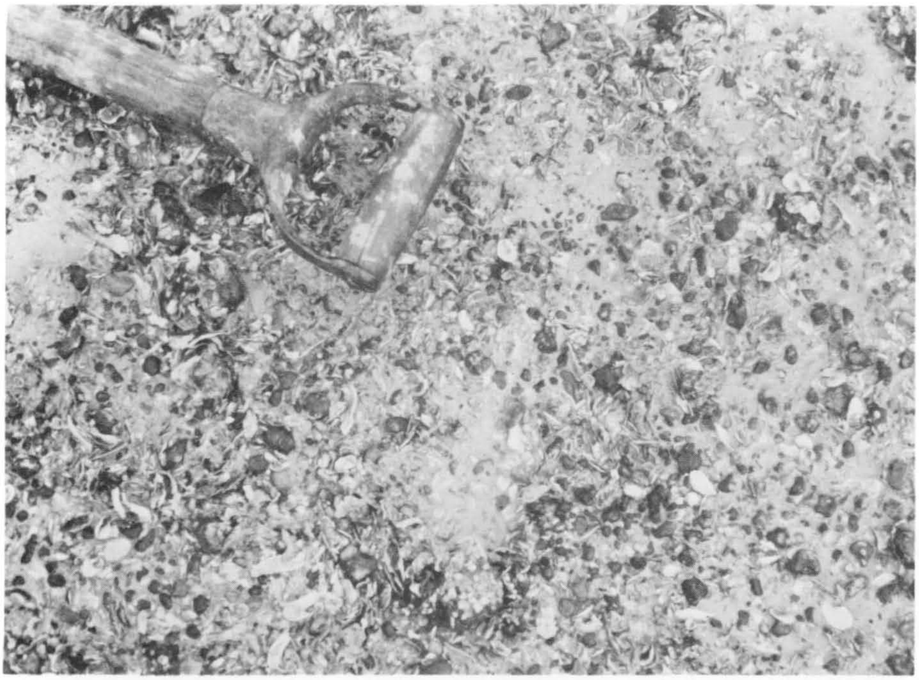


Plate 12, fig. 1. Gravel pavement on the east side of Herbert Creek. Although this sample is located within the intertidal zone, the gravels of the subtidal zone are believed to have a similar in situ appearance. (GA/7871)

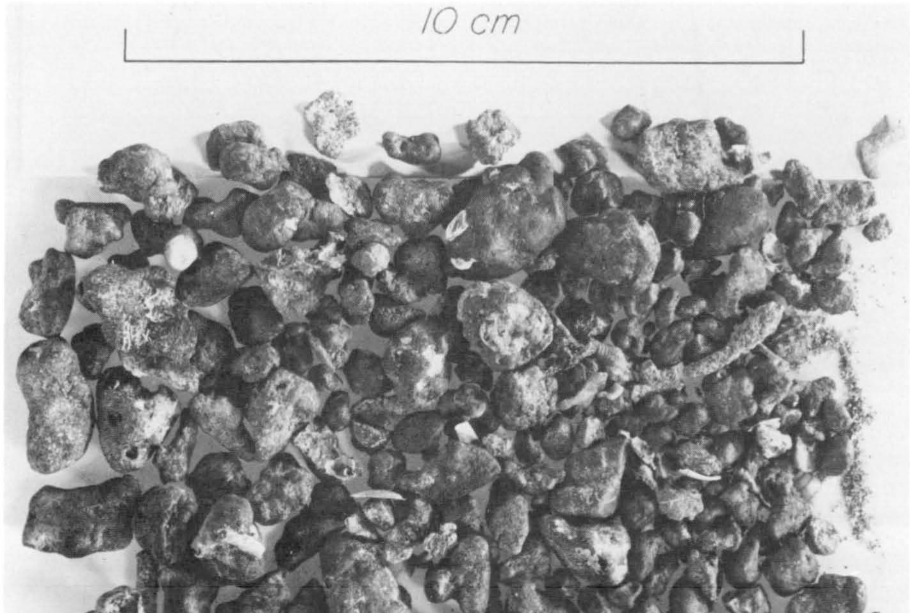


Plate 12, fig. 2. Calcareous gravel (sample washed and sieved) from the shallow marine environment at the northern end of the study area. (GA5771)

Plate 13, fig. 1. Well rounded calcareous nodules (radiocarbon age of 16 000 years B.P.) of possible pedogenic origin from the shallow marine environment at the northern end of the study area. (GA/5775)

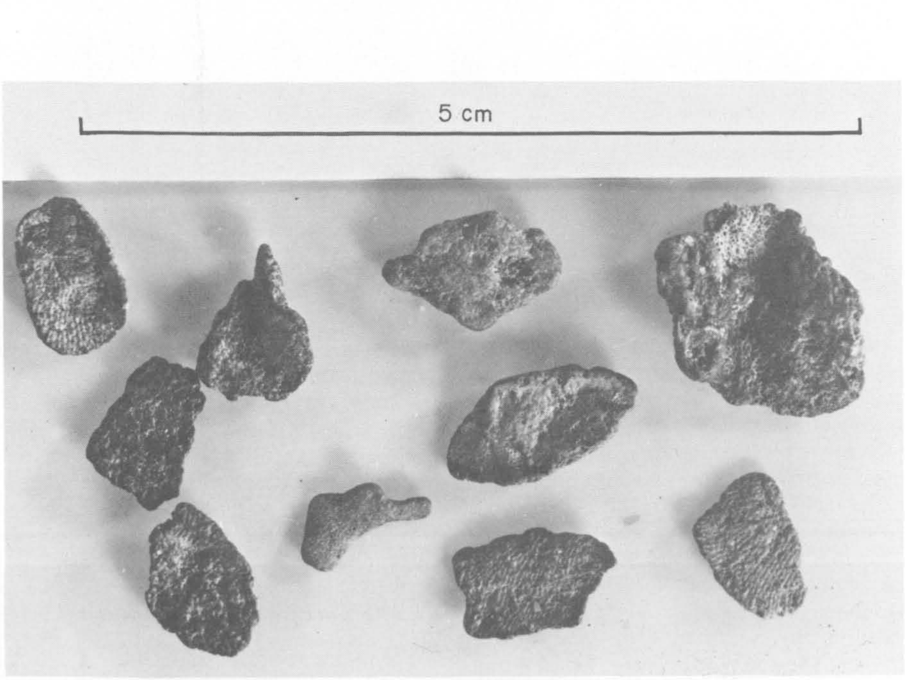


Plate 13, fig. 2. Rounded 'flakes' of coralline algae from shallow marine gravel at the northern end of the study area. (GA/5776)

TABLE 2. GRAINSIZE AND CARBONATE STATISTICS

		Shallow marine (63)	*Open intertidal (100)*	*Mangrove channel (33)*	*Mangrove swamp (27)*	*Supratidal flat (65)*	*Total Broad Sound (Mangrove channel excluded) (256)*
	Mean grainsize	2.23 (2.16)	3.55 (1.76)	6.62 (1.70)	7.85 (1.07)	8.62 (0.96)	5.06 (3.09)
	Grainsize standard deviation	2.60 (1.37)	1.31 (1.03)	2.93 (0.98)	2.81 (0.34)	2.73 (0.43)	2.15 (1.18)
	Grainsize skewness	-0.12 (1.33)	0.63 (1.80)	0.46 (1.25)	0.25 (0.49)	-0.19 (0.33)	0.19 (1.37)
	Grainsize kurtosis	1.74 (4.83)	4.99 (8.50)	1.25 (5.85)	-0.92 (0.93)	-0.65 (0.35)	2.06 (8.36)
Carbonate not removed	Number with gravel component	53	20	8	0	4	77
	(%Gravel	18.9	1.9	1.4	0.0	0.2	5.5
	(%Sand	52.1	80.4	27.3	8.6	4.2	48.7
	(%Mud	19.0	17.6	71.3	91.4	95.5	45.8
	(%Silt	9.1	9.7	30.0	38.7	29.8	17.8
	(%Clay	9.9	7.9	41.3	52.7	65.8	28.0
Carbonate removed	Number with gravel component	33	12	9	0	9	54
	(%Gravel	1.7	0.9	0.9	0.0	0.4	0.9
	(%Sand	84.6	71.3	13.4	2.2	3.7	44.9
	(%Mud	33.7	27.9	65.7	97.6	95.6	54.2
	%Carbonate	56.5	31.3	23.4	16.5	4.3	29.0
	%Carbonate in gravel fraction	96	67	51			
	sand fraction	55	37	62	79	10	
	mud fraction	22	0	6	3	3	

Summary of all grainsize parameters and other relevant statistics.
Values are the means unless otherwise stated. Standard deviation values are given in brackets.

in a landward direction and is exposed in the intertidal zone. Like the gravels of the shallow marine environment these relict sediments are being modified at the present time but the gross sedimentary characteristics are primarily the result of early Holocene conditions rather than the inter-tidal conditons now prevailing.

Coarse gravel-size deposits composed of shell debris form beach deposits at a number of places in the Charon Point area (Pl. 14, figs. 1 & 2), and at Turtle Island (Pl. 15, fig. 1). These deposits, which are in part storm beaches, extend from the upper part of the intertidal zone into the extratidal zone. The shelly beach at Charon Point results in part from reworking of shells from old mangrove deposits which are now being eroded. Some shelly deposits result from the reworking of old cheniers (see later) which are composed predominantly of shells.

Coarse gravels which do not appear to be relict lag deposits and which are composed predominantly of non-calcareous material are also found at Charon Point and on Turtle Island (Pl. 15, fig. 2). At Upper Head on Charon Point (Pl. 16, figs 1 and 2), Palaeozoic bedrock abuts the intertidal zone and the material is locally derived. The development of gravel at this locality appears to be the result of relatively high wave energy particularly when there is a northeasterly sea. These conditions prevent the development of mangrove, and ensure that the bedrock is subject to extensive erosion. At Turtle

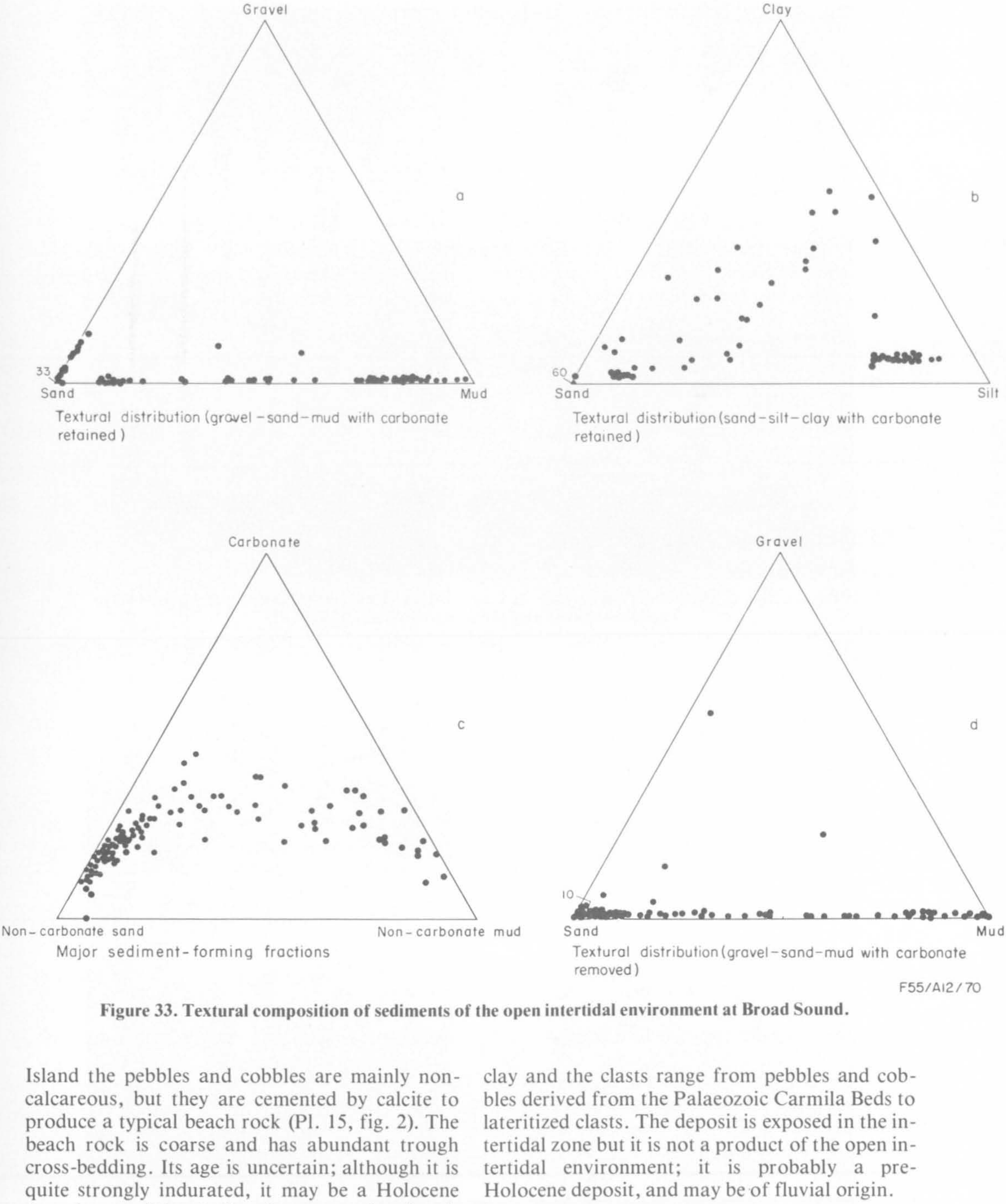


Figure 33. Textural composition of sediments of the open intertidal environment at Broad Sound.

Island the pebbles and cobbles are mainly noncalcareous, but they are cemented by calcite to produce a typical beach rock (Pl. 15, fig. 2). The beach rock is coarse and has abundant trough cross-bedding. Its age is uncertain; although it is quite strongly indurated, it may be a Holocene deposit, possibly similar in age to beachrock from elsewhere on the Queensland coast, described by Hopley (1971). In a similar conglomerate exposed at the northern end of Rosewood Island, and at the northern end of The Hoogly, the matrix comprises poorly indurated clay and the clasts range from pebbles and cobbles derived from the Palaeozoic Carmila Beds to lateritized clasts. The deposit is exposed in the intertidal zone but it is not a product of the open intertidal environment; it is probably a pre-Holocene deposit, and may be of fluvial origin.

Intertidal Sand

Sand is the dominant sediment of the open intertidal environment forming extensive sand sheets and ridges (Pl. 17, figs 1 and 2). Using the classification of Nelson & Bray (1970) it is mainly

Plate 14, fig. 1. Shelly beach near Charon Point. Influx of coarser sediment and higher-energy conditions have killed the mangrove trees. (GA/3661)

Plate 14, fig. 2. Sharp boundary between the steeply dipping shelly beach and current-rippled intertidal sand shown in Plate 16, fig. 1. (M/4118)

Plate 15, fig. 1. Prominent shelly beach flanking Turtle Island. A well developed rock platform is evident at low water. At the apex is a seaward-dipping beach rock deposit. The island is about 0.5 km wide. (SA/4087)

Plate 15, fig. 2. Conglomeratic beach rock in the intertidal zone flanking Turtle Island. (M/1137)

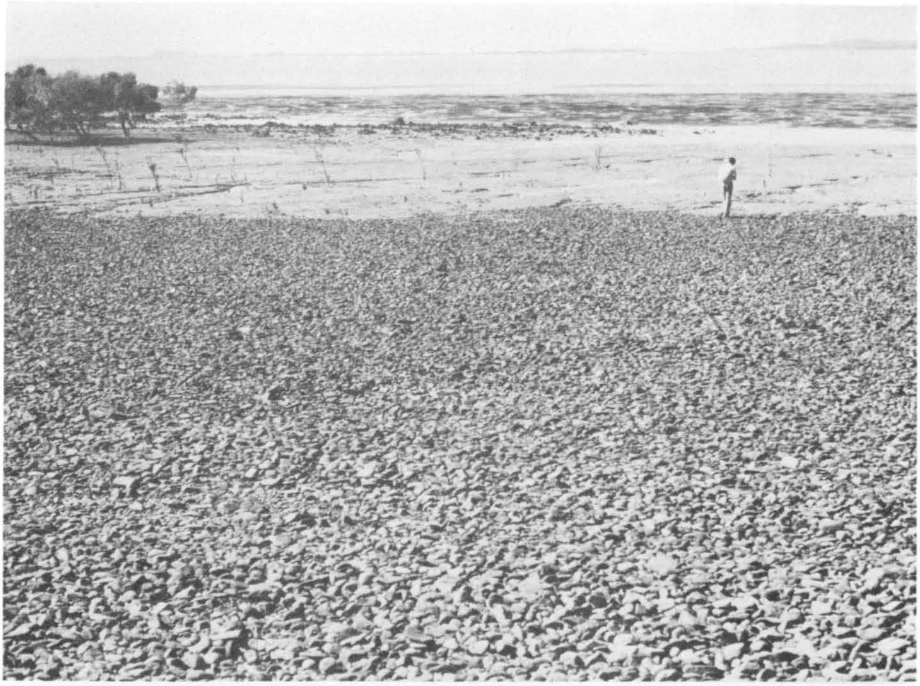


Plate 16, fig. 1. Gravel beach at Charon Point. The gravel gives way seaward to mud and finally sand. (GA/5583)

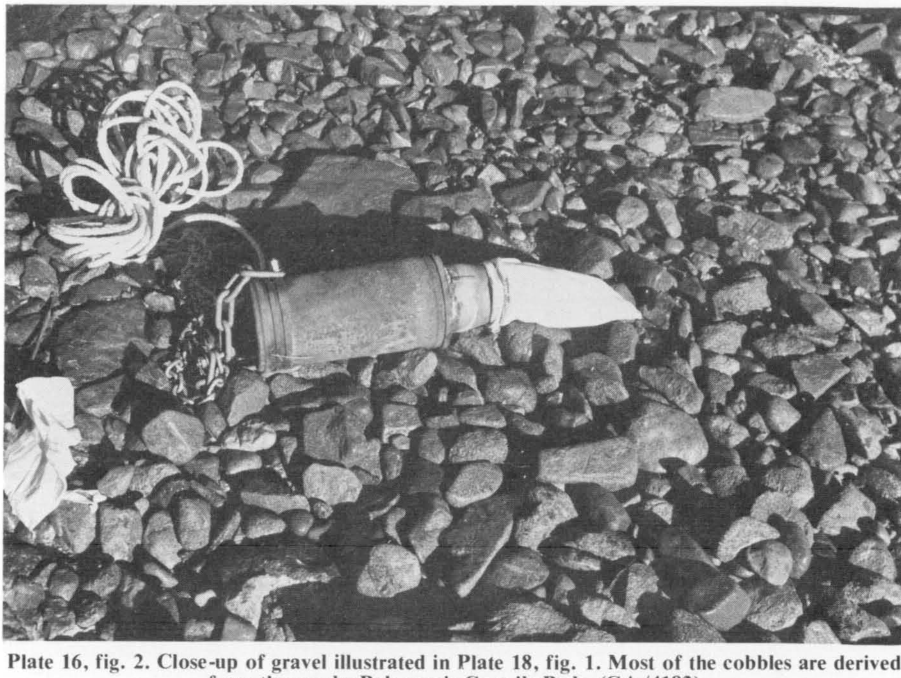


Plate 16, fig. 2. Close-up of gravel illustrated in Plate 18, fig. 1. Most of the cobbles are derived from the nearby Palaeozoic Carmila Beds. (GA/4183)

Plate 17, fig. 1. Extensive intertidal sand body near the mouth of the Styx River. Looking southwest from an altitude of about 1500 m. Megaripples are visible on the flanks of the sand bank. (GA/3641)

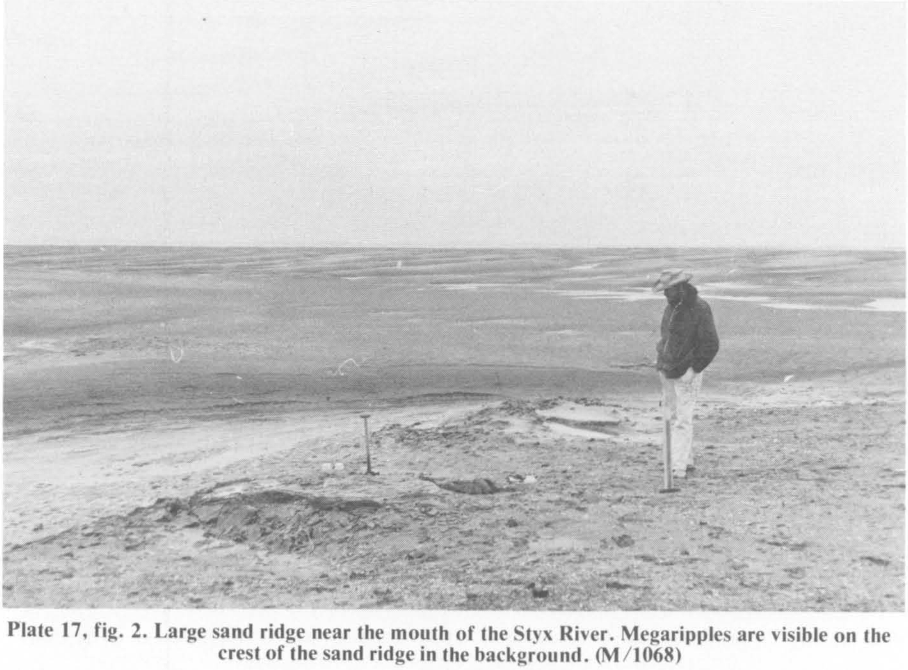


Plate 17, fig. 2. Large sand ridge near the mouth of the Styx River. Megaripples are visible on the crest of the sand ridge in the background. (M/1068)

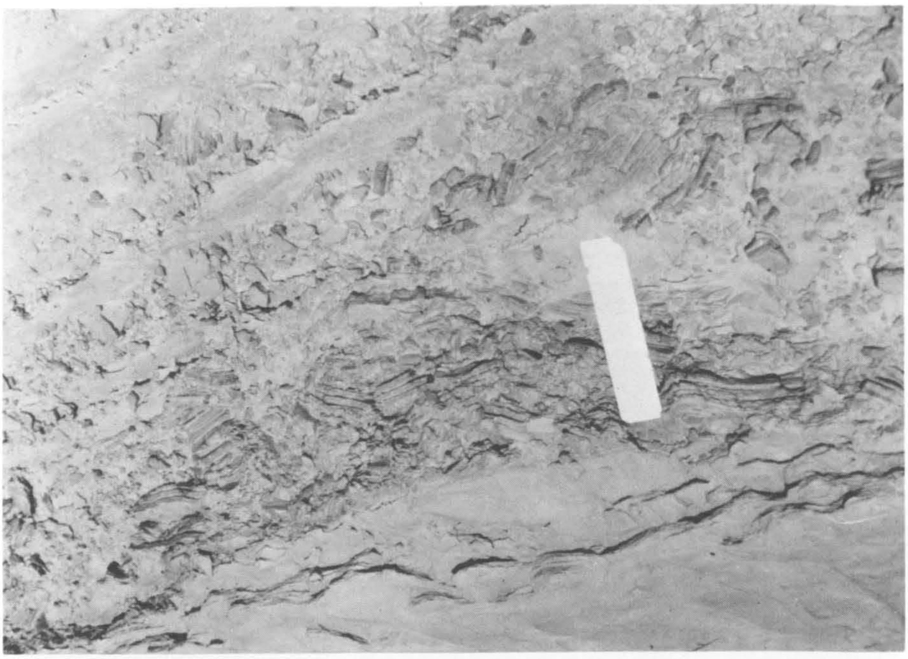


Plate 18, fig. 1. Development of an intraformational breccia caused by the break-up of muddy laminae; 2 km southeast of Island Bluff. White scale is 15 cm long. (GA/7868)

Plate 18, fig. 2. Mud-balls in the open intertidal environment at the southern end of Herbert Creek. White scale is 15 cm long. (M/1068/12A)

Plate 19, fig. 1. Ripple marks on intertidal sands resulting from unidirectional current flow. White scale is 15 cm long. (M/1068)

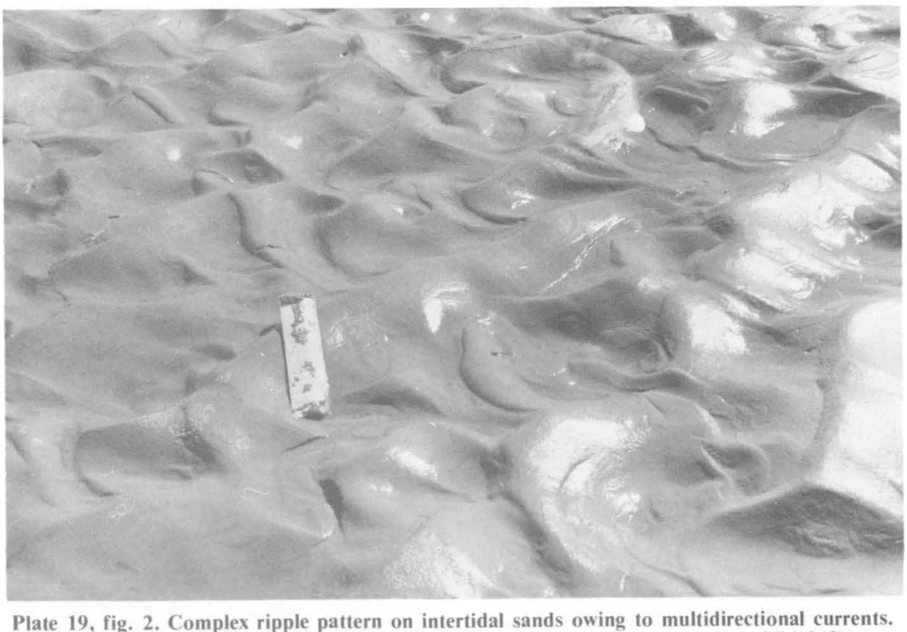


Plate 19, fig. 2. Complex ripple pattern on intertidal sands owing to multidirectional currents. White scale is 15 cm long. The lustrous surface is due to a thin veneer of mud. (M/1068)

E

Plate 20, fig. 1. Low megaripples on a Herbert Creek sand ridge. (GA/78555)

Plate 20, fig. 2. Modification of the megaripple pattern on a sand ridge on the east side of Herbert Creek, caused by latitudinal water flow off the ridge during ebb tide. (m/1221) a calcareous sand (Fig. 33c) which is generally well sorted; the open intertidal environment has the lowest standard deviation of any of the Broad Sand environments (Table 2). Some muddy sands are present in the sand bodies, usually as thin laminae which commonly break up to give intraformational breccias (Pl. 18, fig. 1). In addition, some mud is transported into the sand facies as mud-balls (Pl. 18, fig. 2). As a result of the disaggregation processes used before grainsize determination such a sediment will be classified (using the Folk (1954) classification) as a muddy sand, but a more realistic classification based on the original characteristics of the sediment might be gravelly sand.

The mean grainsize of the sediment largely depends on distance from the mouth of the estuary. A marked seaward increase in grainsize is largely due to increasing abundance of coarse shell debris to seaward (Pl. 23, fig. 2) but the same trend is still apparent even with the carbonate fraction removed. In the Styx River for example both the mean grainsize and the decreasing percentage of mud in the non-carbonate fraction demonstrate the trend of seaward increase in grainsize in the open intertidal environment. This could indicate that much of the sand-size material has been derived from the continental shelf; alternatively it may be a reflection of progressive removal of finer material in the higher-energy conditions prevailing in the seaward direction. This question is considered later.

About one-third of the intertidal sand is composed of shell debris, predominantly bivalve, echinoderm, gastropod, and coral fragments. Carbonate nodules identical with those in the shallow marine environment are also common. As in the shallow marine environment few living organisms are evident; only hermit and fiddler crabs are present, and they produce extensive bioturbation of the sandy sediments in areas where they are common; in these areas sandy fecal pellets are a common sedimentary component. In protected pools in the upper parts of the estuary, foraminifers are abundant, producing some localized areas of highly calcareous sand (Fig. 31). Thus, there is no clearly defined trend of seaward increase in calcium carbonate in the intertidal sand facies.

Fragments of carbonaceous material are commonly present in the sands, mainly plant debris from the mangrove swamp environment, which has floated into the zone of sand deposition in the open intertidal environment. Most such material is probably removed on the next tide, but a minor amount is incorporated into the sand. Little of this carbonaceous material is likely to be preserved as conditions are oxidizing for some distance below the sediment-water interface. This is reflected in the brown colour (10 YR 6/2 to 10 YR 5/4) in most of these sands. However at a few localities (such as localities 260 and 109) the sands are brown (10 YR 6/2) at the surface, but grey (N 4) at depths of 5 cm and greater. The mean pH value of porewaters of the intertidal sands is 7.6, which is slightly less than that for Broad Sound surface waters (pH 7.9).

A wide range of sedimentary structures is evident in the intertidal sands. Intraformational breccias and mud-balls have already been mentioned, but current-induced bedforms and associated sedimentary structures predominate. These include small unidirectional current ripples (Pl. 19, fig. 1), oscillation ripples, complex interference ripples (Pl. 19, fig. 2), and cross-bedding. The most prominent features are the megaripples and associated structures of the sand ridges (Pl. 20, figs. 1 and 2), which occur widely throughout Broad Sound (Fig. 35).

Differences in the names and definitions of bedforms are common, but limits proposed by McCave (1971 p. 201) are followed. McCave stated: 'The distinction between ripples, megaripples and sandwaves is based on wavelength and height, the approximate transition values being respectively: wavelength — 60 cm and 30 m; height — 4 cm and 1.5 m.' On the basis of this classification, all of the intertidal structures may be termed megaripples. The megaripples generally range in height from 10 to 50 cm though a few megaripples of 1-m amplitude were exposed. The wavelength generally ranges from 3 to 15 m. At any one locality all the megaripples have the same form and are oriented with their axes at right angles to the tidal currents. A typical echo-sounder trace of a megaripple field on the top of sand ridge is shown in Figure 34. Although most of these large-scale bedforms are megaripples, a few may fall into the sandwave class. Large structures were noted at several localities in deeper water on the flanks of the sand ridges; their amplitude is of the order of 2 to 4 m but their wavelength is of the order of only 20 m (Fig. 34). Many of these are believed to be in part an erosional feature; scouring of megaripple troughs as a result of waterflow off the sand ridges is believed to be responsible for many of the high features with an amplitude commonly encountered in sand-waves but with a wavelength more characteristic of megaripples. At most localities, the steeper avalanche face slopes seaward at an angle of 11 to 23° but generally averaging about 14°. The stoss face dips at 3° to 6°. Megaripple orientations are shown in Figure 35; from this it is evident that most of the megaripples are ebb-tide oriented, suggesting a net seaward movement of sediment. Small-scale ripples are commonly superimposed upon the

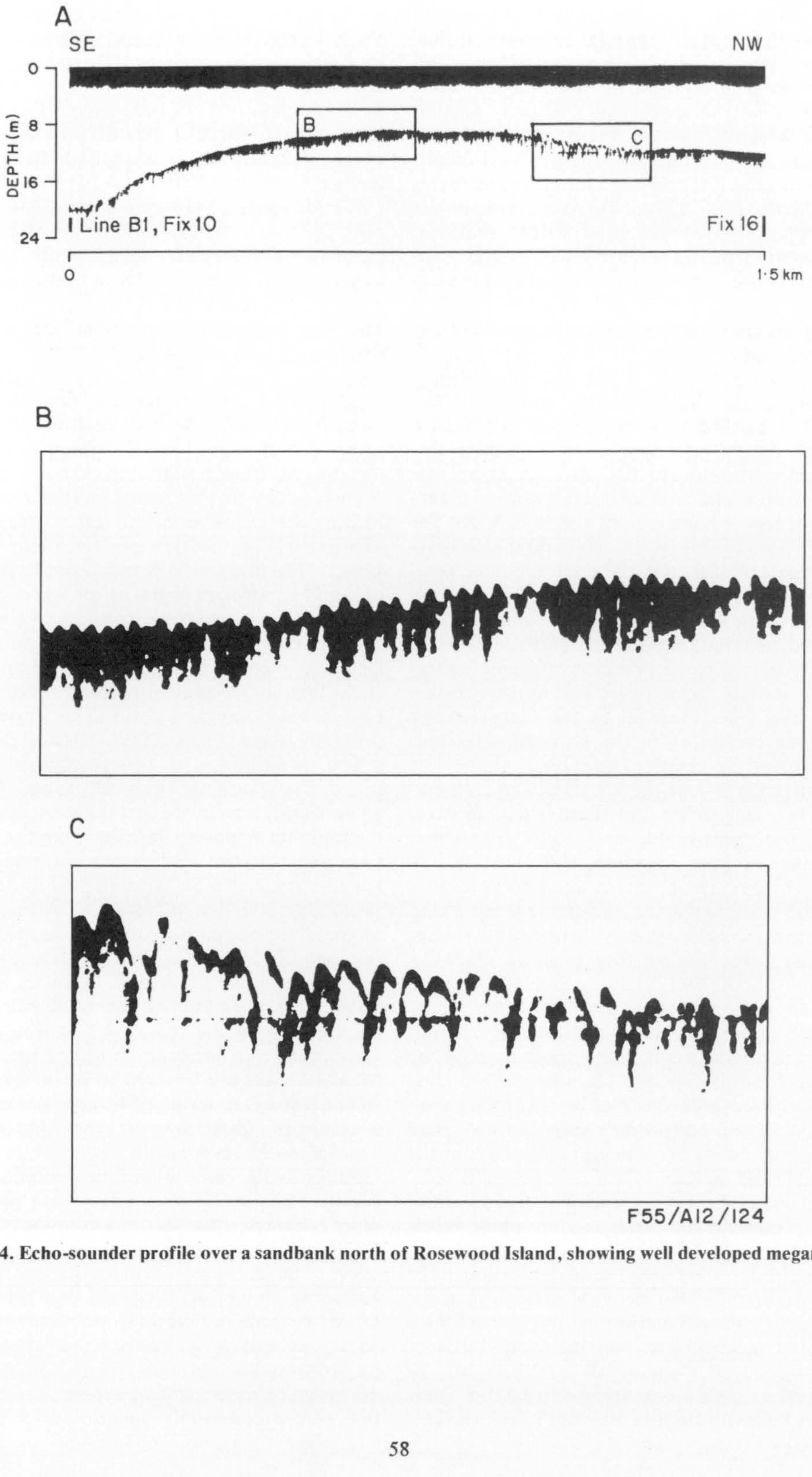


Figure 34. Echo-sounder profile over a sandbank north of Rosewood Island, showing well developed megaripples.

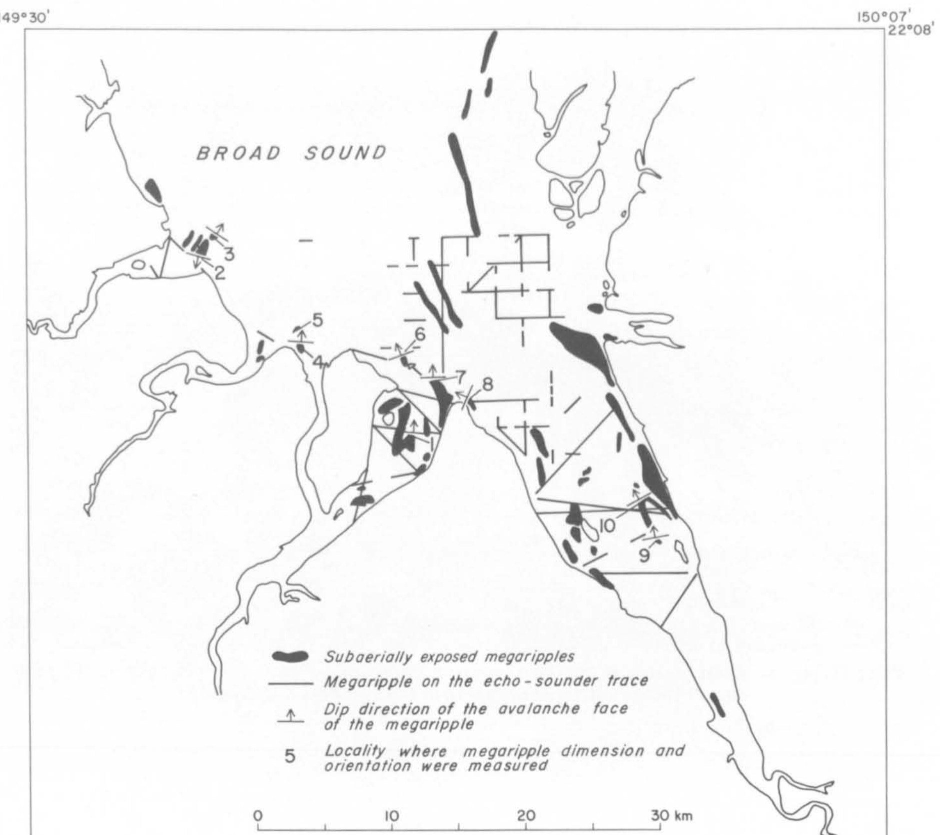


Figure 35. Distribution of megaripples at the southern end of Broad Sound.

megaripples on the stoss face; like the megaripples, these are normally oriented with the ebb-tide. However, at the mouth of St Lawrence Creek (Locality 2, fig. 35) where the megaripples are flood-oriented, the small-scale ripples are ebb-oriented. Modification of the megaripple pattern commonly occurs as a result of transverse water-flow off the sand ridge, at about mid-ebbtide, as the ridge becomes subaerially exposed. With sufficient flow this can result in disruption of the megaripple pattern (Pl. 20, fig. 2). Generally mid-ebb flow is restricted to the troughs, producing a small-scale unidirectional current-ripple pattern at right angles to the megaripple pattern. With further decrease in tidal level a series of isolated pools remains in the megaripple troughs; oscillation ripples are commonly overprinted on the other ripple patterns in these areas of standing water. As the pools may remain undisturbed for up to nine hours, there is ample time for clay-size material to settle out of suspension; consequently a thin veneer of mud is commonly present in these areas.

Intertidal mud

Muds are present in the open intertidal environment as a narrow band, generally no more than 100 m wide but in places attaining a width of 250 m (Fig. 28). The muddy facies is adjacent to the muds of the mangrove swamp environment; rarely the boundary is gradational, but generally it is marked by an escarpment 0.5 to 1.0 m high. The seaward boundary of the mud facies with the sand facies is generally sharp. In places a narrow stretch of shallow-marine sediments separates the muddy and sandy facies of the open intertidal environment. In such cases there is commonly a stepped escarpment at the base of the mud (Pl. 21, fig. 1).

In addition to this rim of mud, muddy sediments are locally present in intertidal areas protected by sand ridges from the high-energy conditions normally prevailing in this environment. Muddy sediments are also present in the upper reaches of the estuaries, where fluvial influences are dominant and a large amount of mud is carried into the system by rivers (Fig. 28).

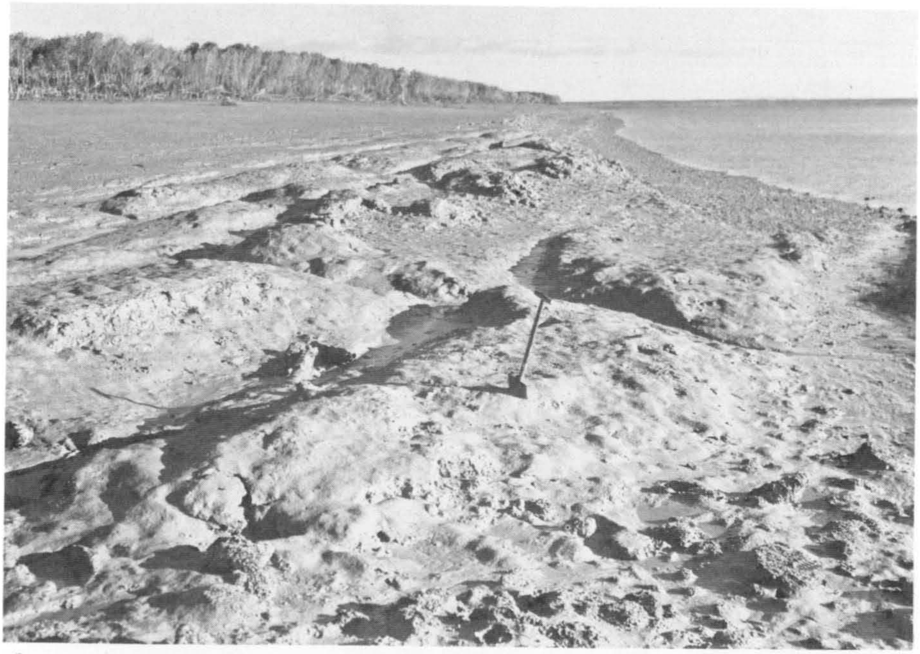


Plate 21, fig. 1. Muddy facies of the open intertidal environment flanking mangrove on the east side of the Styx River, 1 km south of Charon Point. (GA/4018)

Plate 21, fig. 2. Gravel composed of mud-balls and shell fragments, derived from old mangrove deposits which are undergoing erosion at the present time. Pen is 15 cm long. Locality is 2 km south of Charon Point, Styx River. (M/1091)

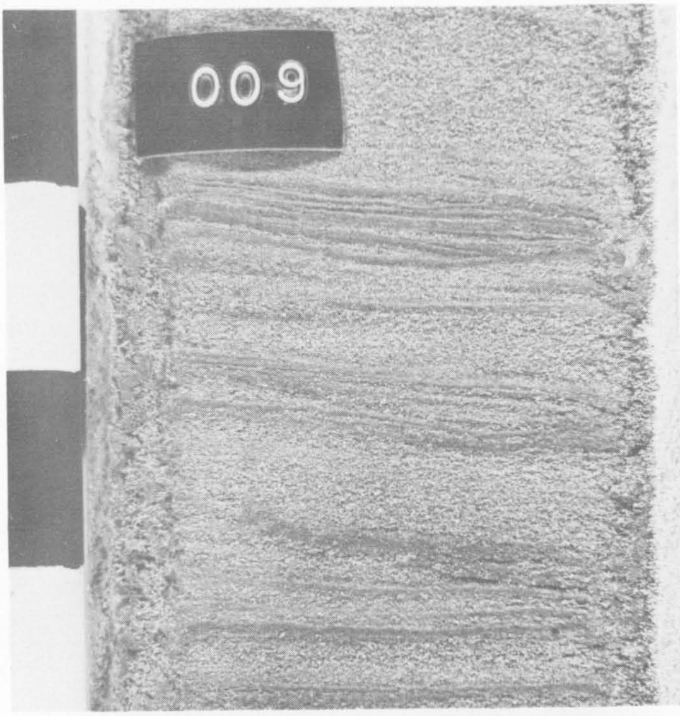


Plate 22, fig. 1. Sectioned core of intertidal sands with mud laminae (dark). The sample was obtained from the upper part of Herbert Creek. Core has a diameter of 6.5 cm. (GA/6128)

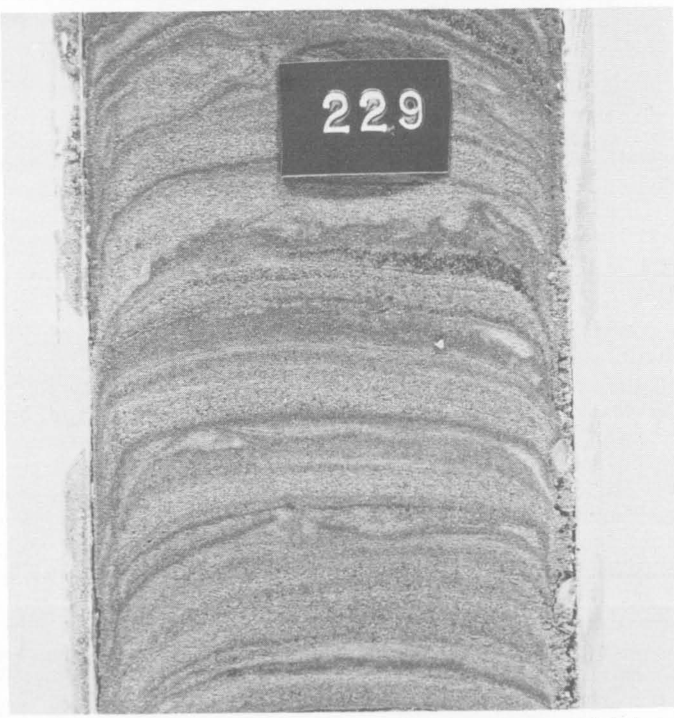


Plate 22, fig. 2. Muddy sand with well defined laminae from the upper part of St Lawrence Creek. Core has a diameter of 6.5 cm. (GA/6132)

Plate 23, fig. 1. Fine muddy sand from the muddy facies of the open intertidal environment to the east of Island Bluff. A U-shaped burrow is indicated by the arrow. Core has a diameter of 6.5 cm (GA/6136)

The sediment ranges from sandy mud to mud (Fig. 33a), or based on the Nelson & Bray classification it is predominantly a calcareous mud (Fig. 33c), Mud clasts (Pl. 21, fig. 2) are comparatively common on the outer edge of the facies and a few gravel-size shell fragments are also present. In places, sand and mud are present together but more commonly they occur as discrete laminae (Pl. 22, figs. 1 and 2). Mixed sand and mud-sized material probably only occurs as a result of bioturbation producing homogeneity of the sediment (Pl. 23, fig. 1). The mode of origin of the fine laminations is un certain; the fine material is mainly derived from the adjacent mangrove swamp environment and the sand from the sandy facies of the open intertidal environment. It is suspected that the muds are deposited mainly during periods of spring tides when the seaward edges of mangrove muds are more subject to erosion; this mud is deposited in the adjacent intertidal zone. In the upper reaches of the estuary, mud is also deposited during the summer wet season when fluvial inflow is at a maximum. During times of low runoff, sandy laminae result both from winnowing of the muds and from some landward movement of intertidal sand.

The intertidal muds range from light olive grey (5 Y 8/2) to medium grey (N 5), and are significantly darker than most other modern Broad Sound sediments. This is reflected in the redox conditions which range from +200 mV to -390 mV. The pH ranges from 6.9 to 7.3 and averages 7.1, which is significantly more acid than the sands of the open intertidal environment. There is commonly a strong smell of hydrogen sulphide on digging into the intertidal muds. Despite this, there is some infaunal activity

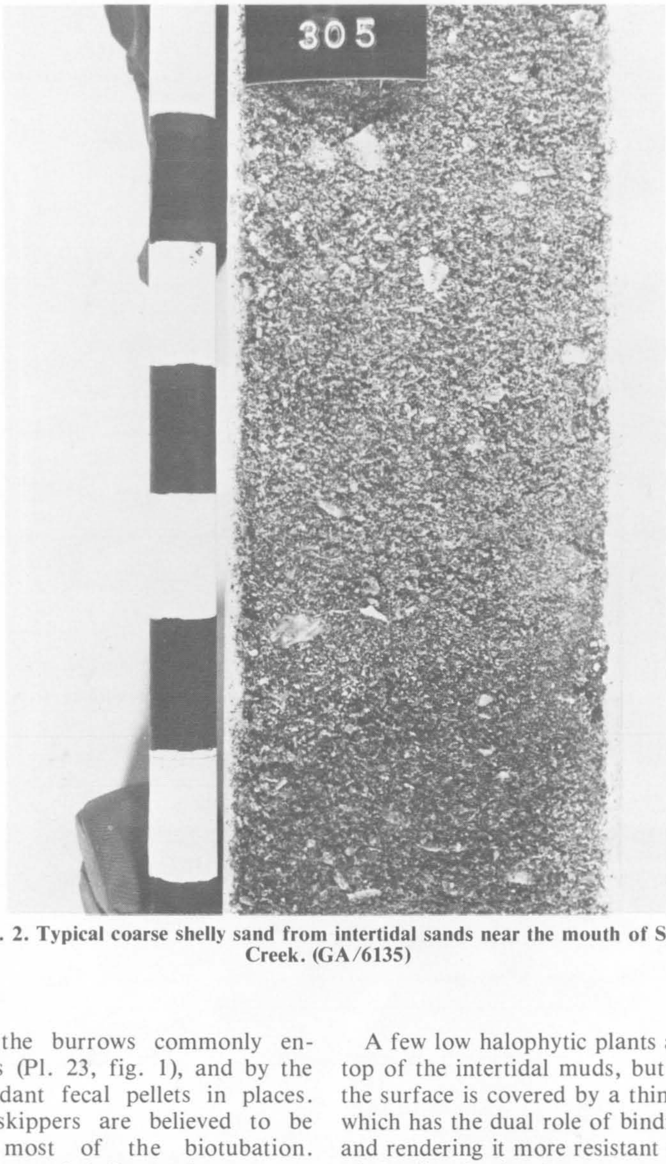


Plate 23, fig. 2. Typical coarse shelly sand from intertidal sands near the mouth of St Lawrence Creek. (GA/6135)

as indicated by the burrows commonly encountered in cores (Pl. 23, fig. 1), and by the presence of abundant fecal pellets in places. Crabs and mud-skippers are believed to be responsible for most of the biotubation. Gastropod and pelecypod shells are also common but are believed to represent a thanatocoenosic assemblage.

In places, particularly where there is active progradation of the present shoreline (Fig. 6), there are a few small scattered mangrove trees growing. More commonly, living mangrove is absent but there are abundant mangrove fragments in the mud ranging from leaves and small twigs to large tree trunks several metres long. All such plant material has generally been derived locally from erosion of the adjacent mangrove muds, commonly as a result of slumping at the escarpment on the seaward edge of the mangrove swamp environment.

A few low halophytic plants are present at the top of the intertidal muds, but more commonly the surface is covered by a thin veneer of algae, which has the dual role of binding the sediments and rendering it more resistant to erosion. Some of the fine laminations present in the muds are probably algal laminations. In addition to modification by burrowing, some laminations are commonly disturbed by load-casting; the most prominent feature is, however, that the muds have a well defined seaward depositional dip of 4° to 10°.

Mangrove Channel Environment

The mangrove channel environment extends from the subtidal to the supratidal zone and is located mainly within the intertidal zone (Fig. 23). It has a channel-like form extending for up to 5 km inland, with a maximum width of 500 m (Fig. 25). Wider channels have a regular arcuate-

Plate 24, fig. 1. Wide mangrove channel on the east side of the Styx River. (GA/3963)

Plate 24, fig. 2. Narrow mangrove channel on the east side of the Styx River, showing a number of sharp changes in river direction. (GA/4131)

Plate 25, fig. 1. Typical mangrove channel at high tide. (M/1091/19)

Plate 25, fig. 2. Typical mangrove channel at low tide. The channel is flanked by mud and has a typical V-shaped profile. (GA/7859)

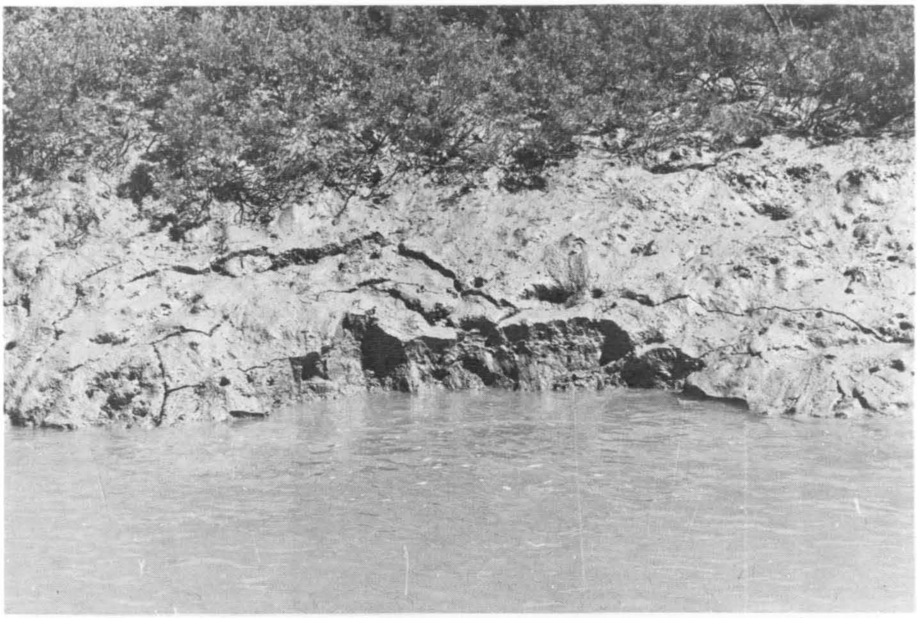
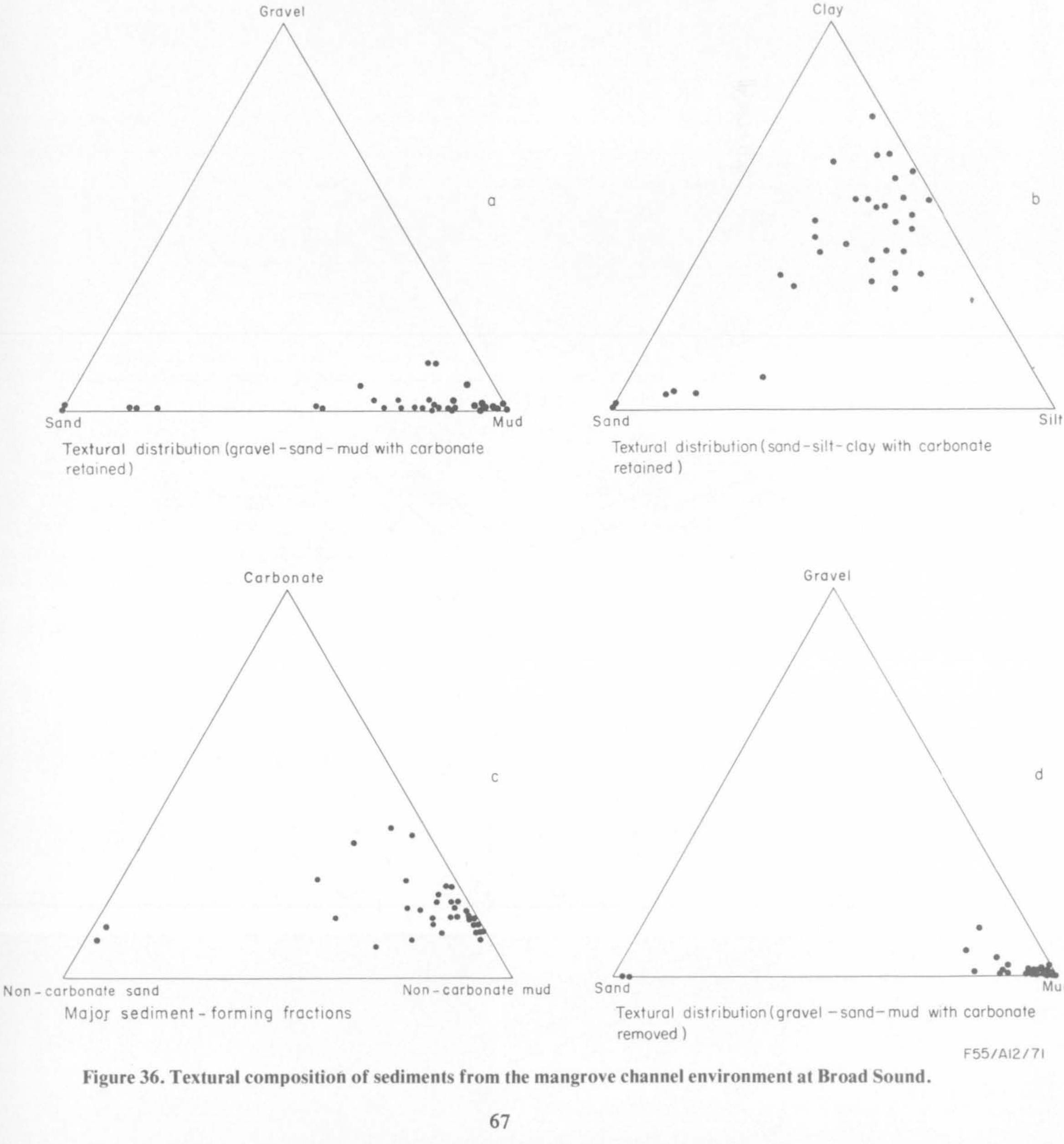


Plate 26, fig. 1. Unstable slopes on the flanks of a mangrove channel on the east side of the Styx River, 2 km south of Charon Point. (M/1091/34)

Plate 26, fig. 2. Large slumped block of mangrove material on the flanks of a mangrove channel on the east side of the Styx River, 2 km south of Charon Point. (M/1091/21) form (Pl. 24, fig. 1) but many smaller channels have a straight pattern interrupted by sharp changes in direction (Pl. 24, fig. 2). The channels are flanked by mangrove trees, which extend partway down the channel walls (Pl. 25, fig. 1). At low water most contain only a few centimetres of water or a few with sand bars at their mouths retain water up to 1 m deep. During flood and ebb tides most are swept by strong currents. At low water the channels have a typical V-shaped cross-section (Pl. 25, fig. 2), with gradients of up to 30°. As the walls are composed predominantly of mud, such steep slopes are unstable and slumping is common. This ranges from small-scale slumps (Pl. 26, fig. 1) to large-scale slumps several metres across which may carry large mangrove trees along with them (Pl. 26, fig. 2). On a few of the gentler slopes (less than 10°) more stable conditions prevail, and finely laminate sediments have a marked seaward depositional dip, similar to the mud facies of the open intertidal environment.

The sediments of the mangrove channel environment are derived, primarily by slumping, from the adjacent mangrove swamp environment. They are greenish grey (5 GY 6/1) to dark



Textural distribution (gravel - sand - mud with carbonate retained)

Textural distribution (sand - silt - clay with carbonate retained)

Major sediment - forming fractions

Textural distribution (gravel - sand - mud with carbonate removed)

Figure 36. Textural composition of sediments from the mangrove channel environment at Broad Sound.

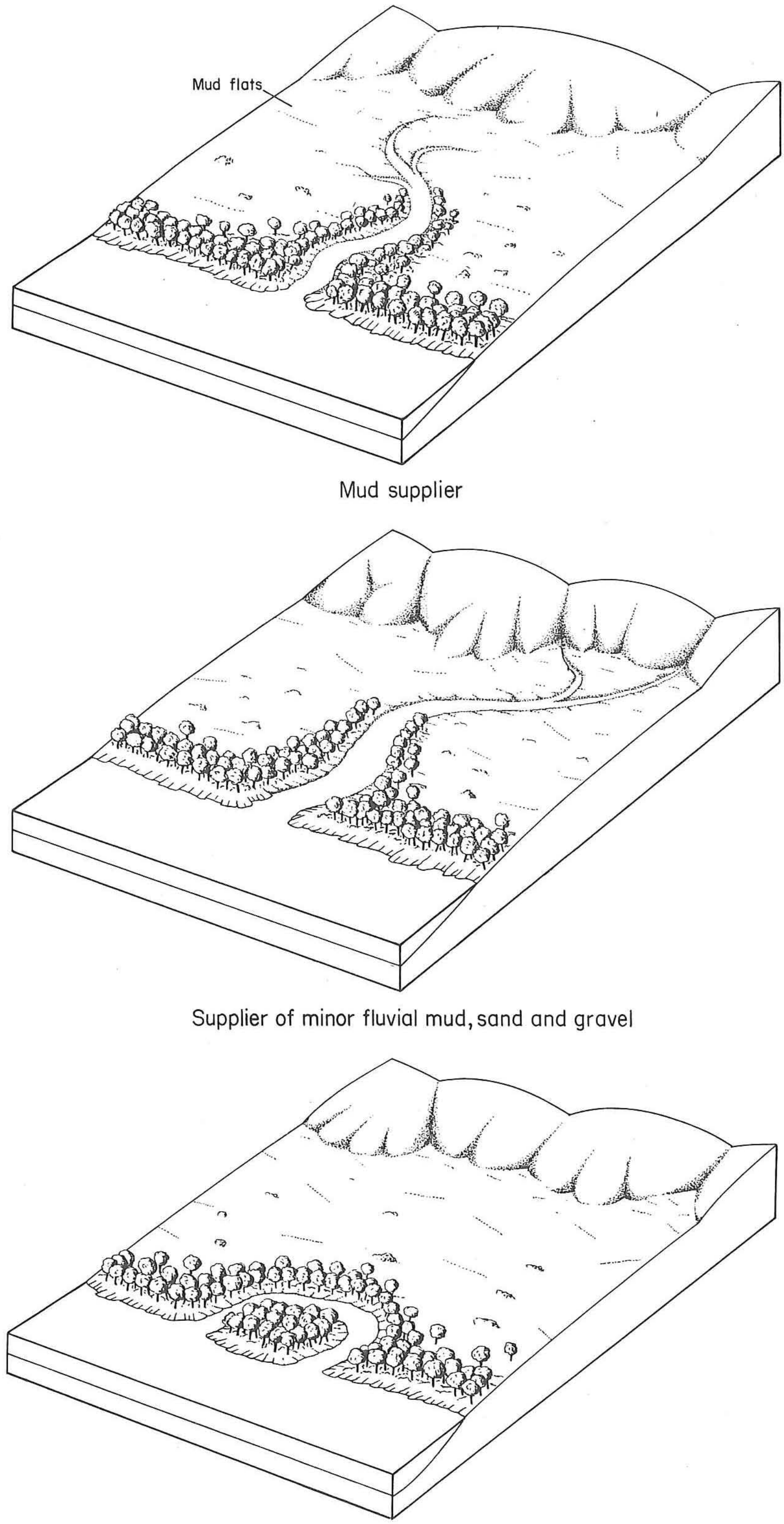


Figure 37. Mangrove channels as typified by their sediment.

grey (N 4) and generally unstratified except on low-angle channel flanks. Carbonate abundance is intermediate between that in the open intertidal and mangrove swamp environments (Fig. 36, Table 2). A few shell (bivalve) fragments are present in the muds, but crabs are the commonest faunal element and are responsible for extensive burrowing in the banks of the channel. Crabs up to 20 cm across the back, with a span across the claws of 50 cm, were caught in the channels; animals of this size are capable of carrying out a considerable amount of bioturbation. A rare type of faunal modification of the channel form was that of the few large salt-water crocodiles in the area, which made 'slides' up to 1 m across, down some of the banks. A few halophytic plants grow on the upper parts of the channel banks (Pl. 26, fig. 1), but elsewhere the banks are bare.

Some channels open at both ends into the open marine environment (Fig. 37) and current velocities are comparatively high. As a con sequence, sand from the open intertidal environment is swept into the channel, and mud is removed; although the banks are composed primarily of mud, the bottom is sandy. In a few places, currents are sufficiently strong to winnow out sand and mud, and a lag gravel similar to the pre-Holocene lag gravels of the shallow marine environment is exposed on the bottom. The predominance of mud and sandy mud in the mangrove channel environment is evident in Figure 27; however, subordinate sand plus muddy sand, and gravelly mud are also apparent (Fig. 36). This points to the two basic types of mangrove channel in the Broad Sound area, namely the 'blind' mangrove channels which supply mud derived from the supratidal flats into the Broad Sound estuarine system, and the open-ended mangrove channels which in many ways may be regarded as a narrow arm of the open intertidal environment (Fig. 37). Although open-ended mangrove channels are 'mud suppliers', they are also 'sand receivers' from the sand facies of the open intertidal environment. This is evident in the next chapter, where statistical analysis groups a few mangrove channel samples with the open intertidal samples. A third type of mangrove channel also contributes a small amount of terrigenous sand and gravel from the land (Fig. 37).

The mangrove channel sediments are predominantly olive grey (5 Y 5/2 and 5 Y 6/1) to dark grey (N 4). A redox value of +220 mV and a pH value of 7.8 were obtained at a single locality. A study of the water in mangrove channels (Cook and Mayo, in prep.) revealed that the ebb-tide water has a higher salinity and much lower pH than normal Broad Sound water. Where the channel water stagnates at about low tide, conditions in the water column probably become anoxic for a short time.

Mangrove Swamp Environment

The mangrove swamp environment extends from the upper part of the intertidal zone into the supratidal zone. In places it forms a belt up to 5 km wide. The most extensive developments occur near Island Bluff and at the southern end of Long Island (Pl. 27, figs. 1 and 2). Elsewhere, the mangrove swamp forms a narrow irregular belt flanking the mangrove channels (Pl. 28, fig. 1). Where mangrove is actively colonizing the open intertidal environment (Pl. 28, fig. 2), the boundary of the mangrove swamp environment is gradational with the open intertidal muds and sands. Areas where the shoreline is actively prograding are shown in Figure 6. Elsewhere, there is generally a sharp boundary, marked by a low escarpment (up to 1 m high) between the mangrove swamp and open intertidal environment (Pl. 29, fig 1). On the landward side of the environment the boundary with the supratidal flat environment is generally gradational over a few metres. In a few places the mangrove swamp environment abuts directly against the coastal grasslands or the uplands.

A dominant feature of this environment is the dense vegetation which traps and binds the sediment (Pl. 29, fig. 2). Even more important is the ability of the mangrove to modify what can be at times the comparatively high-energy conditions prevailing in places in the intertidal zone to a low-energy environment. As a consequence, some of the suspension load in the sea water is able to settle out. A detailed survey was not made of the flora of the mangrove swamps, but there is an obvious landward gradation from low bushy immature mangrove with well developed stilt roots and pneumatophores on the outer edge of the environment (Pl. 30, fig. 1), to tall (10 m and more) thick mature mangrove trees in the interior part of the mangrove swamp (Pl. 30, fig. 2, Pl. 51, fig. 2), grading into dense low bushy mangrove adjacent to the supratidal flats. On the basis of identification of plants by R. Pullen of the CSIRO Division of Plant Industry, it appears that *Rhizophora stylosa* is a major mangrove type. On the seaward edge of the environment *Aegiceras corniculatum* is common, whereas along the margin of the mangrove channels *Avicennia marina* is abundant. On the boundary between the mangrove swamp and supratidal flat environments the dominant species appears to be *Ceriops tagal*.

Associated with this progressive change in vegetation type is a change in the substratum from soft grey (N 4) fetid mud on the seaward edge of the mangrove swamp environment

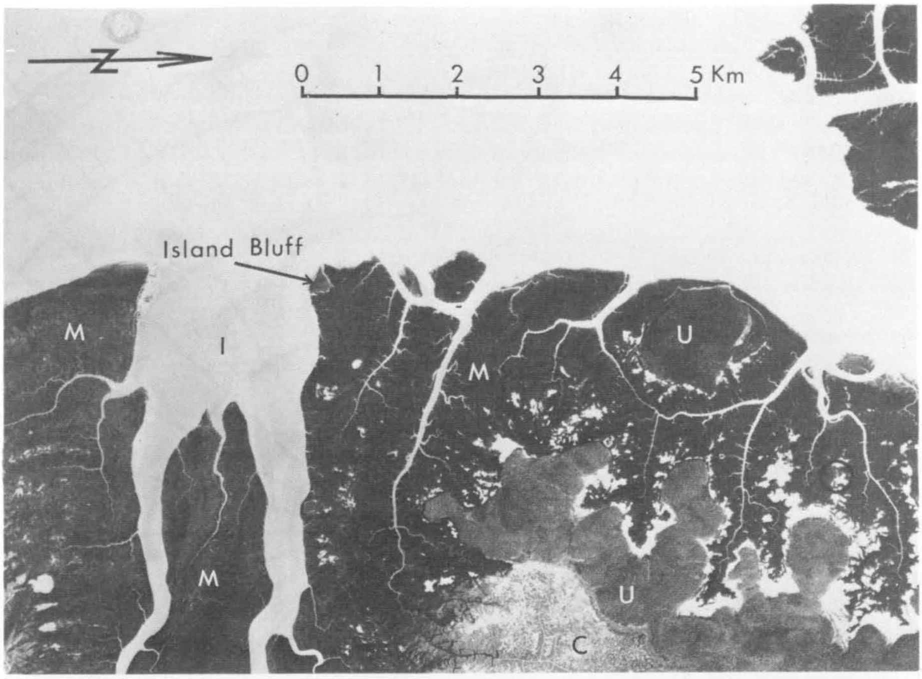


Plate 27, fig. 1. Extensive mangrove swamps near Island Bluff on the east side of Broad Sound. Symbols indicate open intertidal (I), mangrove swamp (M), coastal grassland (C), and uplands (U). (GA/7829)

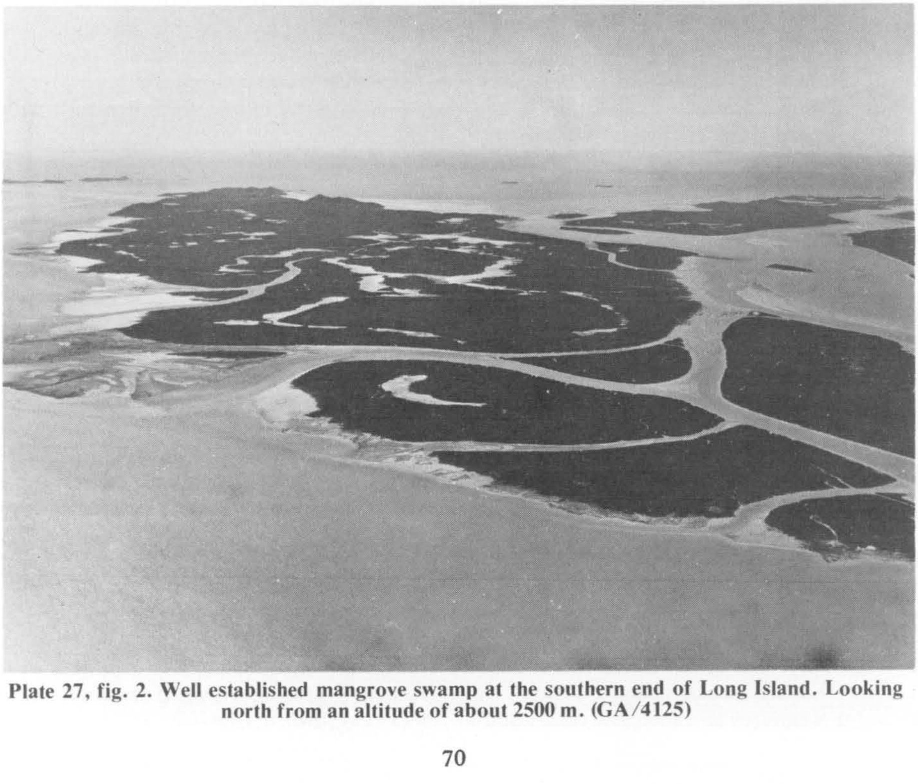


Plate 27, fig. 2. Well established mangrove swamp at the southern end of Long Island. Looking north from an altitude of about 2500 m. (GA/4125)

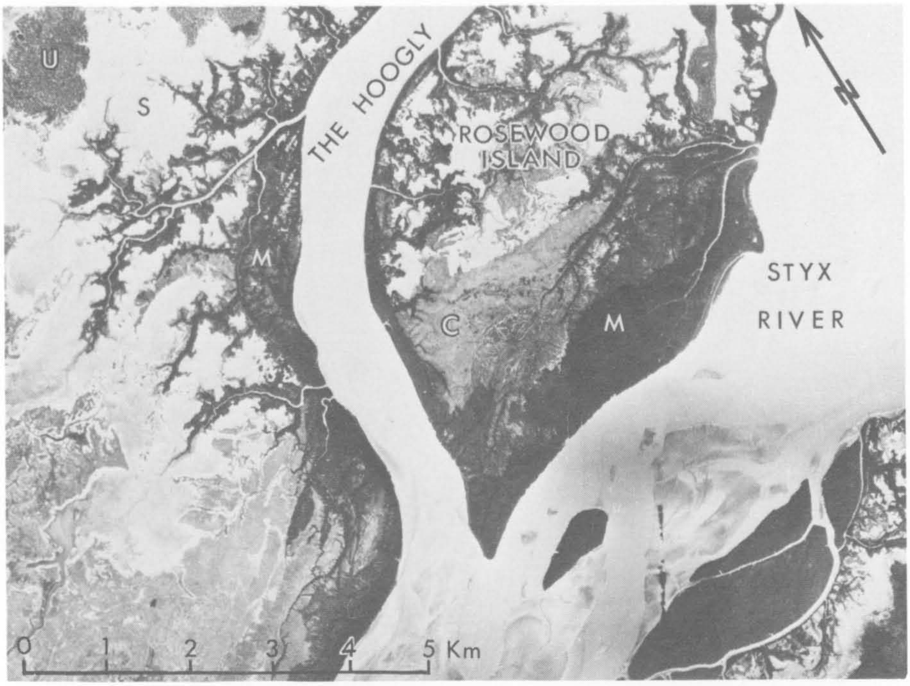


Plate 28, fig. 1. Limited development of mangrove adjacent to The Hoogly and flanking narrow mangrove channels. Symbols indicate mangrove swamp (M), supratidal flats (S), coastal grassland (C), and uplands (U). (GA/7831)

Plate 28, fig. 2. Pioneering mangrove on a sand bank in the upper reaches of Herbert Creek. Looking east across Herbert Creek from an altitude of about 1500 m. (GA/3642)

F

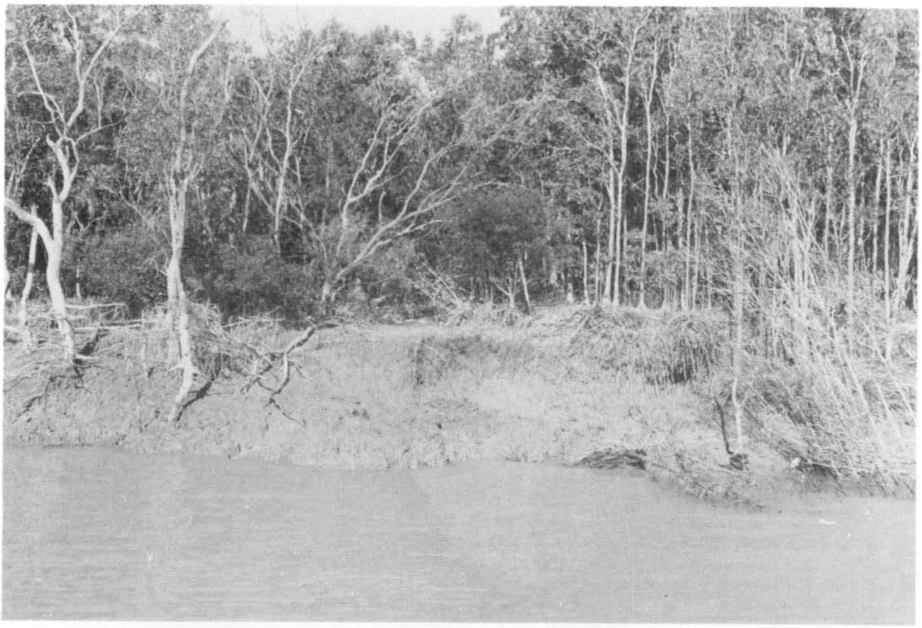


Plate 29, fig. 1. Low cliff (height about 1 m) on the outer boundary of mangrove swamp adjacent to the Styx River. The cliff is the result of present-day erosion. (M/1068)

Plate 29, fig. 2. Mangrove pneumatophores acting as sediment binders and trappers near Charon Point. (GA/4081)

Plate 30, fig. 1. Thick development of mangrove stilt roots on the seaward side of the mangrove swamp environment on the east side of the Styx River, 1 km south of Charon Point. (M/1100/29)

Plate 30, fig. 2. More mature mangrove development near Charon Point. Note the abundance of pneumatophores and the irregular surface due to bioturbation. (M/1068) (within the intertidal zone) to tacky mottled dark yellowish brown (10 YR 4/2) mud over most of the mangrove swamp environment, grading into brownish grey (5 YR 4/1) mud on the landward side. Similarly there appears to be a progressive landward decrease in the abundance of sand and silt in the mangrove sediments.

The mangrove sediments are predominantly muds (using the classification of Folk, 1954) with minor sandy muds (Fig. 38a). Removal of the calcareous fraction reduces all except one of the samples to mud (Fig. 38d) indicating that the sand-size material is predominantly calcareous (biogenic). Using the Shepard (1954) classification, most of the mangrove sediments are clayey silty clays (Fig. 38c). The carbonate content is intermediate between the mangrove channel and supratidal flat sediments (Fig. 27) and ranges from 0 to 30 percent $CaCO_3$. There is a progressive landward decrease in carbonate abundance (Fig. 31). Most of the carbonate is in the form of bivalve fragments, though both whole and fragmentary gastropods are also present in places. The dominant living organisms are crabs

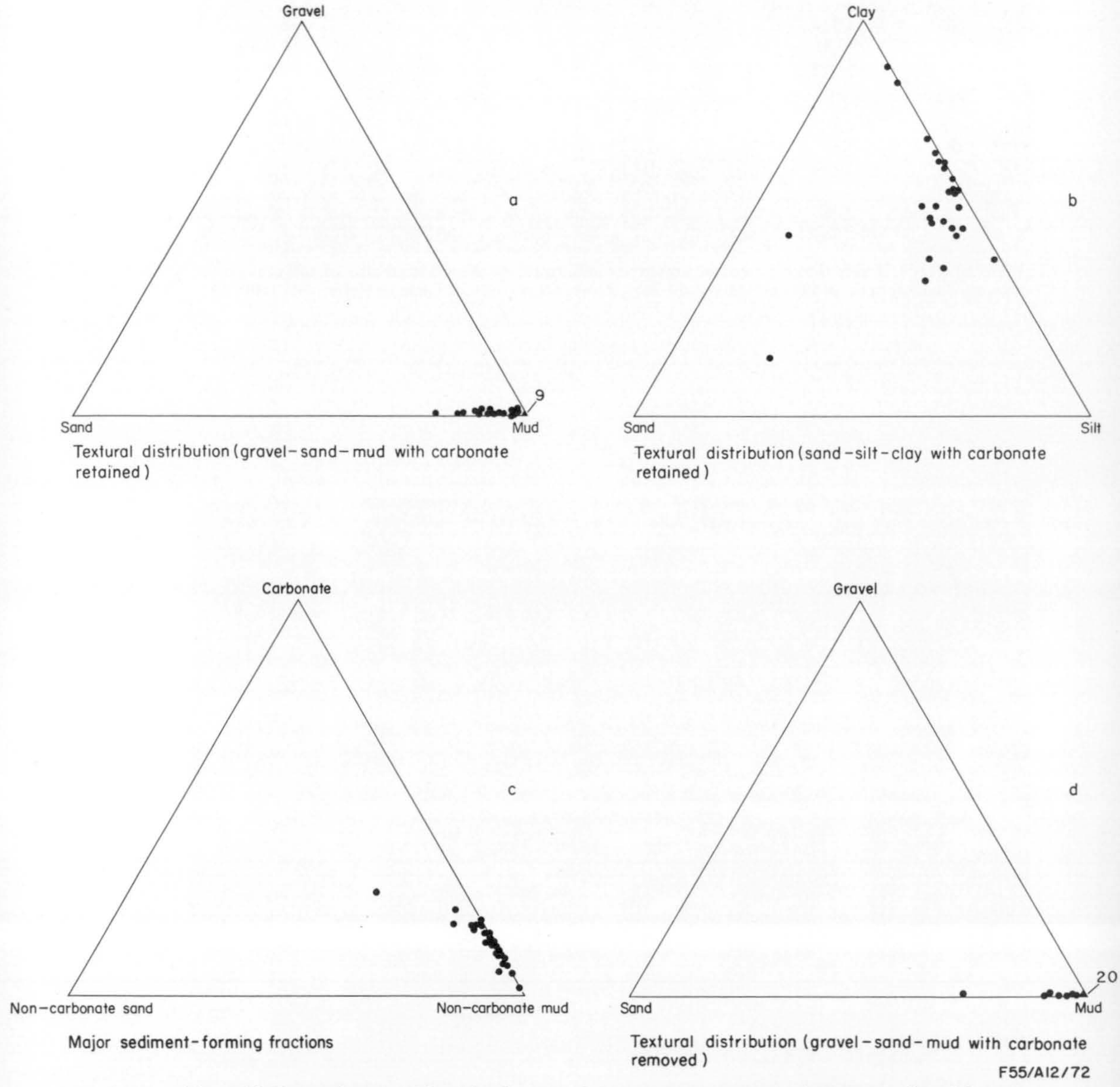


Figure 38. Textural composition of sediments of the mangrove swamp environment at Broad Sound.

and worms, with some gastropods and a few oysters on the seaward edge of the environment. There is marked bioturbation of the muds by these organisms (Pl. 31, fig. 1), and this together with root activity results in extensive aeration of the sediments (Pl. 31, fig. 2). As a result, there is extensive oxidation of the wood and leaf fragments in the muds of the mangrove swamps of the supratidal zone. This is reflected in the brown colour of these muds and the redox potential of the sediments, which averages +140 mV. The pH ranges from 6.6 to 7.3 and averages 6.8. Conditions are rather different in the intertidal zone of the mangrove swamp environment, where the redox potential of the sediments is commonly negative.

There is also a marked difference between the present-day mangrove muds and the buried mangrove muds. The older deposits will be discussed later but it is important to note that once the mangrove muds are buried below the supratidal flats, they rapidly become less oxidizing (a redox potential of -360 to +220 mV and averaging +80 mV) and much more acid (a mean pH value of 4.9).

Apart from burrows, root casts, and wood fragments, a few sedimentary structures are preserved in the mangrove muds. Any stratification is destroyed by bioturbation. Mud-cracks and algal films become increasingly common landward, but such structures are unlikely to be preserved. It seems probable that as in other areas (Thom, 1967) the landward limit of the mangrove environment is the result of a progressive increase in salinity. The seaward limit is imposed by water depth.

It is not clear in the case of colonizing mangrove whether the mangroves colonize an area because of a muddy substratum or whether the muddy substratum is the result of sediment binding and trapping together with conversion of the high-energy to a low-energy environment. At Broad Sound, it appears that both mechanisms may be important at times; however, the ability of mangrove to grow on gravel at Upper Head indicates that mud is not essential for colonization by mangrove. It is probable that when an area builds up to a desirable tidal level for mangrove this is also the level of inundation at which mud is deposited (see next chapter). Thus, the appearance of mud and mangrove is nearly synchronous. The reason why mangrove is actively colonizing in some areas and being progressively eroded elsewhere is uncertain as there is no clear pattern of the erosion-deposition distribution. The most likely reason is that the coast is tending towards the most dynamically stable configuration. Wright et al. (1973) have shown that this configuration is a function of the standing wave. This is achieved by 'sedimentary cannibalism', where one portion of the coast is eroded, supplying the sediment used for progradation in another part of the coast.

Supratidal Flat Environment

The supratidal flat environment is landward of the mangrove swamp environment, and seaward of the coastal grasslands and uplands. It is located primarily within the supratidal zone but the most landward portion extends into the extratidal zone and is within the reach of only exceptionally high spring tides and storm tides. In most areas, the supratidal flats are represented by extensive low-relief mudflats up to 5 km wide (Pl. 32, fig. 1). In places, the environment is channel-like (Pl. 32, fig. 2) with narrow (maximum width of about 50 m) supratidal channels extending for several kilometres into the coastal grasslands until they finally merge into fluvial channels. Damming of some of the supratidal channels by pastoralists is progressively decreasing the area of coastal grassland subject to influx of seawater. In addition, many channels now retain extensive bodies of fresh water on the landward side of the dams. The boundary of the supratidal flats with the coastal grasslands is marked in most areas by a low escarpment 10 to 60 cm high (Pl. 33, fig. 1), suggesting landward movement of the shoreline in places. Further evidence that the coastal grasslands have been more extensive in places, is supplied by the presence of erosional remnants of coastal grasslands, completely surrounded by modern supratidal flats (Pl. 33, fig. 2). In a few places, particularly at the southern end of Torilla Plains, the supratidal/coastal grassland boundary is gradational. There is no escarpment, but a progressive change from bare tidal flats to muds covered by halophytes, into muds with a thin soil veneer and a sparse grass cover, finally giving way to well developed coastal grasslands.

For most of the time, the supratidal flats are subaerially exposed. In a few areas adjacent to the uplands, pools of brackish water may persist for several weeks (Pl. 34, fig. 1). Elsewhere sea water covers the supratidal flats only at high spring tides and then only for periods of 1 to 2 hours although it may persist for several hours in some of the drainage channels. The extent to which fresh water covers the flats during the summer wet season is unknown as the writers made no summer observations though it is suspected that at times there is an extensive cover of fresh water. Shallow channels carry the water across the flats and into the mangrove channels (Pl. 34, fig. 2).

The sediments of the supratidal flats are finer-grained and less calcareous than those of the other Broad Sound depositional environments

Plate 31, fig. 1. Dense intergrowth of mangrove stilt roots, with extensive burrowing of the sediment by crabs, 1 km south of Charon Point. (M/1100/32)

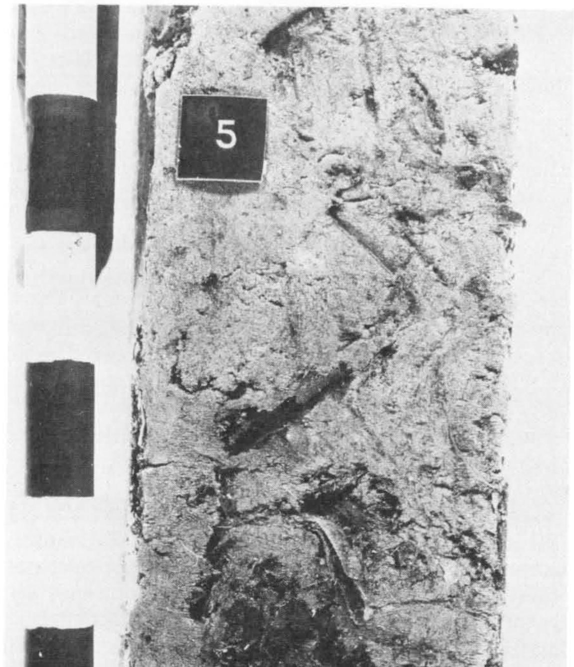


Plate 31, fig. 2. Core (diameter 6.5 cm) of mud from the mangrove swamp environment on the east side of the Styx River, 1 km south of Charon Point. Abundant woody fragments are present in the mud. (GA/6129)

Plate 32, fig. 1. Typical supratidal flats showing the wide low-relief supratidal flats 1 km south of Charon Point. (M/1101)

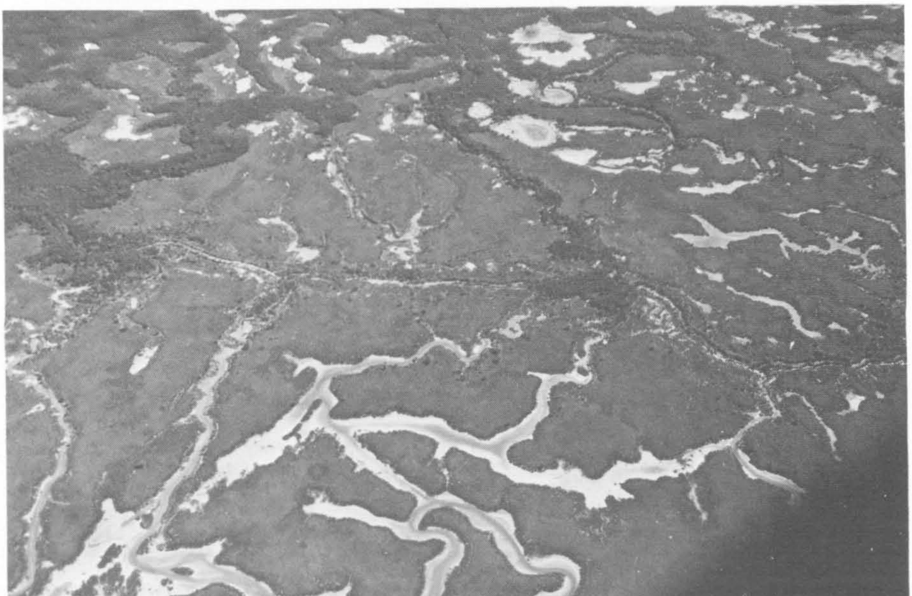


Plate 32, fig. 2. Supratidal channels extending into the coastal grasslands of Torilla Plains, viewed from 1500 m. (GA/4088)

Plate 33, fig. 1. Low scarp on the landward edge of the supratidal flats, where coastal grasslands are undergoing erosion at the present time, on the east side of the Styx River, 1 km south of Charon Point. (M/1101/5)

Plate 33, fig. 2. Erosional remnant of coastal grassland surrounded by supratidal flats, on the east side of the Styx River, 1 km south of Charon Point. (M/1101/6)

Plate 34, fig. 1. Extensive supratidal flats on the east side of Herbert Creek, covered by a few centimeters of brackish water. Well developed algal growth is taking place in the brackish water. (GA/7857)

Plate 34, fig. 2. Shallow drainage channel on supratidal flats south of Charon Point. (M/1101/14)

(Fig. 27). Using the Folk (1954) classification most may be classed as muds, and a few fall into the sandy mud category (Fig. 39). They group mainly into the clay and silty clay fields of Shepard (1954). However, although the supratidal flat sediments are finer-grained (mean grainsize of 8.62, Table 2) than the more seaward mangrove swamp environment (mean grainsize of 7.85), there is a higher percentage of terrigenous gravel in the supratidal sediments (Fig. 30). This is also evident by comparing Figure 39a with Figure 38d. It appears that the relative abundance of coarse material is a reflection of a continental component in the sediments. This is apparent in the field; adjacent to the landward margin of the supratidal muds (most commonly a low escarpment, e.g. Pl. 33, fig. 1) the surface of the flats is commonly covered with coarse sand and fine gravel. Coleman, Gagliano, & Smith (1966) have described a similar feature from northern Queensland, and consider that chemical weathering is an important mechanism for the break-down of boulders in the adjacent soil profile. It is likely that chemical weathering is also an important feature of the outer periphery of the Broad Sound supratidal flats, but in places there

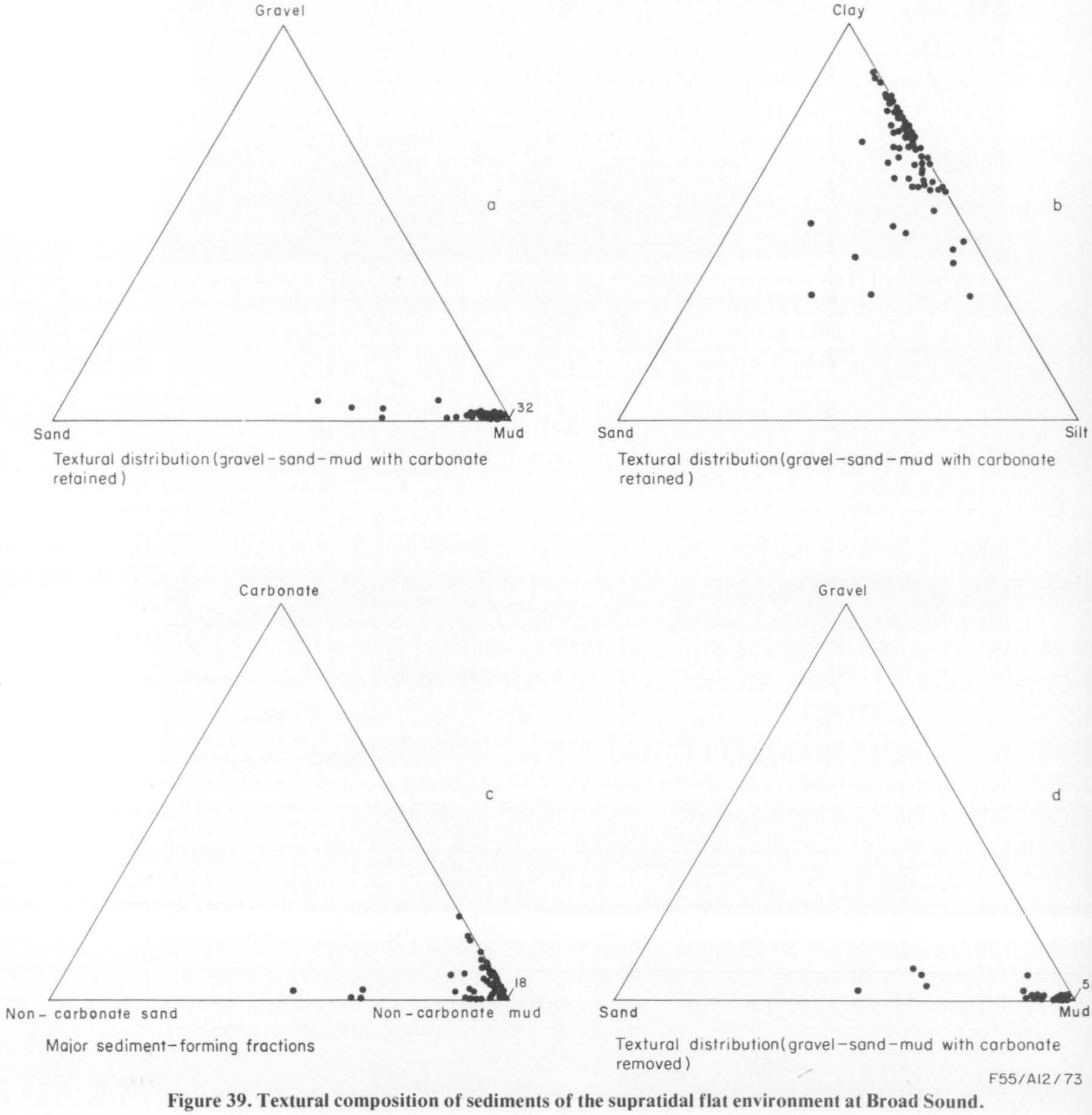


Figure 39. Textural composition of sediments of the supratidal flat environment at Broad Sound.

are small outwash fans of coarse material resulting from fluvial outwash during the wet season. Most of the fine sediment is believed to be derived from the ocean, carried into the environment during high spring tides and storm tides. The baffling effect of the mangrove trees together with the high level of inundation (and the slack water) necessary to reach the supratidal flats ensure that only the finest material (which is capable of being carried in suspension) is carried into the supratidal flat environment. There it settles out of suspension, in some instances the water possibly dissipates slowly through the underlying sediments and the suspended sediment is retained by filtration on the fine surface film; in other cases the water evaporates, and the suspended load together with evaporative salts are left as a residue.

The muds of the supratidal flats are damp and tacky for up to several days after marine inundation, but for the remainder of the time the top 5 to 10 cm is dry and hard except in areas of groundwater seepage. They range from olive grey (5 Y 6/1 and 5 Y 5/2) to yellowish brown (10 YR 4/2). For the top 30 to 60 cm most of the muds are olive grey except where wood fragments are incorporated in the muds (red, yellow, and brown mottles are commonly found around such fragments). At a depth of up to about 60 cm there is an abrupt change in most areas; the mud becomes dark grey (N 3) and there are abundant plant fragments. The darker muds are not supratidal flat deposits but old mangrove swamp deposits ranging in age from a few hundred to several thousand years. In a few places these old deposits are exposed within the supratidal flats as a result of erosion; however, they are readily distinguished from the true supratidal flat deposits by their darker colour.

Owing to the dryness of the muds it was often difficult to obtain reliable Eh and pH values. A mean Eh value of +170 mV was obtained, and this together with the colour of the muds suggest a strongly oxidizing environment. The pH values tend to be slightly acid to slightly alkaline (average of 7.0). This is in marked contrast to the old mangrove deposits underlying the supratidal flats, which are strongly acid and in many cases highly reducing.

In the supratidal zone in general, particularly in the bare mud-flats, both surface and interstitial waters are strongly saline, values in excess of two to three times the salinity of seawater being common. As a result, a thin veneer of evaporites covers the mudflats in many areas; gypsum is abundant in the subsurface, occurring as flat discoid crystals up to 1 cm in diameter. Halite is present in places as an ephemeral surface encrustation (and perhaps also in places in the subsurface) which is rapidly removed either by wind or solution. Traces of bischoffite and bassinite are present in places.

The hypersaline condition of the supratidal zone is not conducive to the development of a prolific biota. Crabs and a large gastropod were the only common fauna. A few small whole and fragmentary bivalve and gastropod shells are found in places on the seaward side of the mudflats. Holocene cheniers (see later) composed almost entirely of shell material are being locally eroded and reworked, and shells are being distributed over the mudflats. However, no major accumulation of modern shell material is known to be forming on the present-day Broad Sound supratidal flats.

Small halophytic plants are common near the mangrove swamp/supratidal flat boundary (Pl. 35, fig. 1) but these rapidly give way to bare mudflats as conditions become more desiccated. In these areas there is generally a thin superficial film of filamentous algae, which probably plays an important role in binding the sediment. This commonly gives the mud a rubbery texture, and also produces fine, though at times irregular, laminae. Extensive algal growth occurs when the mudflats are covered by sea water and also in areas where there are accumulations of fresh or brackish water (Pl. 34, fig. 1). At other times the film becomes desiccated. Doming or blistering of the film (probably as a result of the formation of gas bubbles in the film) is a common early feature of desiccation (Pl. 35, fig. 2), and is responsible for the vuggy texture (comparable with the well-known 'birds eye' texture of carbonate muds) found in many supratidal muds. With further desiccation, the algal film undergoes extensive cracking and flaking (Pl. 36, fig. 1). The development of 'algal rolls' was a particular feature of parts of the mudflats (Pl. 36, fig. 2). These are believed to form by early cracks developing in the algal film, and as desiccation proceeds the film contracts and gradually rolls up rather than fragmenting.

Derived plant material is abundant on the surface of the supratidal flats. Mangrove and eucalyptus leaves are commonly blown onto them and in places leave a well defined imprint. Tracks of birds and animals (mainly kangaroos and cattle) are also common. Twigs and small branches are carried across the mudflats during marine inundation, producing characteristic groove casts on the mudflat surface (Pl. 37, fig. 1). Striations, ripple marks, small mud-balls, and intraformation breccias are common in some of the shallow drainage channels. The most common sedimentary structure of the supratidal flat environment is mud-cracking ranging from superficial cracks in the lower part of the supratidal zone to well

Plate 35, fig. 1. Halophytes growing on the seaward side of the supratidal flats on the east side of the Styx River. Tape divisions are in inches. (M/1100)

Plate 35, fig. 2. Algal mat at an early stage of desiccation. Localized doming is giving a blister-like appearance to the mat. Individual blisters have a diameter of about 1 cm. East side of the Styx River, 1 km south of Charon Point. (M/1102)

Plate 36, fig. 1. Algal mat in the final stages of desiccation. The mat has undergone extensive extensive cracking and flaking; 1 km south of Charon Point. (GA/7858)

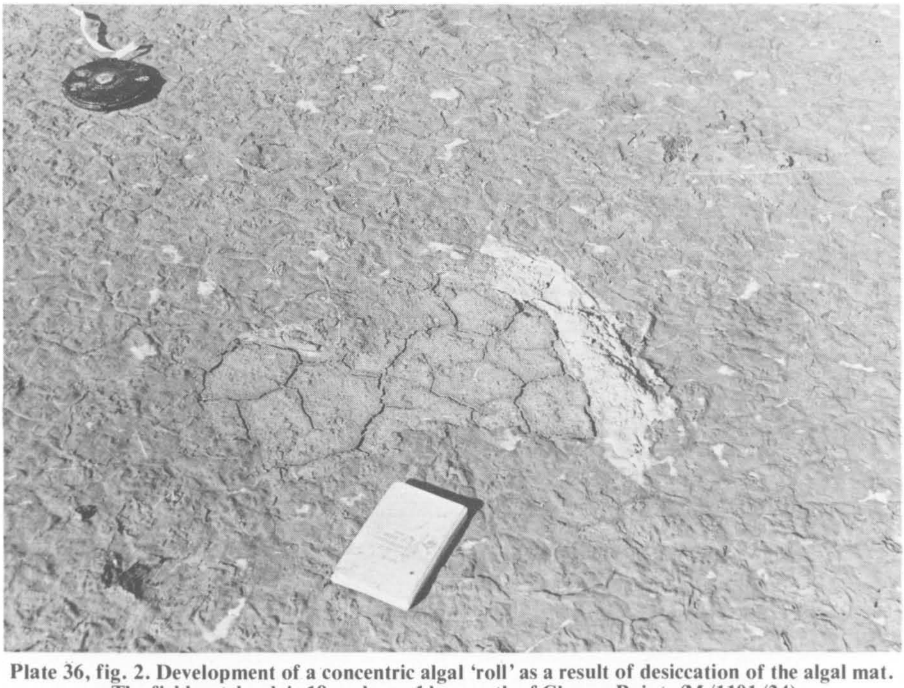


Plate 36, fig. 2. Development of a concentric algal 'roll' as a result of desiccation of the algal mat. The field notebook is 19 cm long; 1 km south of Charon Point. (M/1101/34)

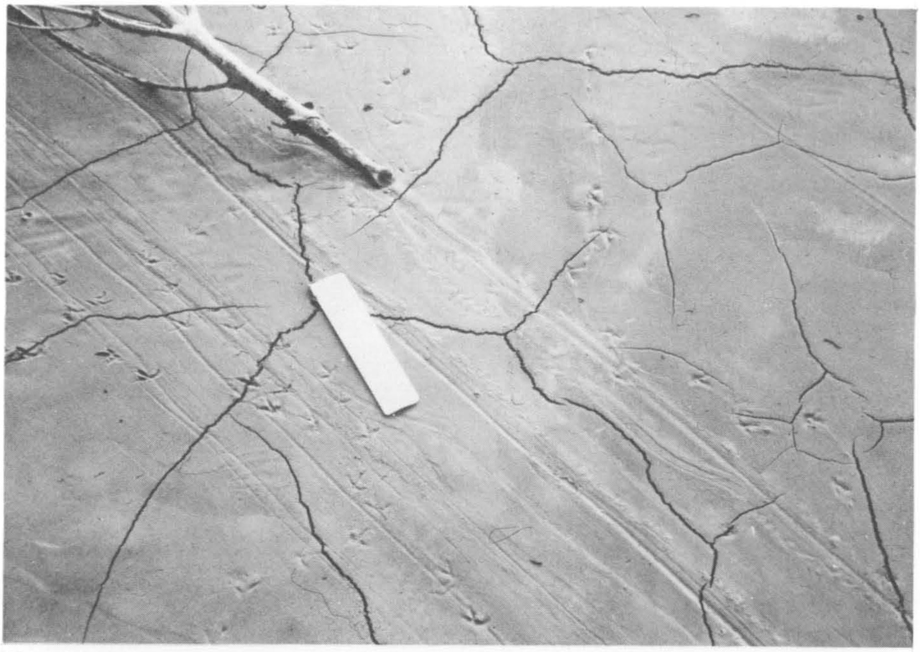


Plate 37, fig. 1. Shallow early-stage desiccation cracks on a mudflat surface 1 km south of Charon Point. Note the development of groove casts (owing to the dragging of a stick over the mud surface), and bird tracks. The scale is 15 cm long. (GA/7866)

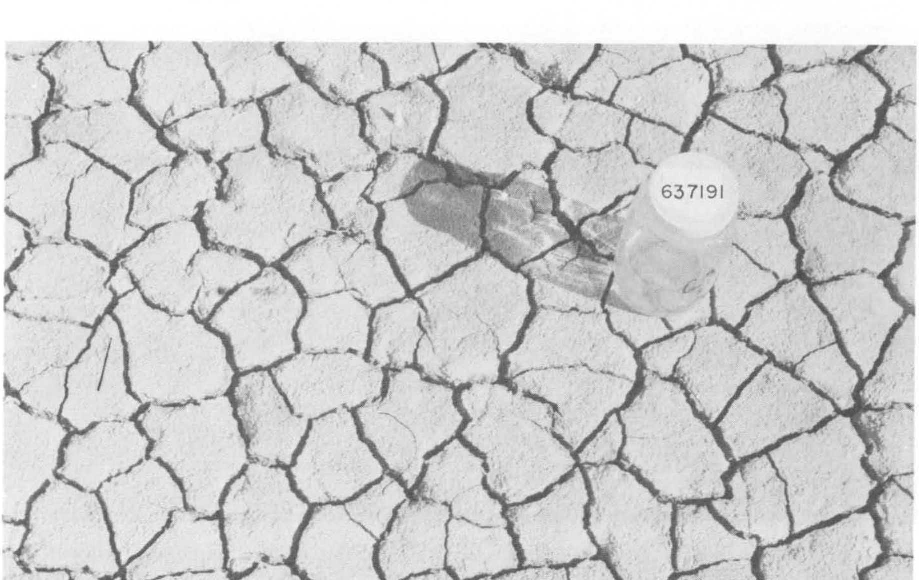


Plate 37, fig. 2. Deep late-stage dessication cracks on a mudflat surface devoid of an algal mat. The white jar top has a diameter of 7 cm. Locality 191. (M/1138) defined cracks up to several centimetres deep as the extratidal zone is approached (Pl. 37, fig. 2).

EXTRATIDAL ENVIRONMENTS

The extratidal environments were considered to be outside the scope of the Broad Sound estuarine study because their affinites are more continental than marine, with soil-forming and fluvial processes dominant (Fig. 24). Coastal grasslands develop as the supratidal flats are progressively removed from the marine sphere. This may happen in response to either vertical or lateral accretion, or uplift. With marine inundation only occurring under the most exceptional circumstances, soil formation is able to take place. In the Torilla Plains area this produces dark saline cracking soils 10 to 20 cm thick, known as wiesenboden or humic gley soils (Isbell & Hubble, 1967), with a well developed grass cover. Vertical accretion of the coastal grasslands probably continues as a result of accumulation of terrigenous and some organic material until the environment is completely removed from the extratidal zone. Late Holocene uplift may also elevate the coastal grasslands above the extratidal zone in places. Alternatively the coastal grasslands are buried by fluvial sediments ranging in grainsize from fine sand to coarse gravel. An excellent example of progradation of an alluvial fan over the coastal grasslands is shown in Plate 7, figure 2.

GRAINSIZE PARAMETERS — SAMPLE CLASSIFICATION AND INTERPRETATIONS

The most common grainsize parameters used in sedimentological studies are mean, standard deviation, skewness, and kurtosis, and the percent values of gravel, sand, silt, and clay fractions. From these parameters it may be possible to determine the provenance of the sediments, or to classify samples into separate depositional groups. If the changes in the parameters can be interpreted geologically, the reasons for changes in other variables associated with the grainsize parameters may also be explicable. The application of this concept to grainsize parameters and other variables is discussed by Griffiths (1963).

Objectives

In order to understand the interrelations between variables measured on the Broad Sound samples the samples should be classified into distinct geologically meaningful populations. If the samples are not classified, major differences between the populations are likely to mask the details within the individual populations.

The first aim here is to classify the Broad Sound sediments into units which reflect the prevailing sedimentological processes. In contrast to the observational type of classification used earlier to group the samples into sedimentary environments, the numerical classification used here is based on the grainsize parameter values. Links between the two classifications will be maintained throughout the discussions.

Once this grainsize grouping has been achieved the geological meaning of changes in the grainsize distribution parameters within each group can be determined. Knowledge of the changes will then simplify the application of the multivariate analytical techniques used for clarifying the interrelations between all variables measured on the sediments. Therefore, the two basic aims of this chapter are: to classify the samples into separate sedimentological groups; and to interpret geologically changes in the grainsize distribution parameters within each group.

Analytical techniques

Four grainsize distribution parameters (mean, standard deviation, skewness, and kurkosis) were determined on all samples collected on the grid pattern, and on the mangrove channel samples. The samples were not treated with acid before analysis, but organic matter was removed (Armstrong, 1973). The phi ($-\log_2$mm) transformation was used with all the analyses because the grainsize distribution of many sediments tends to become symmetrical when a logarithmic size scale is used (Krumbein & Pettijohn, 1938). The causes of any asymmetrical distributions may then be interpreted geologically.

The gravel fraction (more than 2.0 mm) was sieved, the sand fraction (2.0 to .063 mm) analysed with a settling tube, and the pipette method used for the mud fraction (less than .063 mm). Discussion of the problems associated with combining the three different measuring techniques are given by Mayo (1972). Removal of the calcium carbonate before grainsize analysis was at first considered essential to minimize these problems, as well as to eliminate anomalies introduced by the presence of in situ shells and relict carbonate nodules. With the calcium carbonate not removed, however, more than one mode in the sand fraction could indicate the presence of in situ shells and carbonate nodules because of the hydraulic equivalent measuring technique used with the sand fraction. Because the detection of in situ shells and nodules was considered important, and because the gravel fraction was relatively minor compared to the sand and mud fractions, it was decided that the carbonate should not be removed before obtaining the sample grainsize distributions.

Program GRSIZE (Mayo, 1972) was used to combine the results from the three fractions, and output the grainsize distribution parameters, the grainsize frequency distribution, and the percent gravel, sand, mud, silt, and clay. Although the pipette method was used only to analyse mud particles larger than 9 phi the program automatically extrapolated any remaining clay down to 14 phi using a sum of digits technique. The grainsize mean, standard deviation, and frequency distribution of the sand fraction alone were also obtained by excluding the gravel and mud results.

Program GRSIZE uses statistical moment measures to determine the distribution parameters.

The mean for grainsize data, $\bar{X}$, is defined as,

$$x = \frac{1}{100} \sum_{i=1}^{h} x_i f_i \text{ (phi)} \qquad \text{Equation 1}$$

where h = number of grainsize class intervals
x_i = mid-point of the i th class interval
f_i = frequency percent in the i th class interval

The other three statistical measures are determined the second, third, and fourth moments about using the mean.

These are defined as :

$$m_k = \frac{1}{100} \sum_{i=1}^{h} (x - \bar{x})^k f_i \qquad \text{Equation 2}$$

where m_k = k th moment about the mean

Variance = m_2

Standard deviation, $S = \sqrt{m_2}$ (phi units) Equation 3

Skewness, $g = \frac{m_3}{S^3}$ (dimensionless) Equation 4

Kurtosis, $g_2 = \frac{m_4}{S^4} - 3$ (dimensionless) Equation 5

In equation 5, three is subtracted from the initial kurtosis value so that a normal distribution would have a kurtosis of zero.

The gravel, sand, and mud values were also determined on the samples obtained from the grid pattern and the mangrove channel samples, with calcium carbonate removed by dilute hydrochloric acid. From these results (plus the average calcium carbonate content of each environment) the average percent calcium carbonate in the gravel, sand, and mud fractions of each environment was calculated. The grainsize distribution of the sand fraction with the carbonate removed was also analysed using the settling tube, and the results are compared with similar results for the sand fraction without the carbonate removed to detect the presence of in situ shells and nodules. The modes of these sand distributions also aid in determining the sediment dispersal processes in the estuary system.

Calcium carbonate was also removed from samples taken along the centre of St Lawrence Creek, the Styx River, and The Hoogly, and the grainsize distribution obtained by combining sieving, settling tube, and pipette methods as before. This facilitated comparison of the bedload from the upper reaches to the mouths of these watercourses without the problem of in situ shells, and minimized the problem of combining different measurement techniques.

Most of the following discussions will use the grainsize parameters and frequency distributions obtained from the samples with calcium carbonate present. If the carbonate has been removed this will be stated.

Grainsize distribution parameters

The mean can be imagined as the point of balance of the grainsize frequency distribution. If a full range of grainsizes is supplied from the source area, and if the sediment is in equilibrium with the depositing currents, the mean would be expected to be related to the maximum energy of the currents. This would apply under both low-energy and high-energy conditions.

A linear logarithmic relation between current strength and mean grainsize was found by Allen (1971) in high-energy conditions in the Gironde Estuary. The mean grainsize of sediment from high-energy areas of Broad Sound may similarly be expected to reflect those conditions. Spencer (1963) suggested that under low-energy conditions the mean would probably not indicate the energy of the environment, implying that coarser sediments out of equilibrium with the depositing currents are always present owing to relict sediments, slumping, etc. It will be shown that the mean grainsize of sediments deposited under low-energy conditions in some environments does in fact reflect those conditions.

Standard deviation is a measure of spread of a frequency distribution and is commonly used as a measure of sorting of sediment samples, 'standard deviation' being used synonymously with 'sorting'. However, the absolute grainsize standard deviation value does not indicate that a physical process has actually sorted the sediments, and it cannot be used to describe a sediment until it has been shown that the sediment has really been subjected to sorting processes.

Further, the usefulness of absolute standard deviation values between two sediments, one sorted under high-energy conditions and the other under low-energy, is doubtful. Once it has been shown, however, that a sedimentation unit has been sorted, changes in the standard deviation values within that unit may then indicate different levels of physical sorting.

Given the assumption of three basic lognormal grainsize populations (Folk, 1966), the mixing of two or more of these populations in unequal proportions will result in a skewed population. A unimodal distribution, tending to zero skewness, may indicate the sample was deposited under one set of environmental conditions, but problems arise with numerical interpretations as asymmetric distributions can in some circumstances also have zero skewness value. Therefore, to interpret skewness values geologically, the grainsize distributions of individual samples need to be analysed carefully before making final conclusions.

Using the formula for kurtosis in equation 5, a normal distribution would have a kurtosis of zero. Therefore, kurtosis values will depart from zero with a mixing of the fundamental lognormal populations. The main difference between skewness and kurtosis values is that whereas skewness values are positive if minor proportions of a finer grainsize population are mixed with a dominant population and negative if minor proportions of a coarser grainsize population are mixed with the dominant population, kurtosis values are positive in both these cases. Negative kurtosis values would result if one of the fundamental lognormally distributed grainsize populations was truncated by some physical process, whereas the resulting skewness values would be positive or negative depending on whether the coarse or the fine portion of the distribution was truncated. The mixing of two or more populations in almost equal proportions would also result in negative kurtosis.

Clearly, a close study of all available relevant information from a particular study area is essential before any decision on the usefulness of these parameters can be made.

General observations

Discussion in other chapters is based mainly on sedimentary environments. The relation of grainsize parameters to these environments will only be discussed briefly here. After the numerical classification is established the links between the

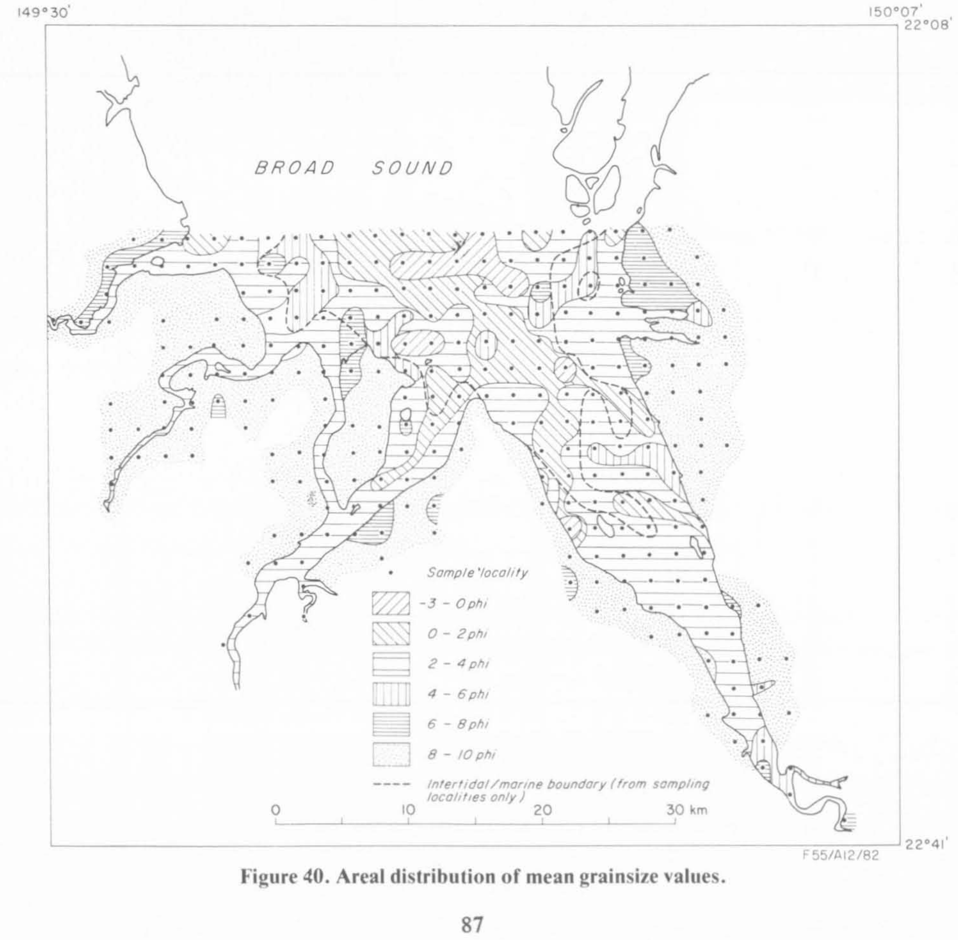


Figure 40. Areal distribution of mean grainsize values.

G

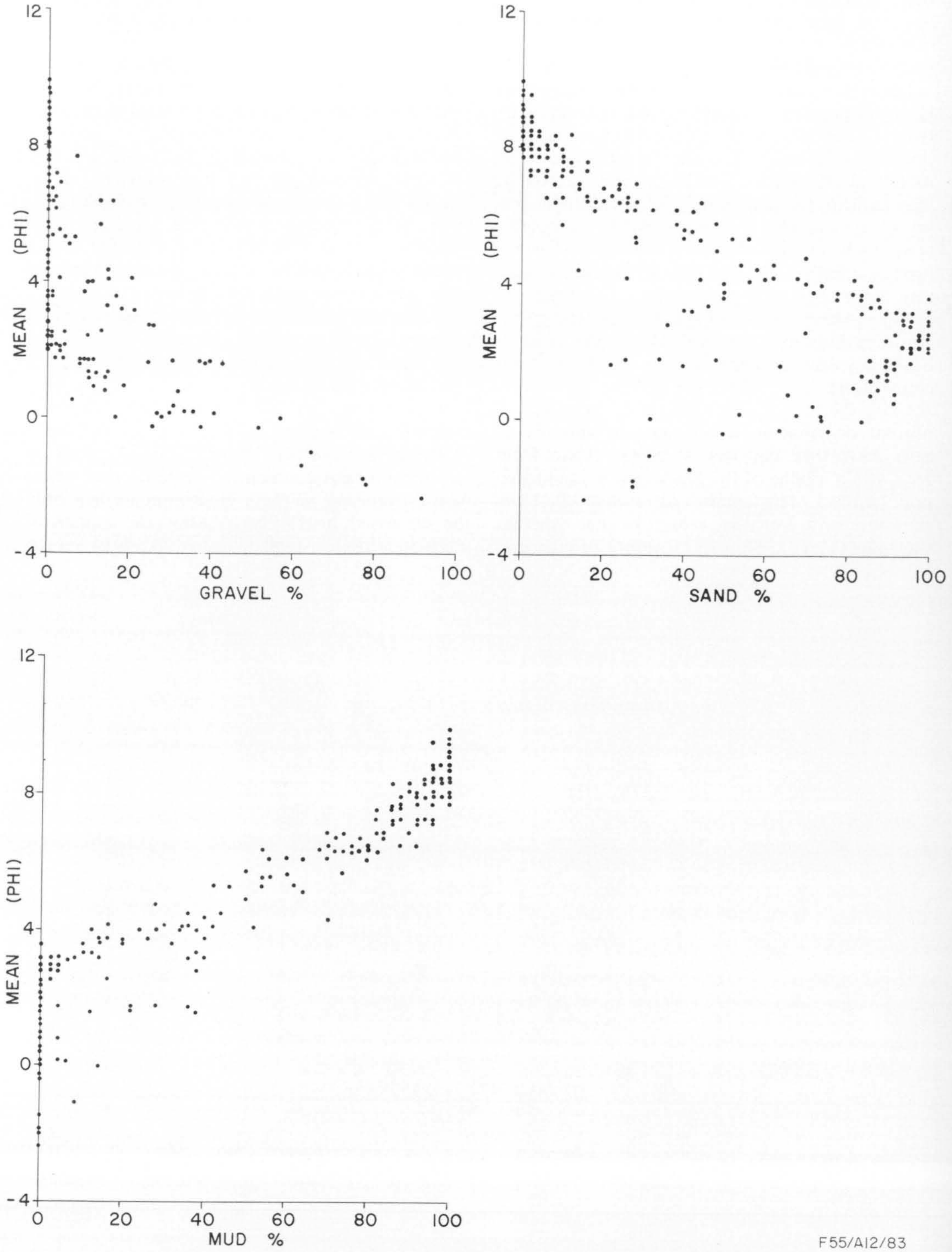


Figure 41. Relation between mean grainsize and gravel, sand, and mud percentages.

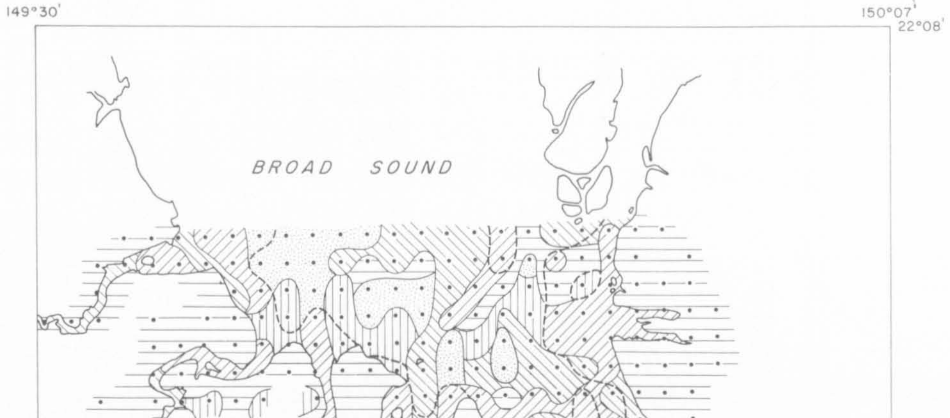


Figure 42. Areal distribution of grainsize standard deviation values.

groupings so formed and the sedimentary environments will be considered. A summary of the relevant grainsize statistics for individual environments plus the total estuary is given in Table 2. A total of 289 samples (256 from the original grid and 33 mangrove channel samples) was used to compile the statistics for this table.

Mean grainsize increases seawards from the supratidal flats to the shallow marine environments (Fig. 40). Generally, increasing mean grainsize (decreasing phi values) reflects increasing gravel and sand and decreasing mud content (Fig. 41). With increasing gravel content there is usually a corresponding decrease in the sand content and so for those samples with mean values less than 2 phi, increasing mean grainsize corresponds to decreasing sand content. The grainsize standard deviation of the open intertidal environment is on average much less than the other four environments (Fig. 42). The areal distribution of the skewness and kurtosis values are shown in Figures 43 and 44, respectively. No overall trends are apparent from either these figures or the statistics in Table 2. The spread of each distribution parameter value in the mangrove swamp and supratidal flat environments is much less than in the other environments.

The frequence distribution of the values of each grainsize distribution parameter for the total estuary is shown in Figure 45. The distribution of the mean grainsize values shows dominant modes at approximately 3 phi and 9 phi; the standard deviation plot also has modes at about 0.5 and 2.5 phi units. This suggests that these two measures may be useful in classifying the samples, and that this classification could be into two major groupings. Both the skewness and kurtosis distributions have only one major mode centering around the zero value, suggesting that these two parameters may not be sensitive in distinguishing samples deposited under different environment conditions.

For samples without acid treatment, high mud, low sand, and zero gravel in the mangrove swamp and supratidal flat environments contrast with high sand plus gravel and low mud in the shallow

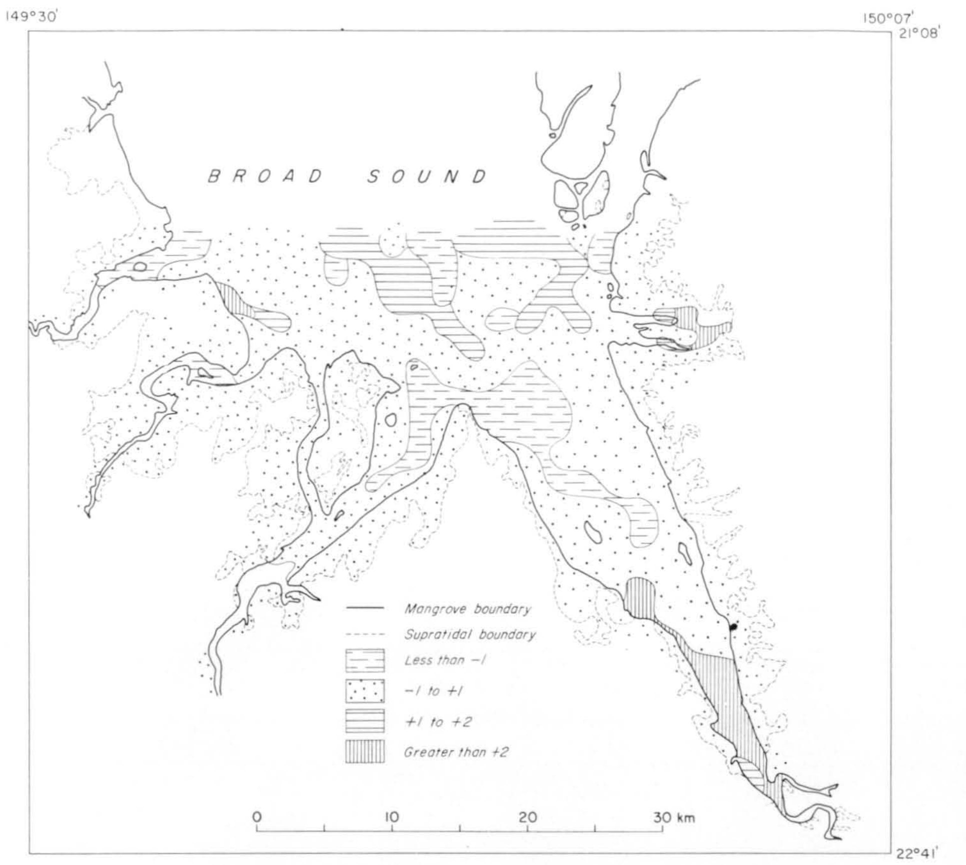


Figure 43. Areal distributions of grainsize skewness values.

marine and open intertidal environments. In the mangrove channel environment, gravel, sand, and mud percentages are intermediate between these two groups but with the mud fraction dominant. Frequency distributions of the percent mud and sand values again illustrate the grouping of the samples into two main populations (Fig. 46): one with almost 100 percent sand content; the other with almost 100 percent mud.

Analyses carried out after removal of the calcium carbonate show that most of the gravel in the marine and intertidal environments consists of shells and calcareous nodules. The gravel in the few samples in the supratidal flat environment is terrigenous non-calcareous material washed in from nearby land. Although some of the terrigenous gravel is transported into the nearby mangrove channels, none appears to reach the mangrove swamp environment. The increase in the number of samples with a gravel component, when carbonate is removed, in both the mangrove channel and supratidal flat environments (Table 2) is believed to be due to splitting error, the carbonate being removed from a separate split.

All environments except the supratidal flats have a high proportion of carbonate in the sand fraction. Where mean grainsize values of the sand fraction with and without the carbonate are available, the differences for each environment is shown in Table 3 and the significance of these means can be tested using either a normal distribution test or a Students *T* distribution test (Hoel, 1962) depending on the number of samples used in the test. The resulting distribution values indicate that the mean of the differences is significantly greater than zero only in the shallow marine and open intertidal environments.

As the sand fraction was analysed by settling tube, which measures hydraulic equivalent sizes rather than grain dimensions, the above result suggests that a significant amount of carbonate in the coarse end of the sand fraction is not in equilibrium with the depositional conditions.

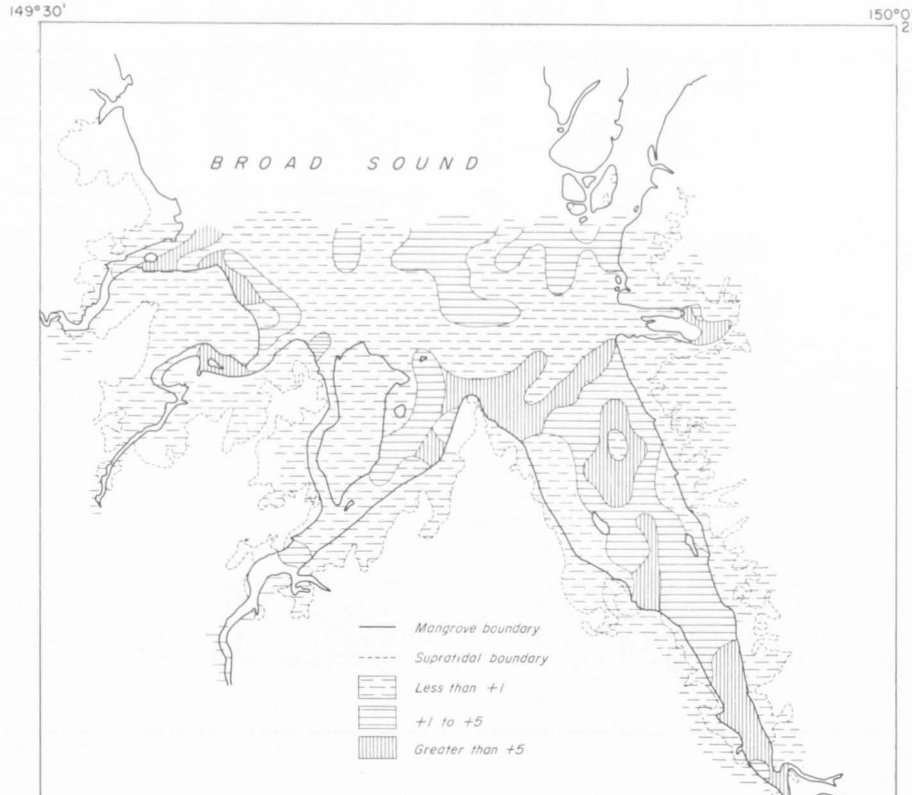


Figure 44. Areal distributions of grainsize kurtosis values.

This coarse carbonate may be in situ shells and nodules. From a study of the frequency distributions of the non-carbonate sand fraction in samples from the shallow marine and open intertidal environments it was evident that most of this in situ carbonate is coarser than approximately 2 phi. Examples are illustrated in Figures 53b and 57a.

Only a small percentage of the mud fraction in each environment is carbonate, the highest being 22 percent in the shallow marine environment (Table 2). In the open intertidal environment the average carbonate content is almost zero. This may indicate a winnowing of the carbonate particles (perhaps platy silt-sized shell fragments) from this environment, and that higher-velocity currents occur in the open intertidal environment than in the shallow marine environment. This is supported by the percentage of carbonate mud in the other environments. A high proportion of these silt-sized particles might be expected to enter the mangrove swamp environment, where they would be quickly deposited in the low-energy conditions and only a small amount would reach the supratidal flats. Although the average engergy of the currents in the mangrove channels is probably between that of the open intertidal and the mangrove swamp environments, much of the carbonate silt transported along the channels during flood tide would be washed out again during the ebb.

SEDIMENT SUPPLY AND DISPERSAL

Grainsize modal analysis may be used to determine the sources of supply and the processes of dispersal of the non-carbonate sediment in the estuary system. The grainsize frequency distribution and mangrove channel samples as well as the non-carbonate grainsize distribution of samples taken down the centre of the watercourses are used in this analysis.

Modal analysis

Shallow marine and open intertidal samples have three important non-carbonate sand frac-

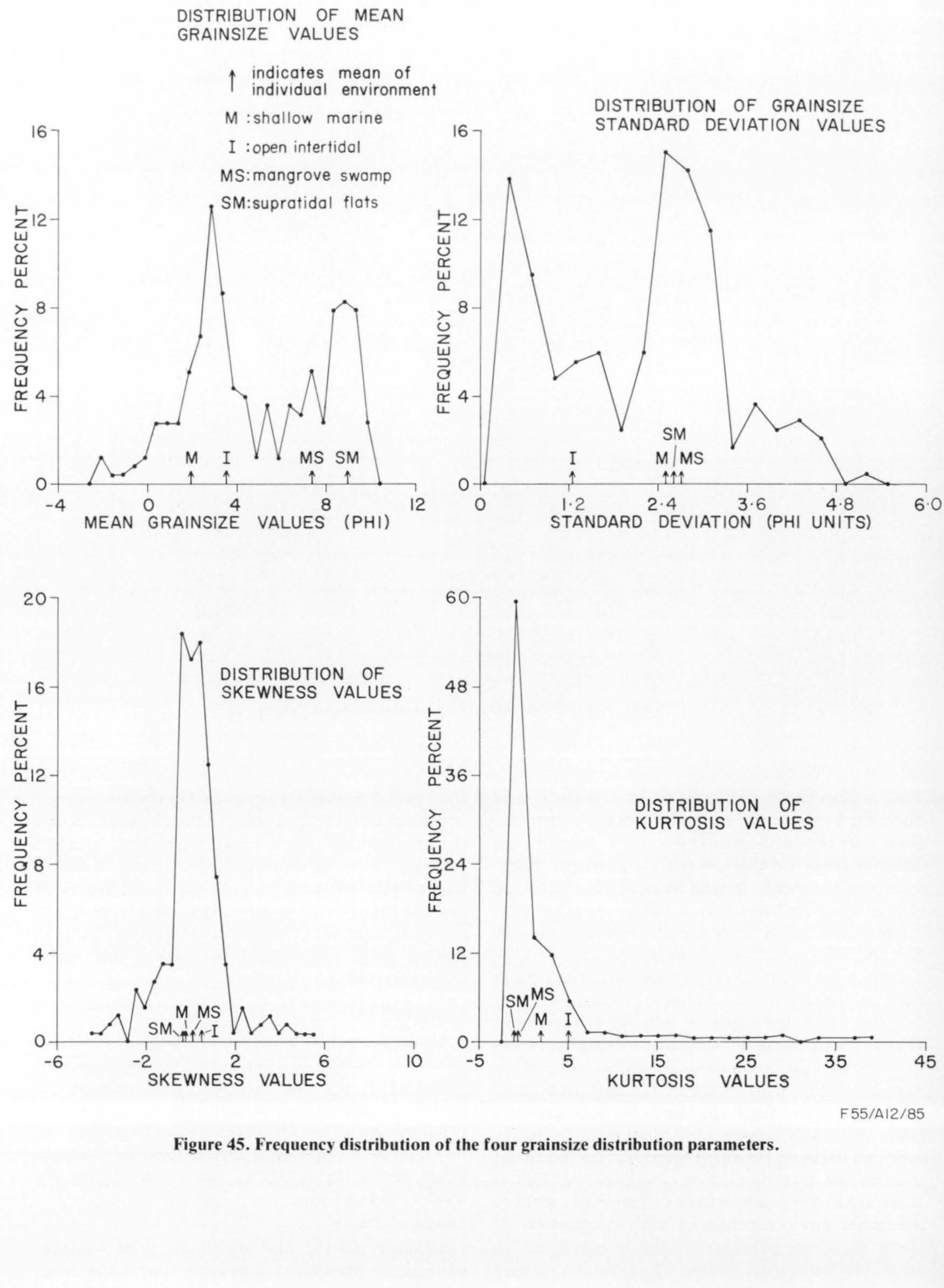


Figure 45. Frequency distribution of the four grainsize distribution parameters.

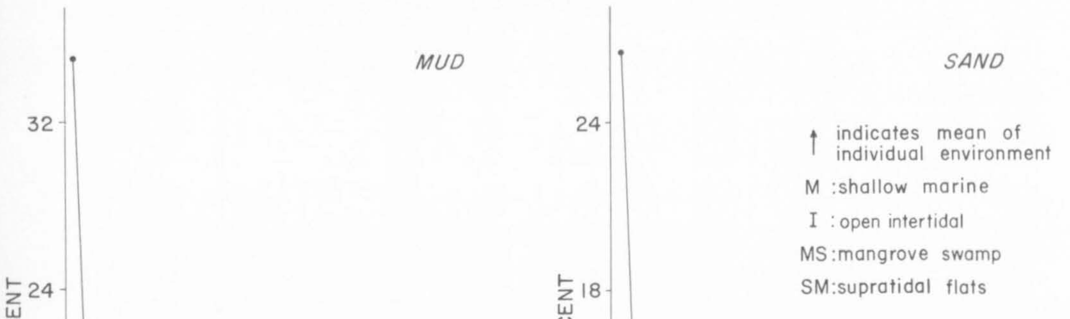


Figure 46. Frequency distribution of the percent mud and percent sand values.

tion modes. These are positioned at less than 1.5 phi, between 2 and 3 phi, and greater than 3.5 phi, and some typical distributions of the non-carbonate sand fraction in the shallow marine and open intertidal environments are shown in Figure 47. Individual samples seldom have more than one of these modes. The percentages of the samples in the shallow marine and open intertidal environments with the dominant mode in each of these three groups are shown in Table 3. Combining both environments, 72 percent of the samples have a dominant sand mode between 2 and 3 phi, and 21 percent have a mode at greater than 3.5 phi. The main difference between the two environments is the greater proportion of sand modes between 2 and 3 phi in the shallow marine environment.

The areal distribution of shallow marine and open intertidal samples with one mode greater than 3.5 phi, and of those with both the 2 and 3 phi and the greater than 3.5 phi modes is shown in Figure 48. These same groupings applied to samples taken down the centre of the Styx River, The Hoogly, and St Lawrence and Waverley Creeks (with carbonate removed) are also shown in Figure 48. The distribution of these groupings points to a general trend for the river channel sediments ranging from greater than 3.5 phi modal types in the upper reaches to samples with a mixture of the two modes, and finally to 2 and 3 phi modal samples at the mouths of the creeks. This trend is shown clearly in Figure 49 in the series of samples taken down the centre of the Styx River. These Styx samples represent the grainsize frequency distribution of the total non-calcareous fraction.

This series of samples ranges from the upper reaches (Fig. 49a) to the mouth of the Styx (Fig. 49d). It appears that the predominantly very fine to coarse silt bedload in the upper reaches is selectively removed, or progressively 'diluted' by coarser material, as the sediments are transported

TABLE 3. SAND FRACTION STATISTICS

		Shallow marine	*Open Intertidal*	*Mangrove channel*	*Mangrove swamp*	*Supratidal flats*
Number of samples with mean grain-size value for the sand fraction		69	99	17	3	10
Mean of difference between sand means (carbonate in and out)		0.648	0.079	-0.225	0.127	0.067
Standard deviation of differences		0.640	0.215	0.606	0.100	0.57
Normal distribution value Student *t* distribution value		8.41	3.65	-1.4	1.8	0.54
95% two-sided critical value		1.96	1.96	-2.12	4.30	2.26
Carbon-ate in	(Sand fraction (Mean grainsize	1.80	2.92	2.63		2.34
	(Standard deviation	0.72	0.54	0.72		0.55
Carbon-ate out	(Mean grainsize	2.44	3.00	2.41		2.41
	(Standard deviation	0.44	0.54	1.11		0.54
% samples with dominant mode in sand fraction range:						
2-3 phi		86	63			
3.5 phi		7	31			
1.5 phi		7	6			

seawards so that eventually only particles in the 2 to 3 phi range are found. This fine sediment stays in suspension, oscillating to and fro with the tides until eventually it is either washed out to sea, or redeposited in the shallow marine or the mangrove swamp and supratidal flat environments. Samples in the upper reaches of the estuaries have a dominant mode greater than 3.5 phi because the sorting process has not yet removed the silt and clay particles.

A check on the non-carbonate sand fraction in the mangrove channel environment showed that the dominant sand mode of most samples was in the greater than 3.5 phi category, and some in the less than 1.5 phi group. The sediment being transported down the channels consists mainly of reworked supratidal flat and mangrove swamp muds, with some material washed directly into the channels from the nearby catchment. Sand transported up the channels from the open intertidal environment mixes with the reworked muds.

Sorting of the fine-grained materials explains the predominance of the sand in the 2 and 3 phi range in both the shallow marine and open intertidal environments. Samples from the open intertidal and the mangrove channel environments with a dominant mode greater than 3.5 phi represent different processes; the mangrove channels and sections of the open intertidal environment bordering the mangrove swamps deposits are the result of mixing of sorted sand from the open intertidal environment and mud from the mangrove swamp environment; the samples in the upper reaches of the main estuaries probably represent primary input sediment from the catchment.

The distribution of the non-carbonate gravel fraction shown in Figure 48 and the paucity of open intertidal and shallow marine samples with a dominant sand mode less than 1.5 phi also help in an overall appreciation of sediment movement in Broad Sound. Non-calcareous gravel is relatively common in the supratidal flat and mangrove channel environments, the shallow marine environment, and the upper reaches of the watercourses. Although much of the gravel in the open intertidal and shallow marine environments is probably relict, a minor quantity may be transported into these zones from the watercourses entering Broad Sound.

Bedload movement

The distribution of non-calcareous gravel and the grainsize frequency distributions of the series of Styx samples may be explained either by landward sand movement, relict gravel in the shallow marine zone, and preferential deposition of silt and clay in the upper reaches of the creeks and rivers, or by seaward movement of sorted 2-3 phi sand.

The decreasing carbonate content from the shallow marine through to the supratidal flat environment (Table 2) supports landward movement of sand, but a high degree of intermixing of marine sediments with any incoming terrigenous material is to be expected, given the prevailing tidal action in Broad Sound. The Sound is a vertically mixed estuary and this, coupled with the fact that apart from some local exceptions the strength of the ebb tide is greater than the flood tide suggest that a net seaward movement of terrigenous sediment and intermixing of marine sediments are likely.

The amount of non-calcareous marine sediments mixed with the locally-derived terrigenous sediments would depend on the available supply of this material. The sediments of the inner shelf zone seaward of Broad Sound contain only about 1 percent mud and 60 to 80 percent calcium carbonate dominated by molluscs and bryozoans (Maxwell, 1968). The carbonate content increases to greater than 80 percent farther seaward around the shelf reefs. Consequently, the amount of marine-derived non-carbonate material (especially mud particles) mixed in the estuary with the locally derived terrigenous sediments is likely to be minor. Conversely, abundant sand-sized quartz and feldspar particles were observed in the upper reaches of the main estuaries.

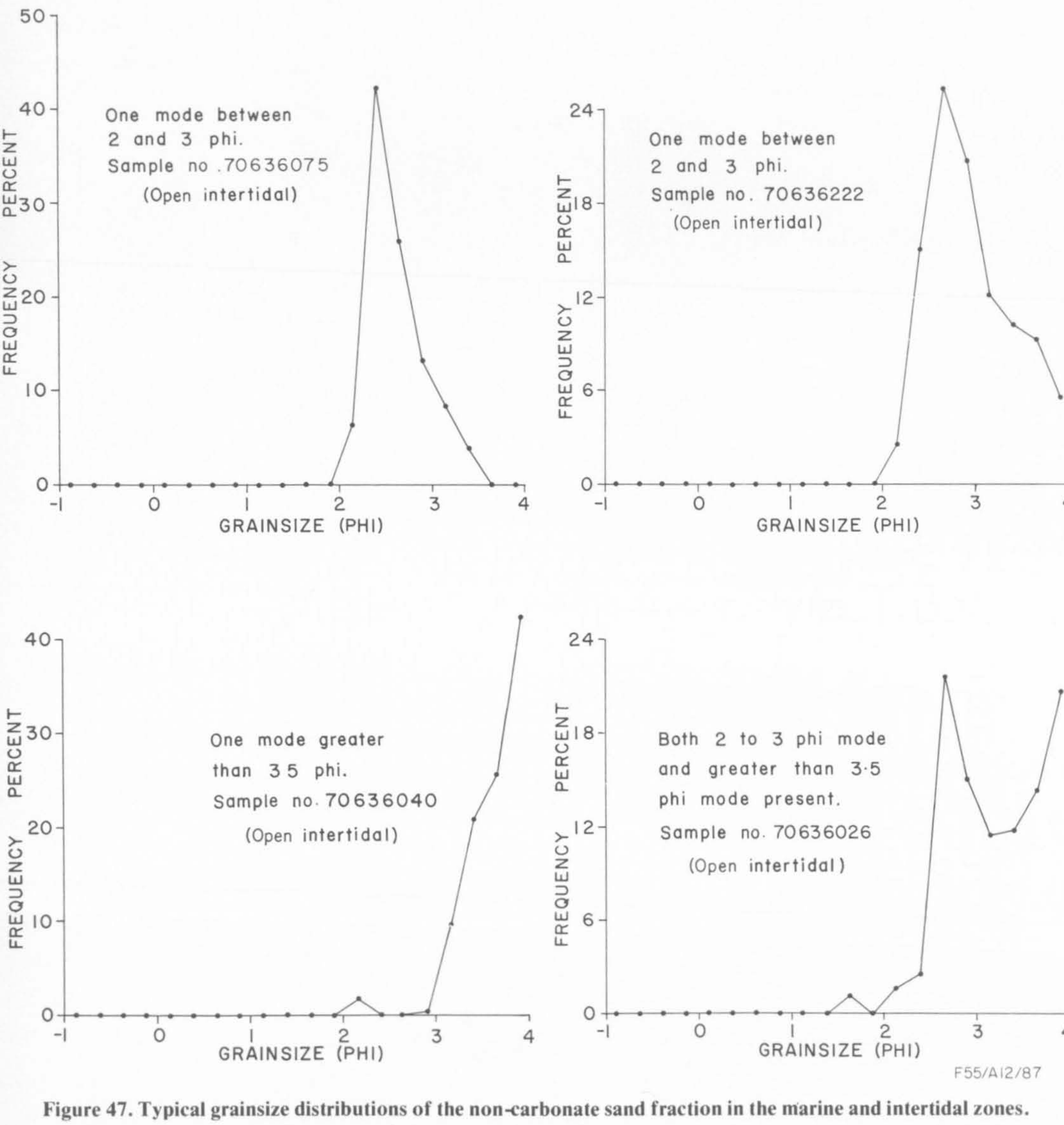
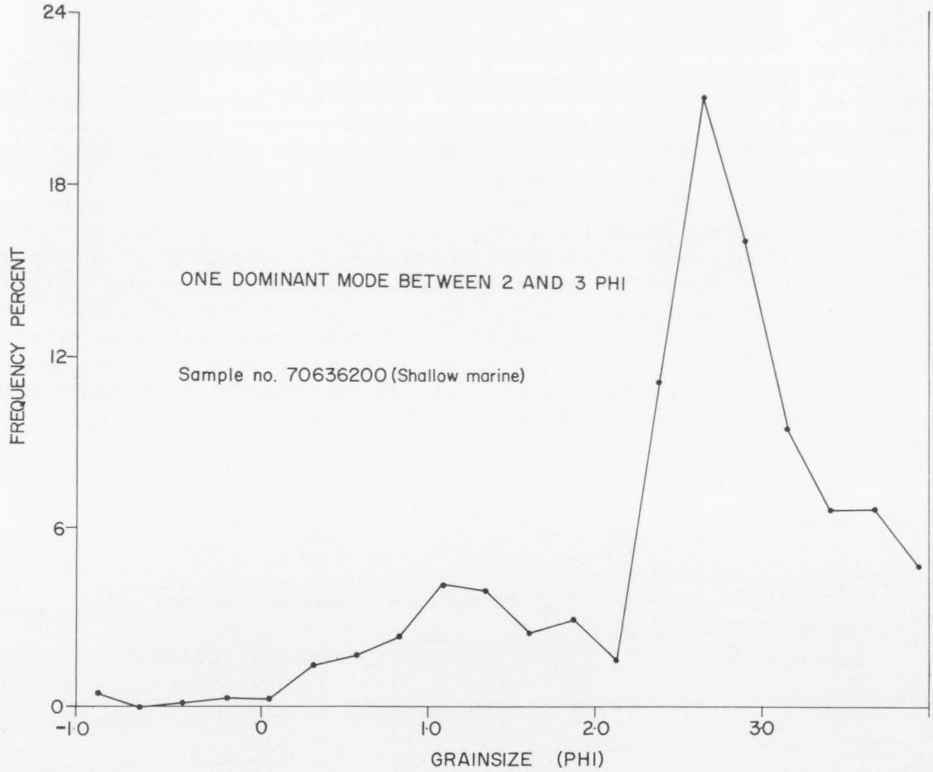


Figure 47. Typical grainsize distributions of the non-carbonate sand fraction in the marine and intertidal zones.



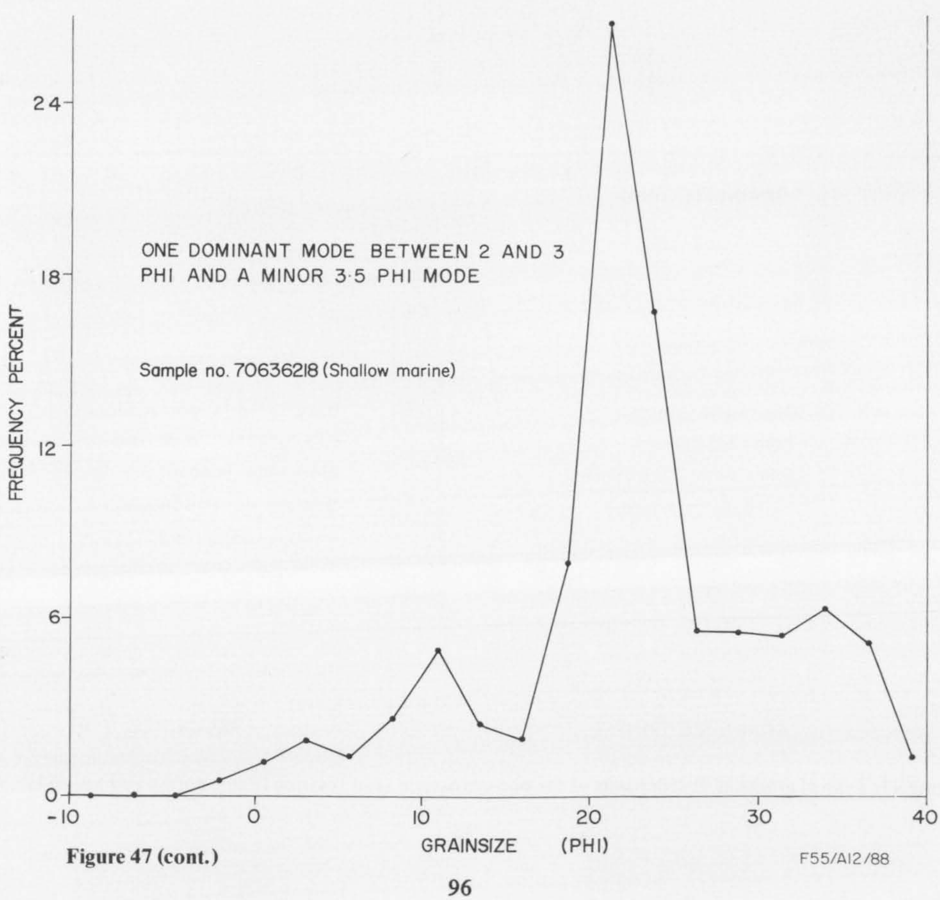


Figure 47 (cont.)

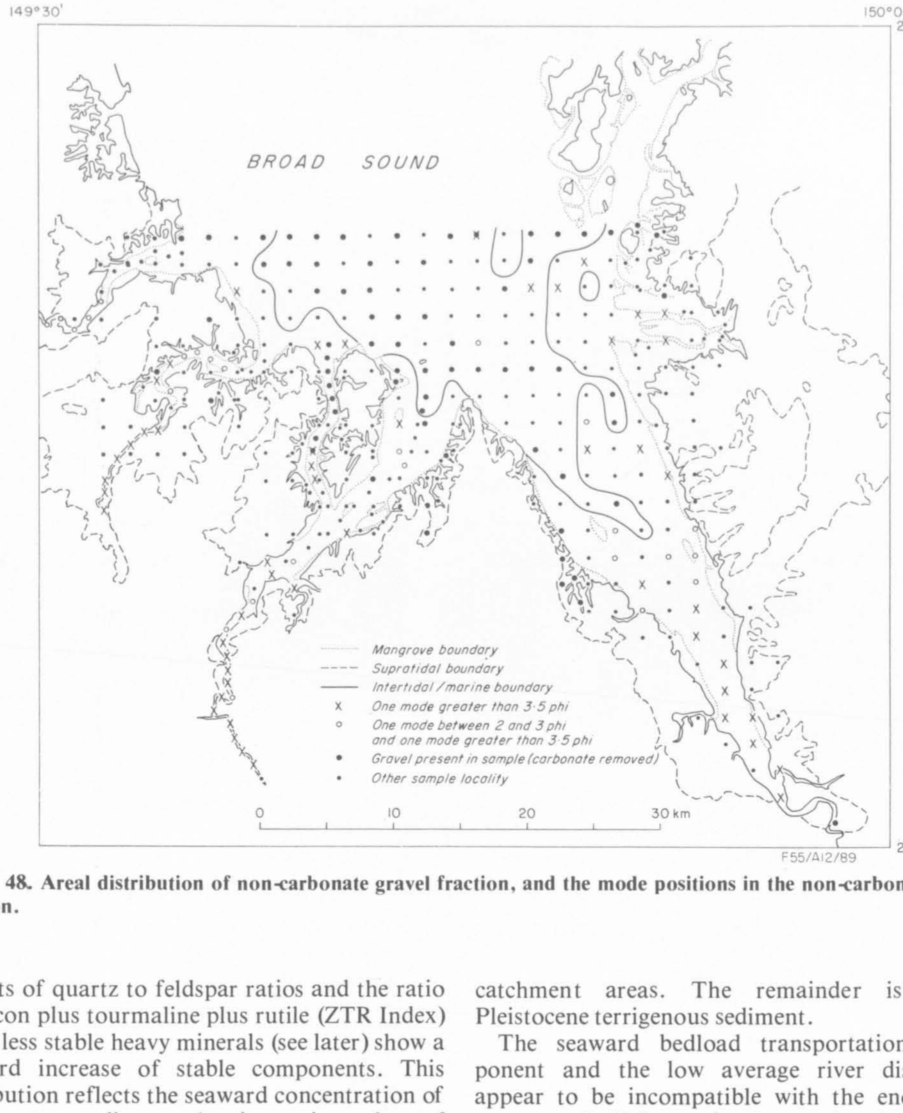


Figure 48. Areal distribution of non-carbonate gravel fraction, and the mode positions in the non-carbonate sand fraction.

Plots of quartz to feldspar ratios and the ratio of zircon plus tourmaline plus rutile (ZTR Index) to the less stable heavy minerals (see later) show a seaward increase of stable components. This distribution reflects the seaward concentration of relict mature sediments, but increasing values of these ratios towards the mouth of Herbert Creek points to a seaward maturing (mineralogically) of the Holocene sediments in the high-energy intertidal zone, supporting the preferential seaward movement of the 2-3 phi sand bodies. This type of estuary sediment transportation contrasts with that indicated by Meade (1969) and Reinson (in press) who noted that with increasing river discharge a two-layer circulation may develop so that suspended matter is moved seaward whereas the bottom sediments move landward. However, at Broad Sound the relative strength of the ebb and flood tides, the seaward changes in grainsize frequency, and the overall sand-gravel distribution suggest that most non-calcareous sediments in Broad Sound are derived from the adjacent catchment areas. The remainder is relict Pleistocene terrigenous sediment.

The seaward bedload transportation component and the low average river discharge appear to be incompatible with the enormous amount of Holocene sedimentation in Broad Sound. Meade (1969) gave several examples showing that most river sediment is supplied to estuaries during periods of flood. The terrigenous sediment supplied to Broad Sound during summer floods is fine sand and mud. During the remainder of the year this newly deposited fine material is winnowed out by tidal currents and redeposited elsewhere in Broad Sound.

Sediment dispersal

It has been pointed out that the preferential removal of calcareous silt from the open intertidal environment may be due to this zone being subjected to higher current velocities than the shallow marine environment. In addition, tidal current velocities decrease with depth. Therefore,

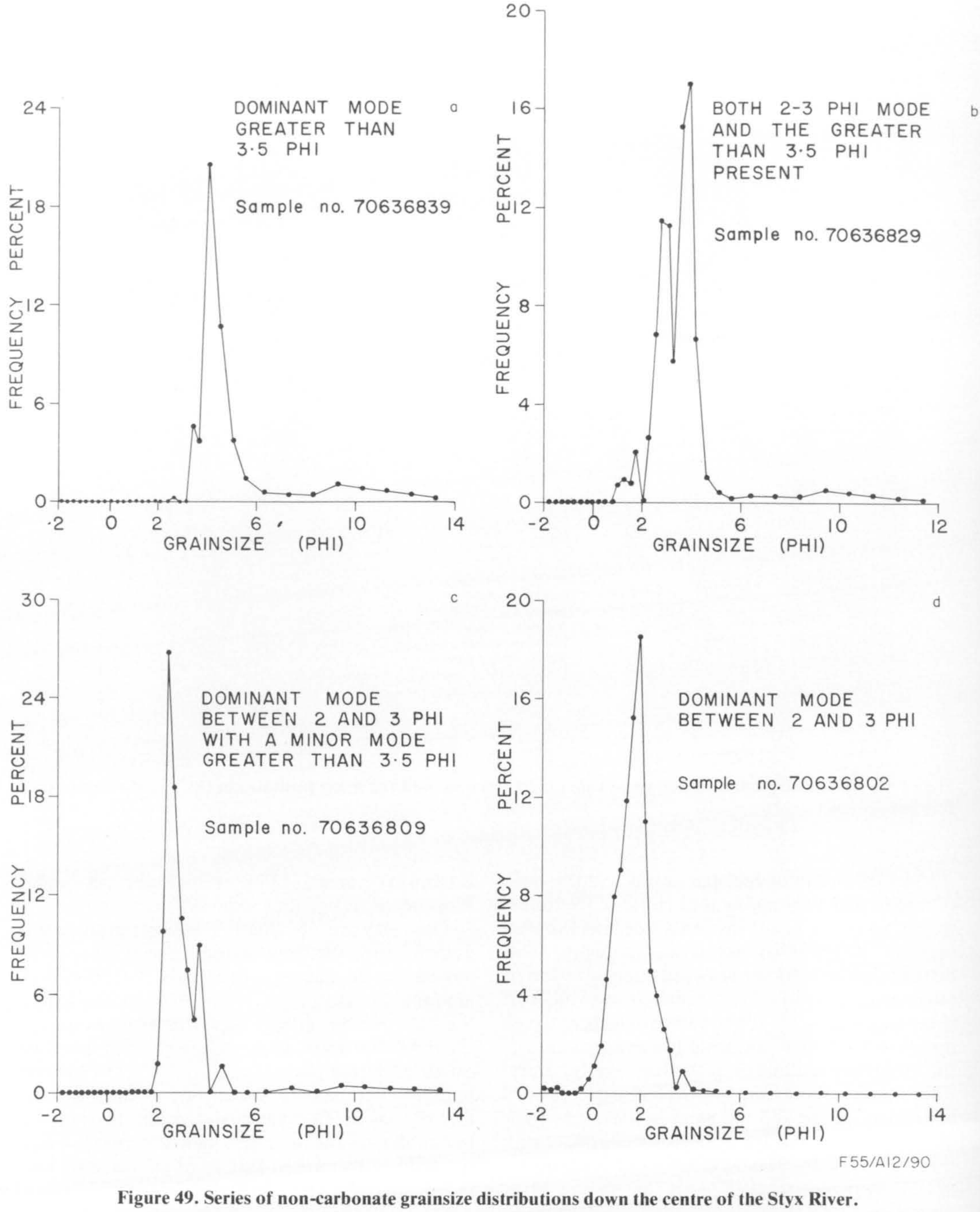


Figure 49. Series of non-carbonate grainsize distributions down the centre of the Styx River.

disregarding the minor uppermost part of the intertidal zone exposed shortly after the start of ebb tide (and before the current velocity builds up), the average current velocity must be higher in the intertidal zone than in the marine zone.

There is a high proportion of mud in many marine samples containing gravel and coarse sand, possibly the consequence of deposition of silt and clay particles in the relatively low-energy shallow marine environment during slack water. Most of the coarse particles are probably relict material from the Pleistocene land surface, although a minor amount may have been dumped into the lower-energy zone during late Holocene sedimentation. In the marine channels current velocities are high and thus deposition cannot occur; consequently sediments in these channels consist only of coarse relict sediments.

Fine suspended particles would rapidly form deposits in areas which were shallow at the top of flood tide as the flood and ebb currents would be of low velocity in those zones. This is particularly relevant to the supratidal zone where deposition occurs in response to slack-water deposition, mainly during spring tides. The supratidal zone includes the supratidal flats and most of the mangrove swamp environment. As the spring tides containing suspended silt and clay particles inundate the supratidal zone the coarser silt particles would be expected to be preferentially deposited in the mangrove swamp environment as most of the suspended load must pass through the mangroves before reaching the supratidal mudflats. In addition, as pools on the supratidal flats evaporate, all the sediment in suspension is deposited, and so a greater percentage of clay could be expected in the supratidal flat environment than in the mangrove swamps, as appears to be the case (Table 2).

Numerical Classification

Different plots of the grainsize distribution parameters may result in different classifications. The ideal classification groups samples into sedimentation units (Otto, 1938), each unit representing one set of uniform depositional conditions. The grainsize distribution of terrigenous particles in a sediment sample depends on the original source material, processes of weathering, transportation and deposition, and diagenesis. Therefore, each grainsize group should represent a distinct combination of these processes. Various plots will be used in an attempt to obtain such a genetic classification. It will be shown that the simple mean-standard deviation plot groups the samples into distinct units which may be genetically significant.

Relations between the distribution parameters

Figure 50a shows the mean grainsize values plotted against the grainsize standard deviations for all samples, each depositional environment being numbered separately. Skewness is added by plotting a diagonal line from each sample point in Figure 50a and representing the sample as a point along this line, the position depending on the skewness value. The resulting pseudo-ternary plot is shown in Figure 50b. Because two samples lying on the same diagonal line from Figure 50a, and having the same skewness, would plot onto the same point in Figure 50b, both figures must be considered when sample groupings are worked out from Figure 50b. This pseudo-ternary plot reveals five main groupings, A to E, which correspond in both diagrams except for groups A and B which overlap to some extent. Finally, kurtosis values were added to this plot by indicating the range of kurtosis values plus a name describing the dominant kurtosis values in each group.

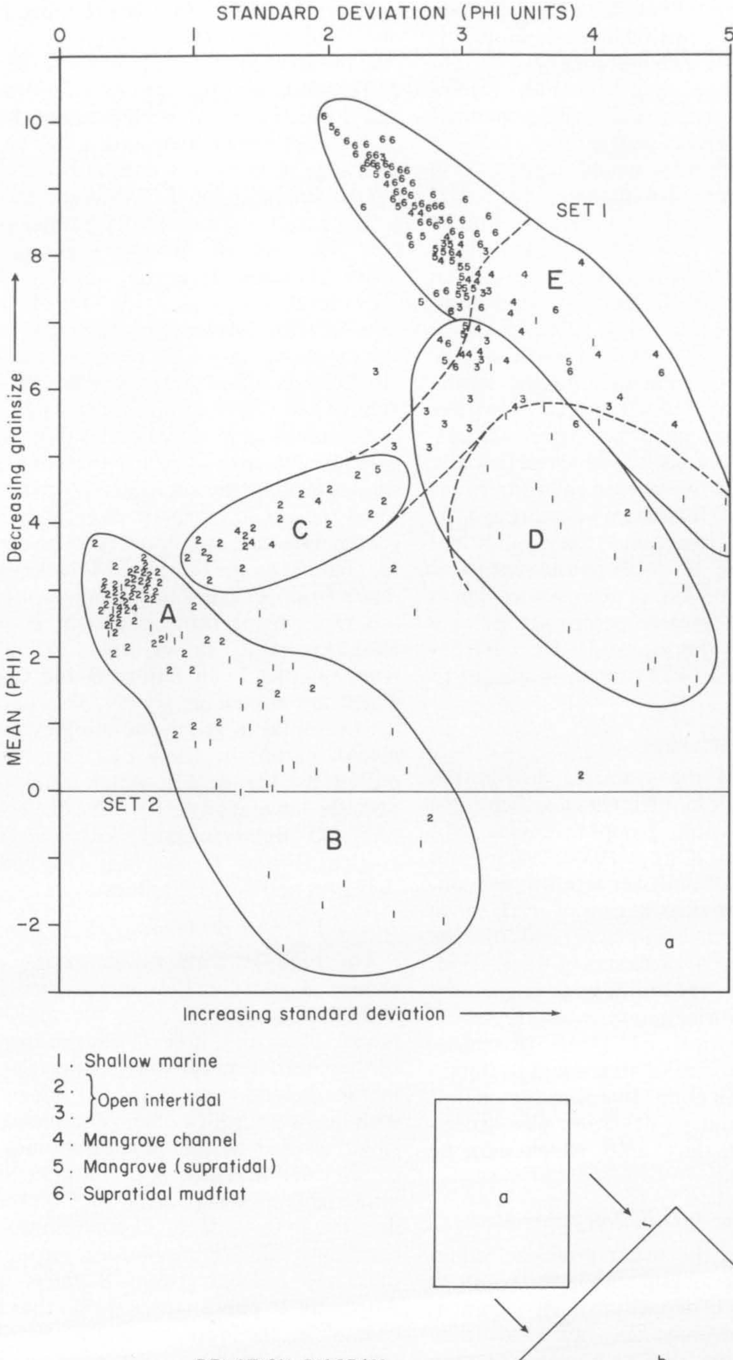
The pseudo-ternary plot separates the samples into five separate groups, suggesting that the mean, standard deviation, and skewness values are useful for classifying the Broad Sound samples. Kurtosis values may also be useful in the sample classification, in which values in groups E and D are predominantly negative, most of group A have low positive values, and most of group B and C have high positive values (Fig. 50b).

Figure 50a also separates the samples into five similar groups; the addition of skewness values to form the pseudo-ternary plot tends to coalesce groups D and E and appears to be of little value for classifying the samples. Most skewness values range from -0.5 to 2.0, the only samples outside this range being those in groups B and C (Fig. 50b). Figure 51 shows other X-Y plots: apart from samples from groups B and C (Fig. 50b), which are shown separately, skewness and kurtosis do little to group the samples. This lack of discrimination by these two variables is exemplified by Figure 51e which shows that most samples have skewness values centering around zero and slightly negative kurtosis. Again, only groups B and C are distinguished by their skewness and kurtosis values.

Ill-conditioning problem

The high kurtosis values of the samples in groups B and C reflect minor modes of gravel and mud separated from the major grainsize mode. Therefore, a small change in the amount of these minor modes may produce large changes in the skewness and kurtosis values. Problems with answers which change drastically with a small change in the input data are called ill-conditioned and this is a common difficulty in numerical analysis (Dorn & McCracken, 1972). A detailed analysis of the ill-conditioning affects of the four grainsize distribution parameters using the samples from groups B and C is given in Appendix 1. This analysis shows that a 5 percent change in the data from the distribution extremities can produce a change of up to about 400 percent in the skewness and kurtosis values. The standard deviation determinations are also sensitive to changes in the input data, but the size and direction of these changes can be predicted with some confidence.

The only two groups (A and B) that are successfully separated by the skewness and kurtosis



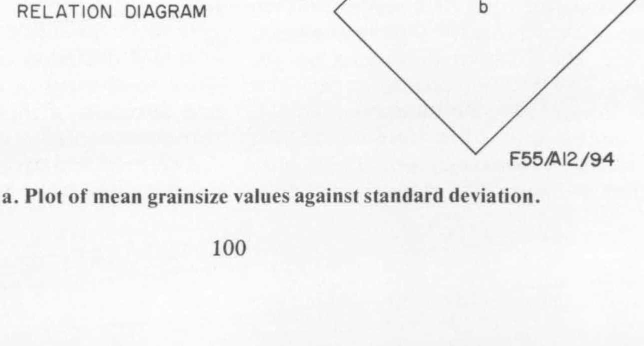


Figure 50. a. Plot of mean grainsize values against standard deviation.

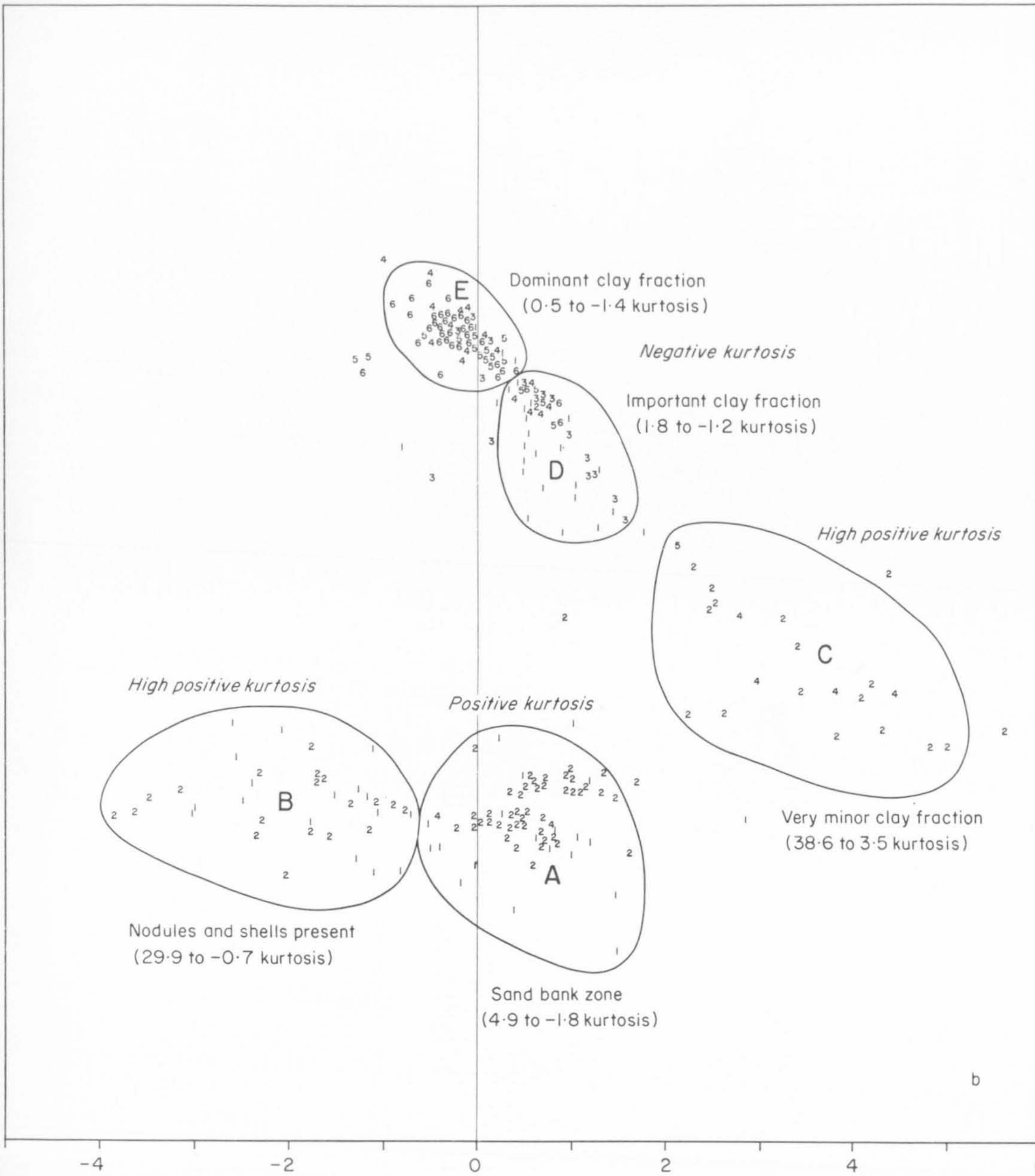


Figure 50. b. Pseudo-ternary mean-standard deviation/skewness plot.

values are most susceptible to ill-conditioning problems. Consequently the sample skewness and kurtosis values will not be considered any further in either the sample classification or the geological interpretations of the grainsize distribution parameters. This leaves two grainsize distribution parameters, mean and standard deviation, to numerically classify the samples. Results from a one-way analysis of variance of mean and standard deviation values (Appendix 2) indicate that the combined sampling and analytical errors do not mask the real variations,

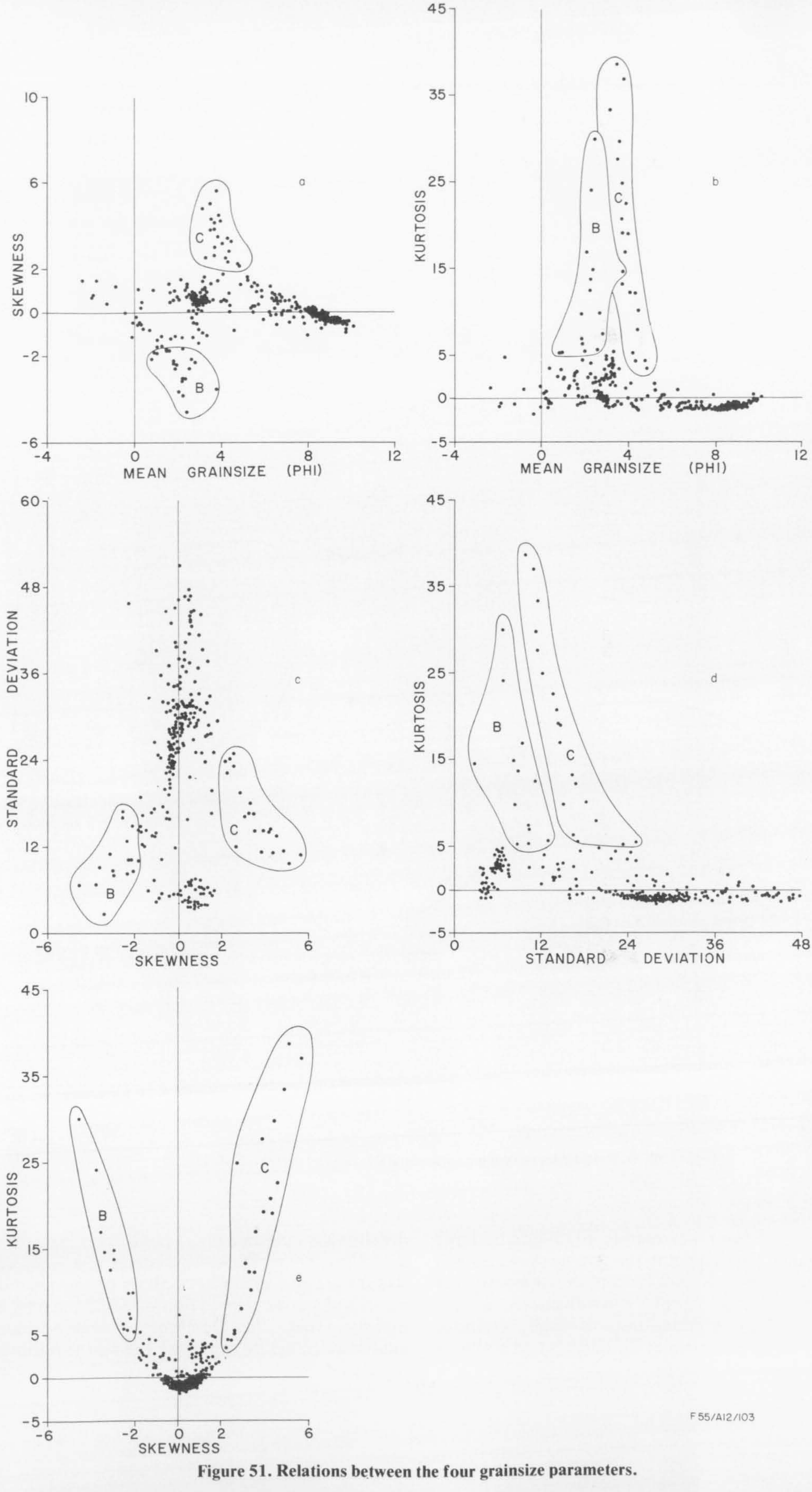


Figure 51. Relations between the four grainsize parameters.

and use of these two variables in any numerical analysis is warranted.

Mean-standard deviation plot

Figure 52 shows the same plot as Figure 50a, but the axes have been removed. Most samples appear to follow a sinusoidal trend similar to that found by Thomas, Kemp, & Lewis (1972) with two basic end-member populations of clay and sand. Folk & Ward (1957) also noted this type of trend with gravel and sand end-member populations and predicted a continuation of the sinusoidal trend into the clay population as a result of the mixing of various proportions of the two end-members. Two Broad Sound grainsize populations (sand and silt-clay) are suggested by the high concentration of samples in two areas of Figure 52. These same two populations were also evident in the frequency distributions of the mean and standard deviation values (Fig. 45) and in the percent sand and mud values (Fig. 46). Not all Broad Sound samples follow the sinusoidal trend, suggesting that some are not related to these two basic populations.

Using the basic sediment sorting and dispersal mechanism described earlier it is possible to partition the samples on the mean-standard deviation plot into four sedimentary units: a sorted sand unit, a sorted mud unit, an unsorted muddy sand unit, and an unsorted gravel unit. The samples representing these units are partitioned into these units in Figure 52 and the same groupings are shown in Figure 50a.

Problems arise when attempting to use stan-

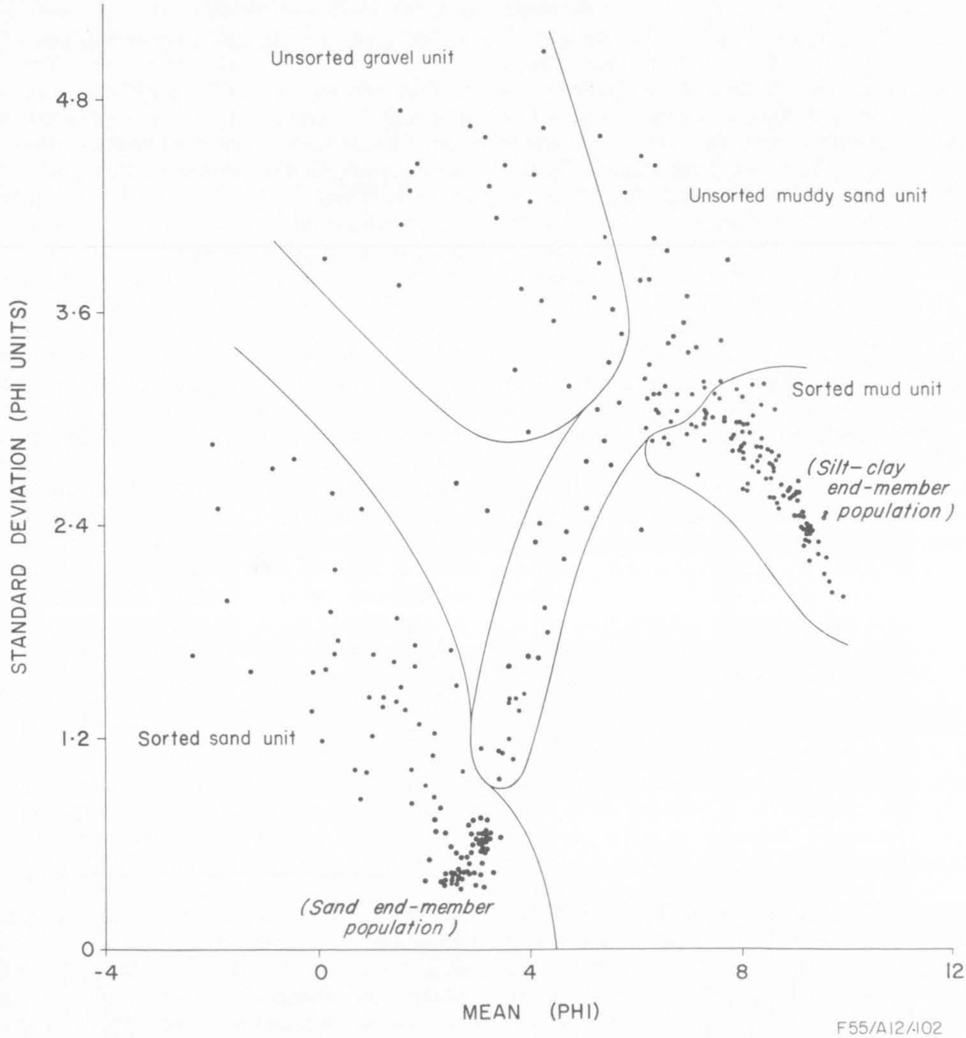


Figure 52. Mean-standard deviation plot.

H

TABLE 4. DESCRIPTION OF DISTRIBUTION PARAMETER VALUES

Distribution parameter	*Range of values*	*Descriptive term*
Mean	less than 2 phi	Coarse
	2 to 4 phi	Medium
	4 to 6 phi	Fine
	greater than 6 phi	Very fine
Standard deviation	0 to 1 phi units	Low
	1 to 2 phi units	Moderate
	2 to 3 phi units	High
	more than 3 phi units	Very high

dard descriptions of mean and standard deviation values because of different methods of parameter determinations, unsuitable range of values, and genetic implications associated with the terms. Consequently, a simple scheme shown in Table 4 will be used for describing the ranges of the mean and standard deviation values within each unit.

Sorted Sand unit. This unit includes those samples in groups A and B in Figure 50a. Samples in group A have a medium mean, a low standard deviation, and one dominant mode between 2 and 3 phi. Two typical unimodal grain-size distributions from this group are shown in Figure 53. Most samples in this group are from the sandbanks of the open intertidal and shallow marine environments. The low standard deviation reflects high-energy sorting, and the one dominant mode suggests uniform depositional conditions. The grainsize frequency distribution of sample 70636223 with the carbonate removed (Fig. 53b) shows that the amount of in situ calcareous material in samples from Group A is negligible.

Coarse mean grainsize and moderate to high standard deviation characterize group B. Group B samples have several minor modes owing to the presence of in situ shells and calcareous nodules. In Figure 54a one minor mode in the sand fraction is due to small nodules, and the other mode in the gravel fraction is due predominantly to shells. Separating the gravel fraction by sieving (-1 phi cut-off) and analysing the sand by the settling tube and the gravel by sieving may influence some of these minor modes (Fig. 54b). Again the samples in this group are from sandbanks of the subtidal and intertidal zones, but they differ from group A samples because of their in situ calcareous nodule and shell content which is reflected in the increasing mean and standard deviation from groups A to B (Fig. 52). Thus, groups A and B represent the sorted sand unit resulting from high-energy wave and current removal of silt and clay from the sandbank sediments of the intertidal and subtidal zones in the Sound. Apart from the in situ shells and nodules the sediment in the unit is in equilibrium with the prevailing high-energy conditions and is the sand end-member population of the Broad Sound sediments. Changes in the mean and standard deviation values indicate changing amounts of in situ shells and nodules.

Sorted mud unit. Earlier, it was suggested that some of the silt and clay winnowed from the bedload and any silt and clay already in suspension will be deposited in the supratidal zone during spring tides. The sorted mud unit (Fig. 52) mainly comprises deposits of this zone. The grainsize frequency distribution of a sample from this unit shown in Figure 55 illustrates the typical bimodal distribution, with one mode in the clay fraction greater than 8 phi and the other between 5 and 6 phi. With some samples, significant modes also occur in the sand fraction owing to the washing-in of particles from the nearby catchment. The clay fraction mode probably represents clay which is deposited either in pools remaining after each spring tide evaporates as clay particles flocculate. The 5-6 phi mode reflects the supply of suspended silt during spring tides. It is important to note that the finest modes in the samples from the upper reaches of the estuaries were between 4 and 5 phi, and therefore the majority of the particles deposited in the supratidal zone enter the estuary as suspended particles. That is, although the coarse silt is being winnowed from the sediments entering the estuary system and deposited in the supratidal zone, deposition in this zone is dominated by the medium to fine silt and clay from the catchment entering the estuary in suspension. The sorted mud unit is thus an example of low-energy sorting with the particles deposited reflecting the prevailing low-energy conditions, and is the silt-clay end-member population of the Broad Sound sediments. The sedimentary environments represented in this unit are the open intertidal (mud facies), supratidal mudflats, mangrove swamp, and mangrove channels. On average, mangrove swamp samples have higher carbonate, higher silt, and lower clay values than supratidal

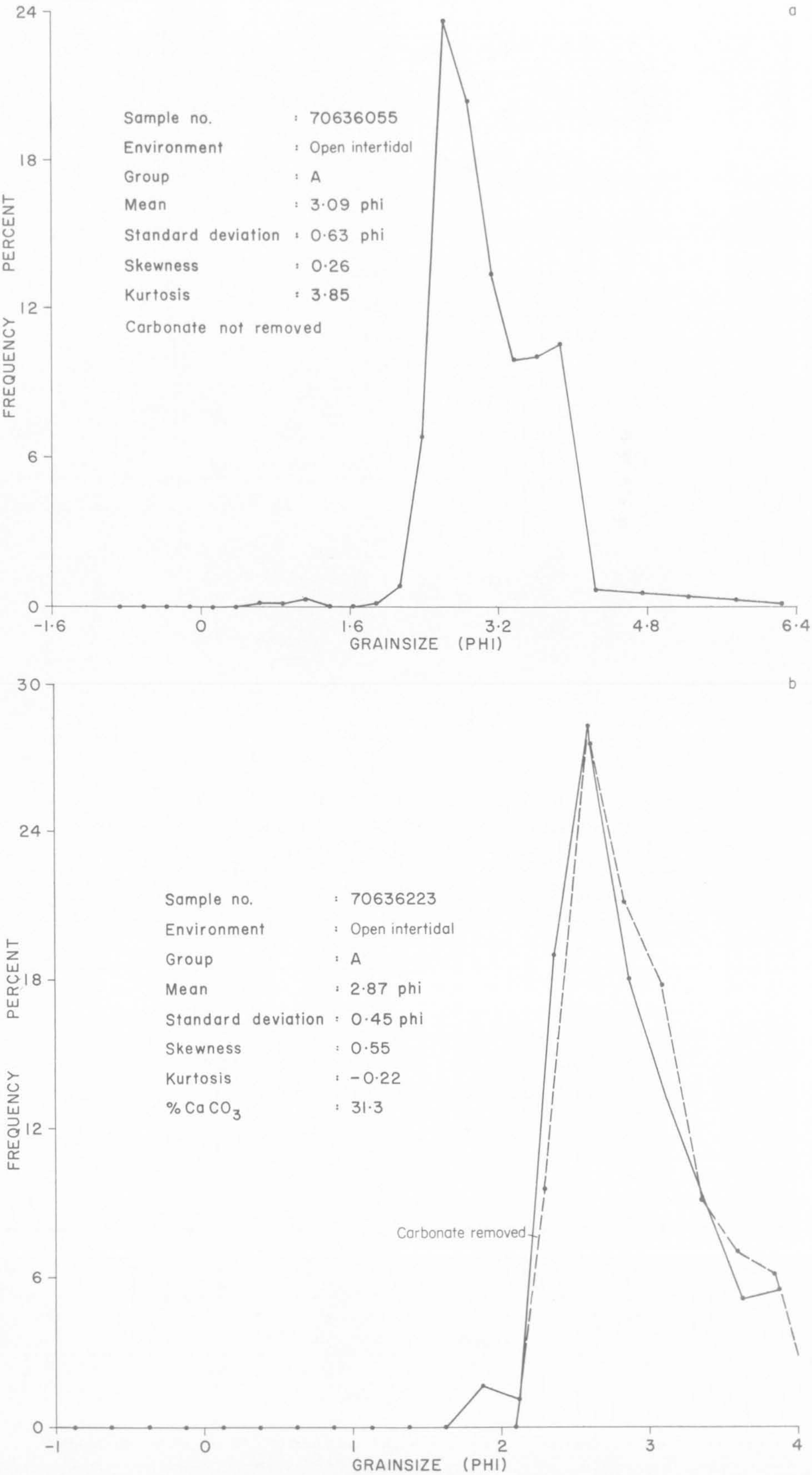


Figure 53. Typical grainsize distribution of the sorted sand unit (without in situ shells and nodules).

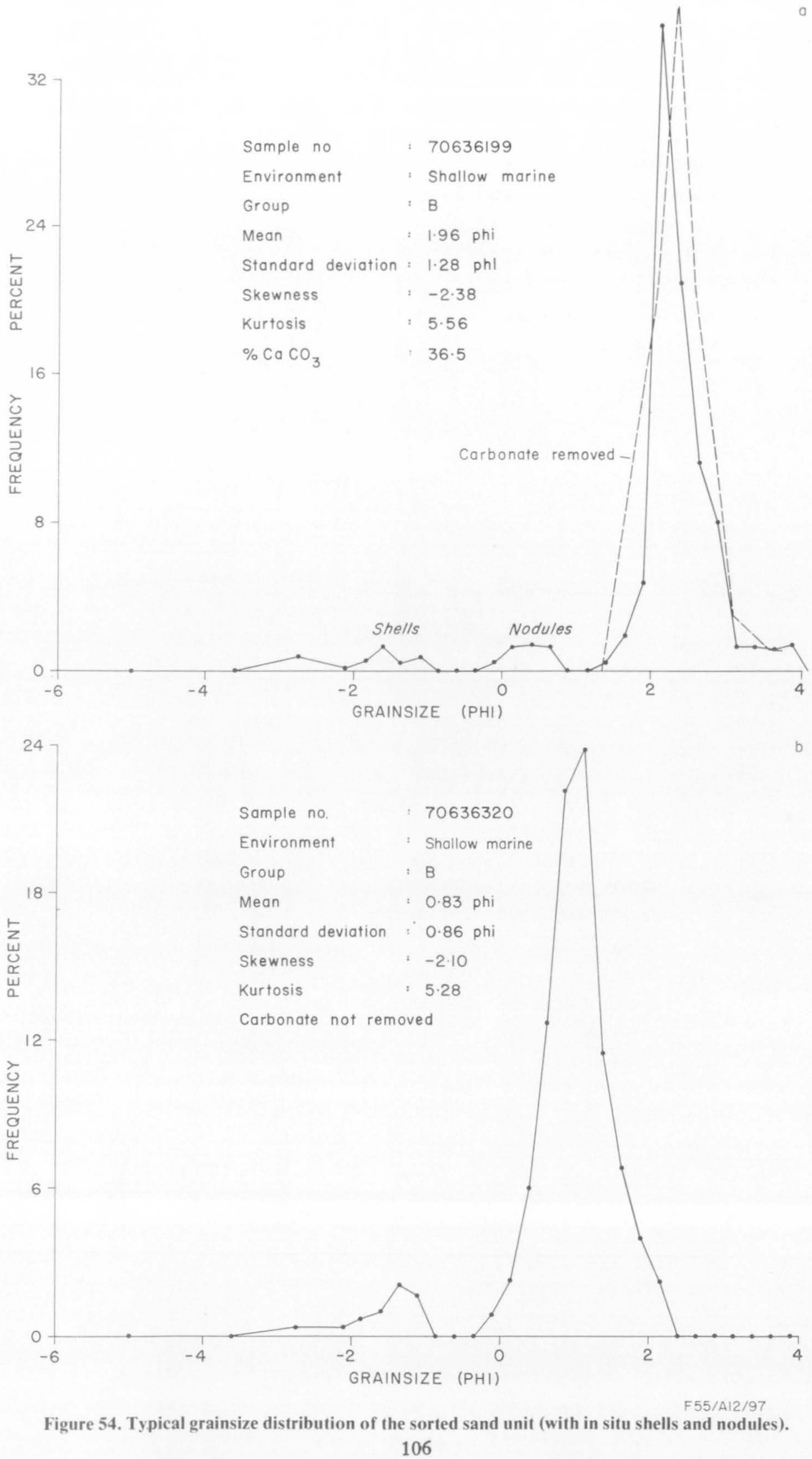


Figure 54. Typical grainsize distribution of the sorted sand unit (with in situ shells and nodules).

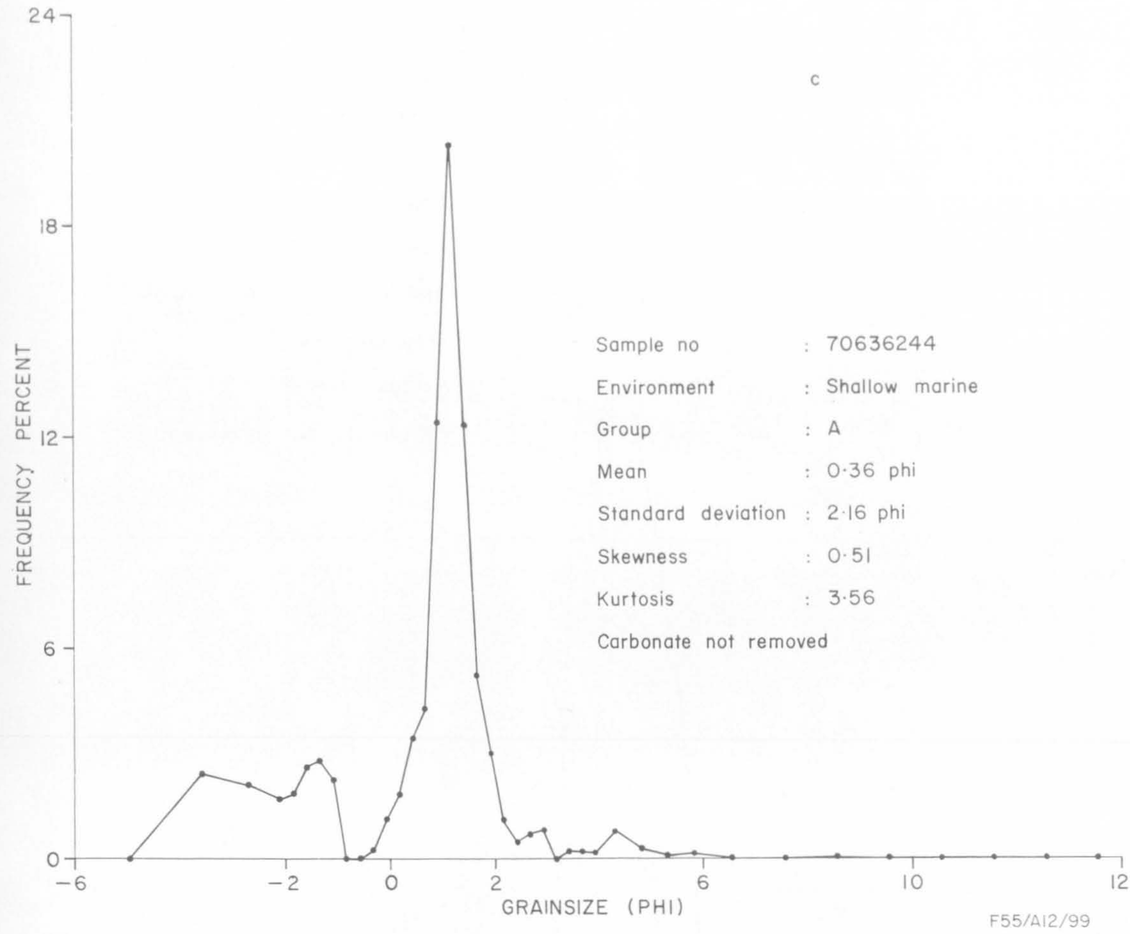


Figure 54 (cont.)

flat samples, reflecting preferential deposition of carbonate silt in the mangrove swamp environment compared to the supratidal flat environment.

Because of these differences this unit could be split into two sub-units: the mudflat type; and the mangrove type (including mangrove swamp, mangrove channel samples, and intertidal mud facies samples). The sub-units can then be treated separately in any subsequent numerical data analysis.

Unsorted gravel unit. Samples of the unsorted gravel unit characteristically have abundant gravel-size shells and nodules yet have a significant mode in the clay-size range, plus varying amounts of sand and silt (Fig. 56). These samples are not part of the broad sinusoidal trend (Fig. 52), suggesting that they are not directly related to the two end-member populations. The unit is found in the deeper lower-energy (compared to the intertidal zone) sub-tidal zone. Figure 56 reflects the mixture of relict gravels, marine carbonate particles, sand from the sorted sand unit, and redeposited silt and clay. Some of this silt and clay could also be relict; much is probably deposited from suspension.

This unit represents sedimentation under low-energy conditions where most of the particles in the sediment do not reflect the low-energy conditions. No physical process has sorted these fine sediments, unlike the fine particles of the sorted mud unit.

Unsorted muddy sand unit. Plots of samples from the unsorted muddy sand unit link the two end-member populations and complete the sinusoidal trend (Fig. 57). Sediments of this unit are of two types. The first type is the primary sediment supplied to Broad Sound. It is found only in the upper reaches of the estuaries. The second type is the result of mixing of sediment from the sorted mud and sorted sand units. It occurs in the lower reaches of the estuaries in the

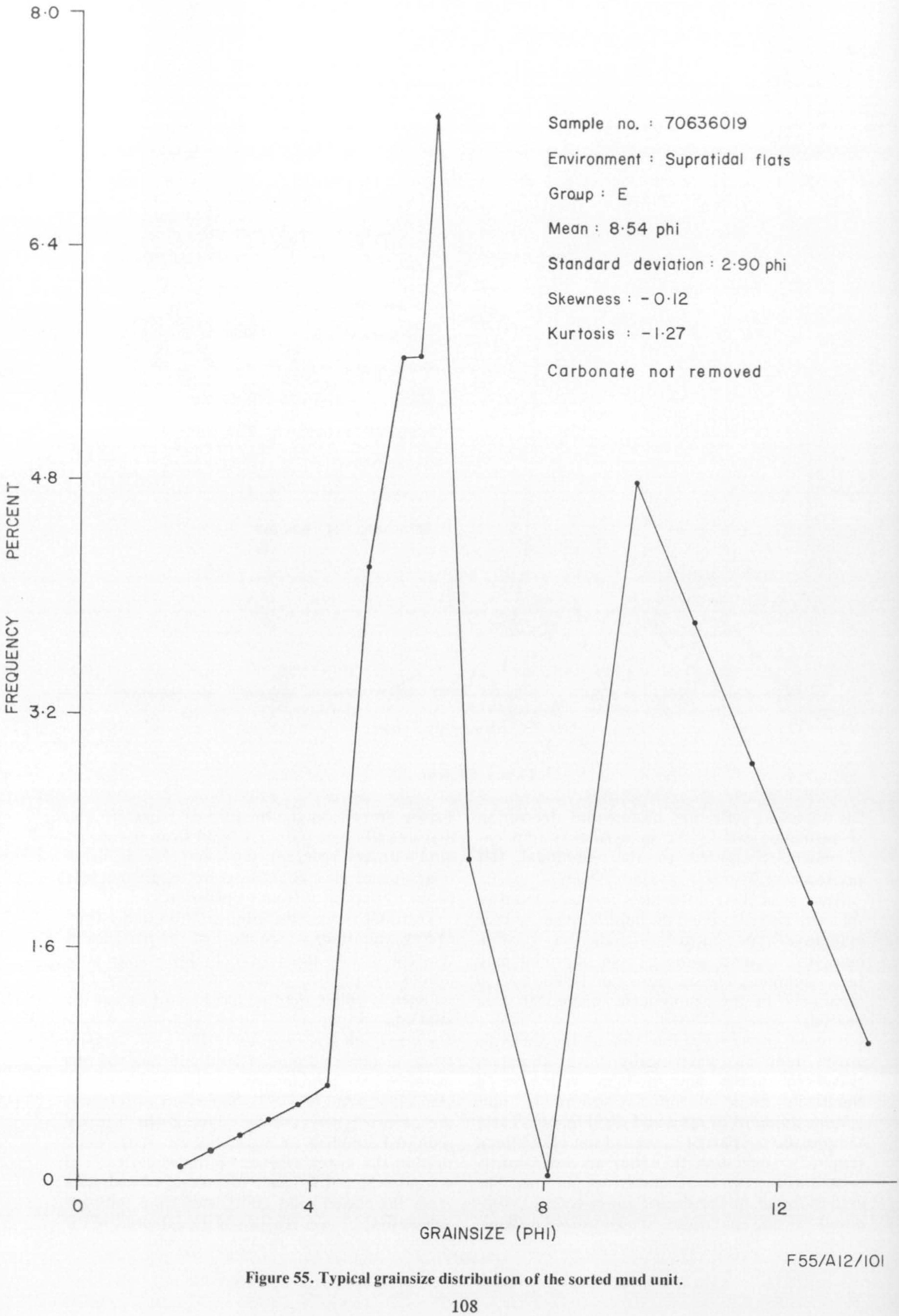


Figure 55. Typical grainsize distribution of the sorted mud unit.

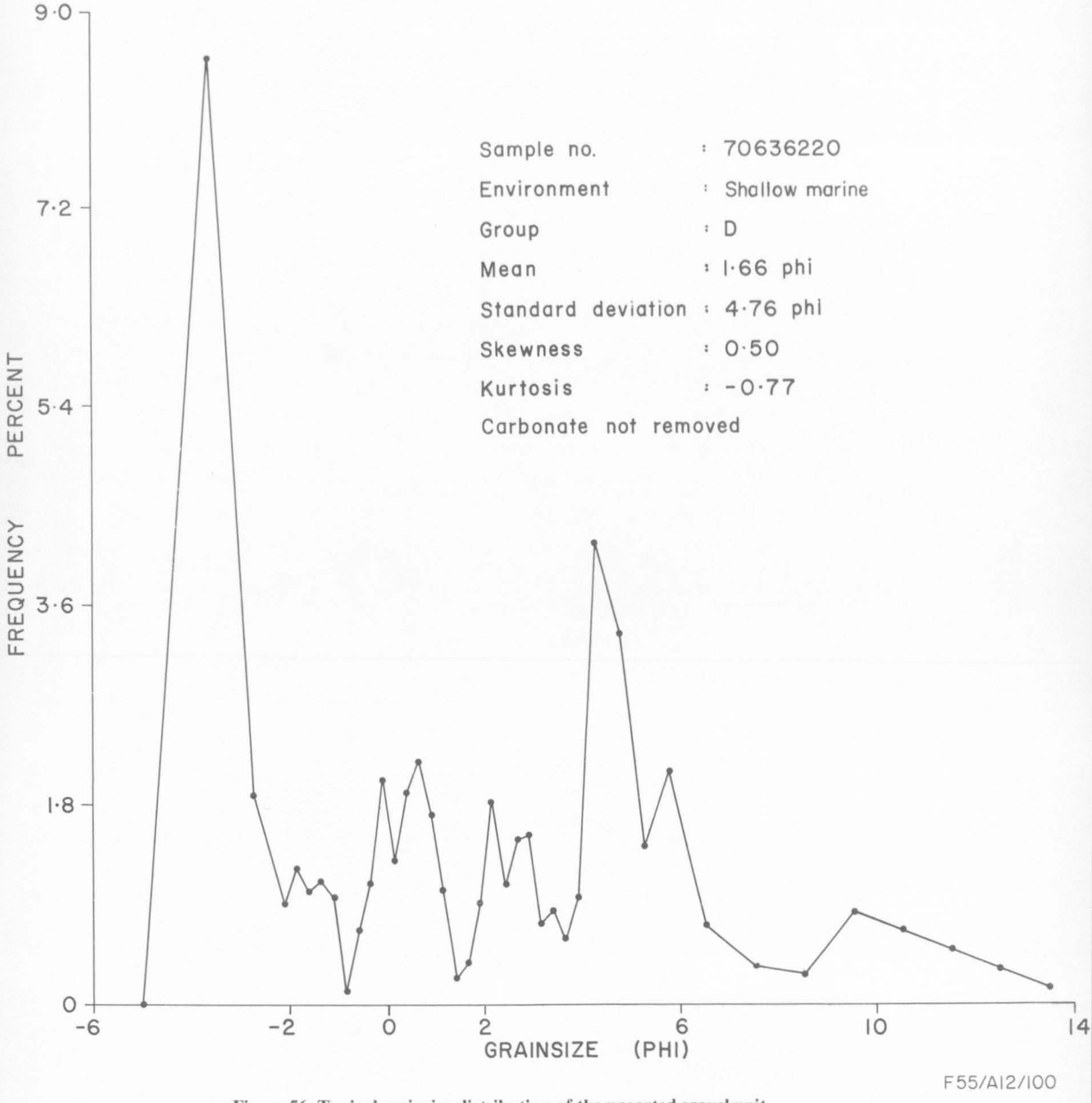


Figure 56. Typical grainsize distribution of the unsorted gravel unit.

open intertidal environment adjacent to mangrove swamp deposits, and in mangrove channels.

Because of this primary sediment in the unit the sinusoidal trend is not entirely the result of a simple intermixing of the two end-member populations. The distribution of these two types is shown in Figure 58. The percentage of clay in the mixed sediment is greater than in the primary sediment. A silt to clay ratio greater than 2 was generally found to distinguish the primary sediment type from the mixed sediment type.

A few mangrove channel, open intertidal, and mangrove swamp samples plot away from the broad sinusoidal trend (Fig. 52) near the unsorted gravel unit, indicating a mixing of the silt-clay population with the relict gravels. The few supratidal flat samples plotting within the un-

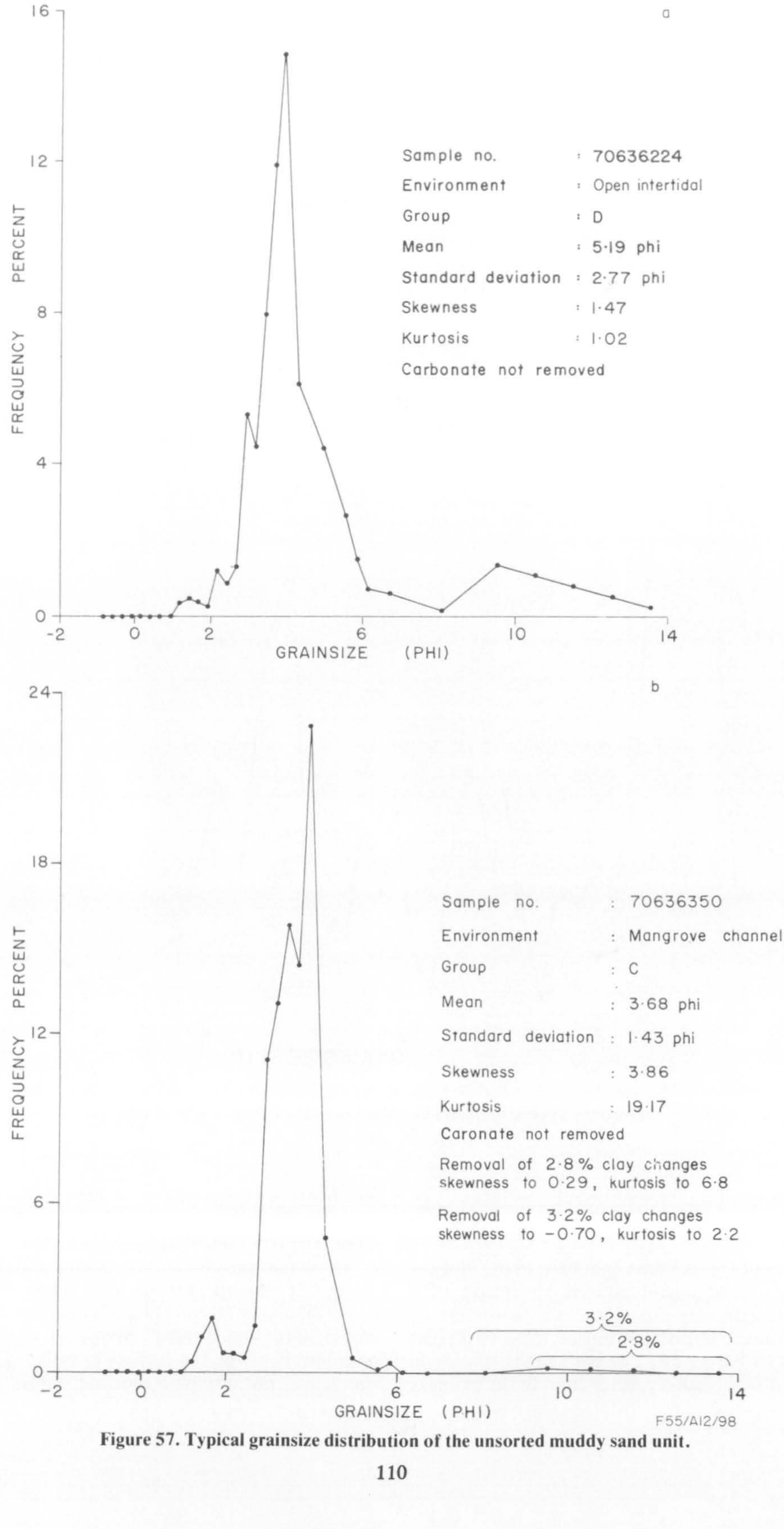


Figure 57. Typical grainsize distribution of the unsorted muddy sand unit.

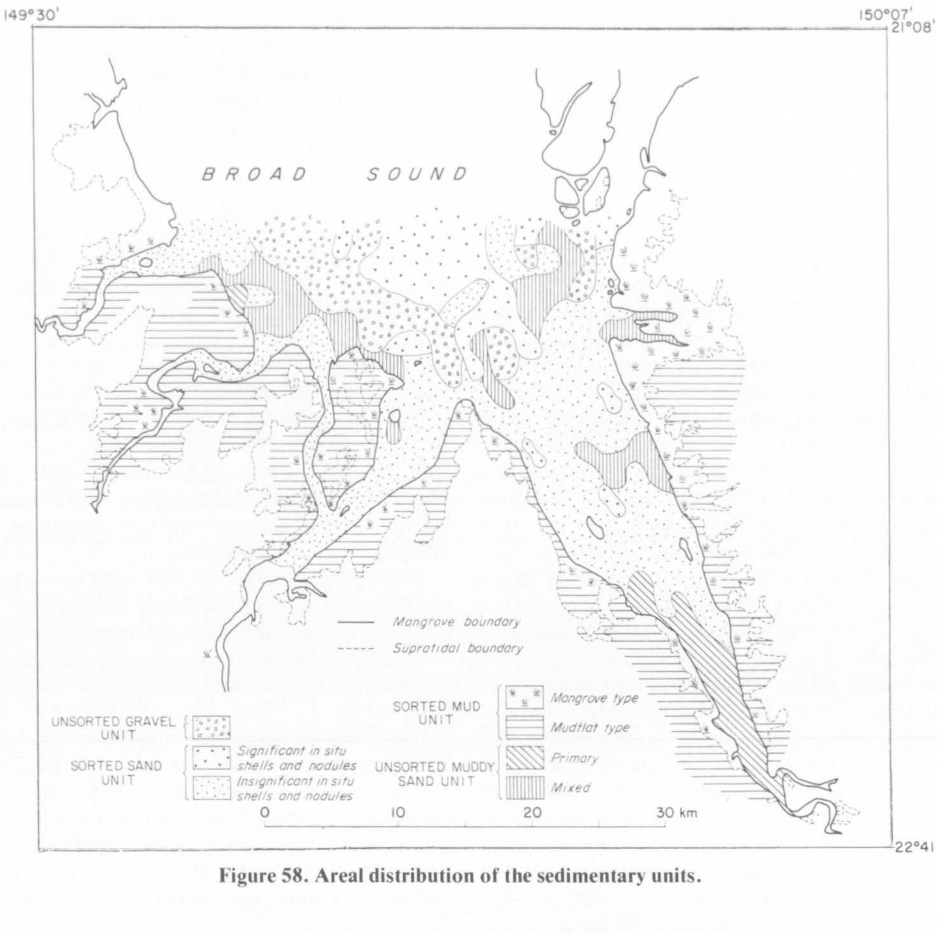


Figure 58. Areal distribution of the sedimentary units.

sorted mud unit are the result of terrigenous sand and gravel being washed from the land onto the mudflats. These samples are not considered in a final genetic classification.

The sediment in this unit is being sorted and is out of equilibrium with the prevailing conditions, the amount of mud remaining at any location being unrelated to the high-energy intertidal currents. Therefore, although the mean grainsize of any sample from the unit will not reflect the velocity of the prevailing currents, the standard deviation will measure the relative degree of sorting of the sample within the unit. Under these high-energy conditions this unit is being sorted into the sand and silt-clay end-member populations.

Because the unsorted muddy sand unit consists of sediment formed by two different geological processes the term 'sedimentation unit' (Otto, 1938) cannot be applied to these units. Nevertheless, the units are directly related to the sedimentary units.

End-member populations

Before discussing the geological interpretations of changes in the mean and standard deviation values within each of the four sedimentary units, some further notes on the two Broad Sound end-member populations are considered necessary.

Many writers have suggested that all sediments are made up of mixtures of three primary lognormal grainsize populations. Folk (1966) noted that 'nature apparently provides us with three dominant modal populations: gravel, sand plus coarse silt, and clay resulting respectively from direct breakage along joint or bedding planes, from granular disintegration and abrasion, and from chemical decay'. Thomas et al. (1972) and Spencer (1963) supported Folk's theory and suggested that the mean ranges from 1.5 to 4.0 phi and standard deviation from 0.3 to 1.5 phi units for the sand population; for the clay population, the mean ranges from 7.0 to 9.5 phi and standard deviation from 1.5 to 3.0 phi units.

The fundamental sand population in this study is shown in the lower right portion of the sorted sand unit in Figure 52. The extension of the plot upwards and to the left of the basic population is due to the presence of in situ shells in some of the sandbank samples. The means of samples in this population range from 2.0 to 3.5 phi and the standard deviations from 0.3 to 0.8 phi units. The means are representative of the modal size of the sediment as the grainsize distributions are unimodal with low standard deviation, but although the sand particles may have been formed by granular disintegration and abrasion they do not constitute a dominant supply mode. It has been shown that there is no dominant sand mode in the sediments entering Broad Sound, and the basic sand population results primarily from the sorting action of the waves and tidal currents.

The silt-clay basic population is represented by the low-carbonate supratidal zone (mangrove swamp and supratidal flat) samples of the sorted low-energy unit. An important difference between the silt-clay population and that of other studies is that the Broad Sound population includes sediments with a bimodal grainsize distribution.

The means of the samples in this population range from 7.0 to 10.0 phi, and the standard deviations range from 2.0 to 3.5 phi units. In the Broad Sound estuary, silt and clay particles are dominant in the terrigenous sediment supply, but it is difficult to determine whether there is only one dominant supply mode in the silt/clay range as only the coarse silt is present as bedload in the upper reaches of the estuaries whereas the medium to fine silt and clay enter Broad Sound in suspension. It is suspected that fine silt and clay are probably the dominant terrigenous supply size. The grainsize distributions of samples representing this population are bimodal with high standard deviation, and therefore the mean does not represent the modes of these samples. The resulting silt-clay population is due not only to the abundant supply of these particles, but also to the low-energy sorting processes discussed earlier.

Therefore, although the concept of end-member grainsize populations is a useful interpretative tool, the range of mean values may not indicate the true modal sizes of the sediments in that population, and all the processes of sedimentation must be considered when determining the reasons for the existence of the populations in each study area.

Geological Interpretations

Mean and standard deviation interpretations

Using the mean-standard deviation plot and the properties of each sedimentary unit, it is now possible to suggest geological explanations for changes in the mean and standard deviation values within each sedimentary unit.

Increasing standard deviation with decreasing mean (increasing size) in the sorted sand unit indicates increasing amounts of in situ shells and calcareous nodules within the sorted sands, which also represents a move from the intertidal to the subtidal parts of the unit.

The same combination of increasing standard deviation with decreasing mean in the sorted mud unit represents the transition from sediments of the supratidal flats to sediments with a higher sand and silt content. This, together with increasing carbonate content, points to a movement from the supratidal flats to the mangrove swamp environment; or with decreasing carbonate content movement to sediments containing significant sand and silt washed from the land. There is also increasing standard deviation with decreasing mean on changing from the supratidal to the intertidal zones of this unit.

Within the unsorted muddy sand unit, decreasing standard deviation with decreasing mean grainsize corresponds to a decrease in mud content which could be due to tide and current action or simply to decreasing amounts of intermixed mud.

Interpretations within the unsorted gravel unit are uncertain because of the nature of the sediments. Increasing standard deviation with decreasing mean indicate increasing amounts of shells, nodules, and terrigenous gravel. A summary of the major differences between the sedimentary units and subunits is given in Table 5.

These interpretations should be important when inter-relations between variables are being determined later (Cook & Mayo, in prep.). Given the sedimentary unit, changes in the mean and standard deviation values can be used to interpret the changes in other variables measured on samples from that unit.

Sedimentation model

It is now possible to postulate a composite model from present-day sedimentation in Broad Sound:

1. The catchment sediment is believed to be transported into the estuary mostly during the annual floods. Much of the silt and clay of this sediment remains in suspension. Some sediment (predominantly very fine sand and coarse silt) is initially deposited in the upper reaches of the estuarine portion of the watercourses.
2. Between floods, particles finer than 3 phi are removed from the intertidal bedload by waves and tidal currents. The 2-3 phi sorted sand particles are moved more rapidly seawards than the coarser sand and gravel and tend to form

TABLE 5. COMPARISON OF THE MAJOR SEDIMENTARY UNITS

	Corresponding field environment	*Relative energy (and equilibrium)*	*Typical grainsize distribution*	*Gravel*	*Sand*	*Mud*	*Geological interpretation with decreasing standard deviation and increasing mean (in phi) except with unsorted muddy sand unit*
UNSORTED GRAVEL UNIT Coarse to fine mean; moderate to very high standard deviation	Shallow marine	Low (not in equilibrium)	Multimodal	Variable amounts of all fractions			Decreasing proportion of shells, nodules, and terrigenous gravel
UNSORTED MUDDY SAND UNIT Medium to very fine mean; moderate to very high standard deviation	Open intertidal, shallow marine	High (not in equilibrium)	Bimodal (dominant mode in very fine sand coarse silt range)		Minor to equal	Major to equal	Decreasing standard deviation with decreasing mean indicates decreasing mud content as sorting process continues
SORTED SANDY UNIT Coarse to medium mean; low to high standard deviation	Open intertidal, mangrove channel	High (in equilibrium)	Unimodal or bimodal (dominant mode in fine sand fraction)		Major		Moving from shallow marine to open intertidal environment associated with decreasing proportion of in situ calcareous shells and nodules
SORTED MUDDY UNIT Very fine mean; high standard deviation	Mangrove swamp, supratidal flats	Low (in equilibrium)	Bimodal (dominant mode in medium silt or clay fraction)		Minor	Major	With decreasing carbonate indicates movement from near-intertidal zone to the mudflats, otherwise from the near-land zone to the mudflats.

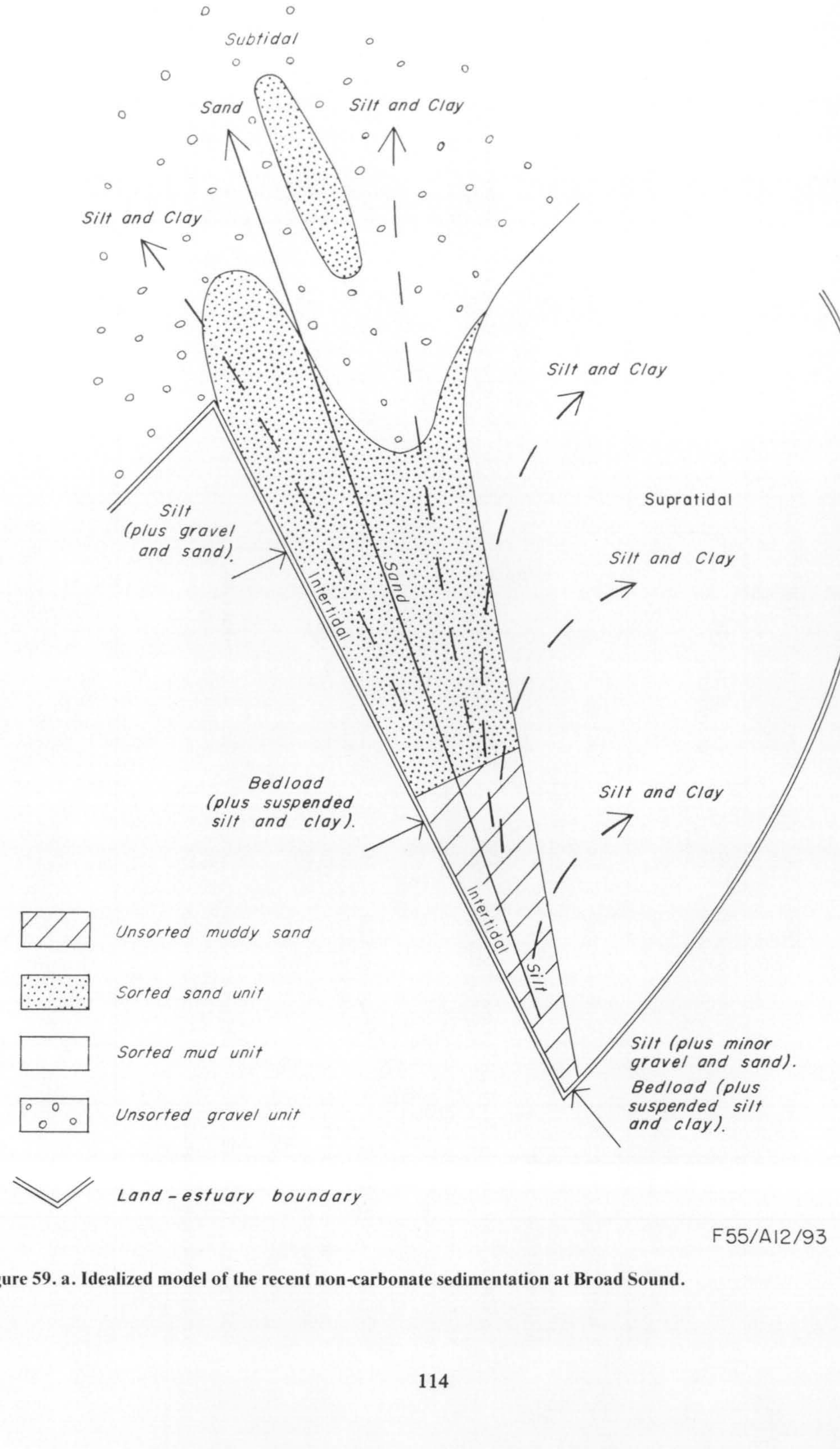


Figure 59. a. Idealized model of the recent non-carbonate sedimentation at Broad Sound.

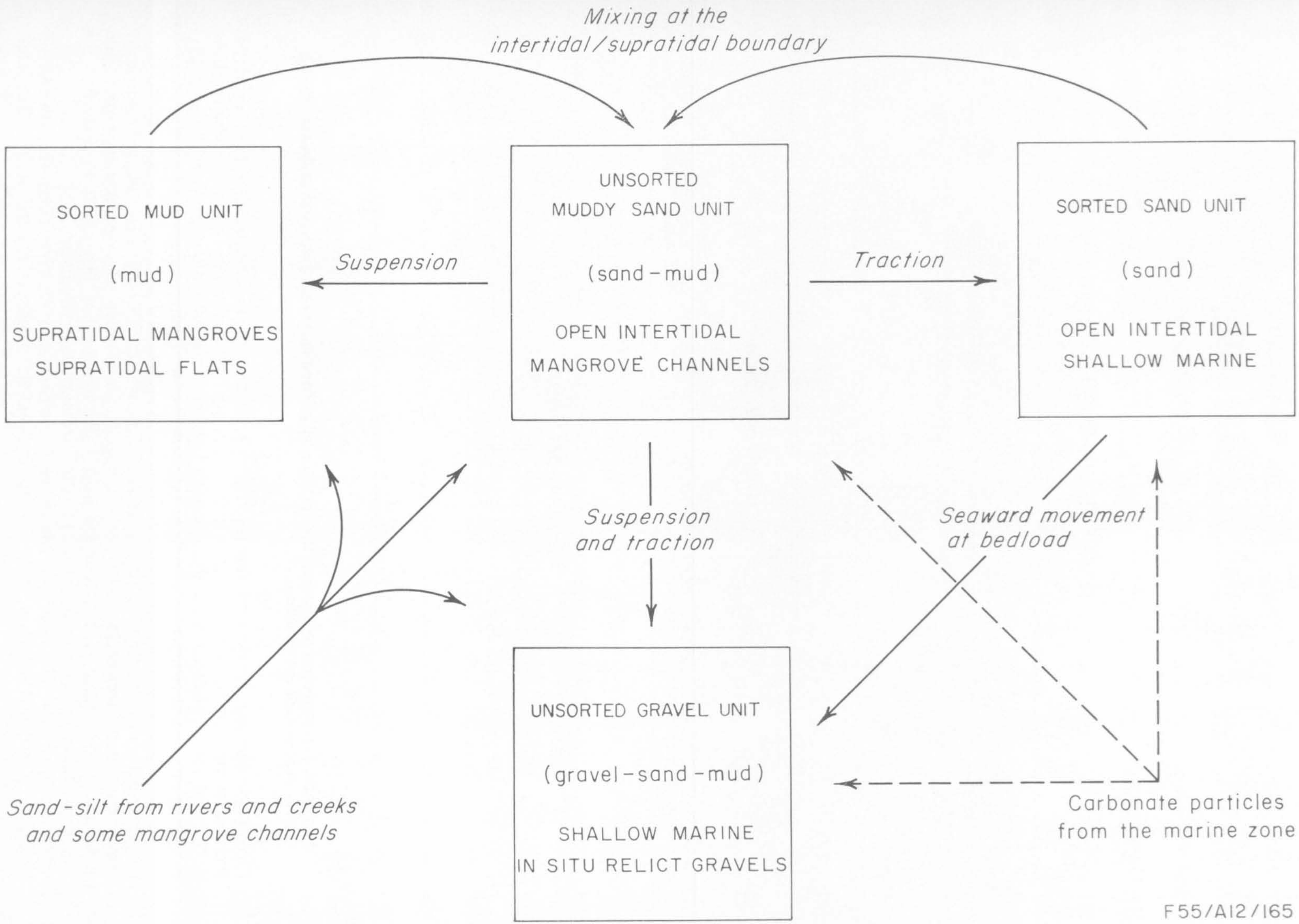


Figure 59. b. Idealized sediment movement in Broad Sound and relation between sedimentary units and field environments.

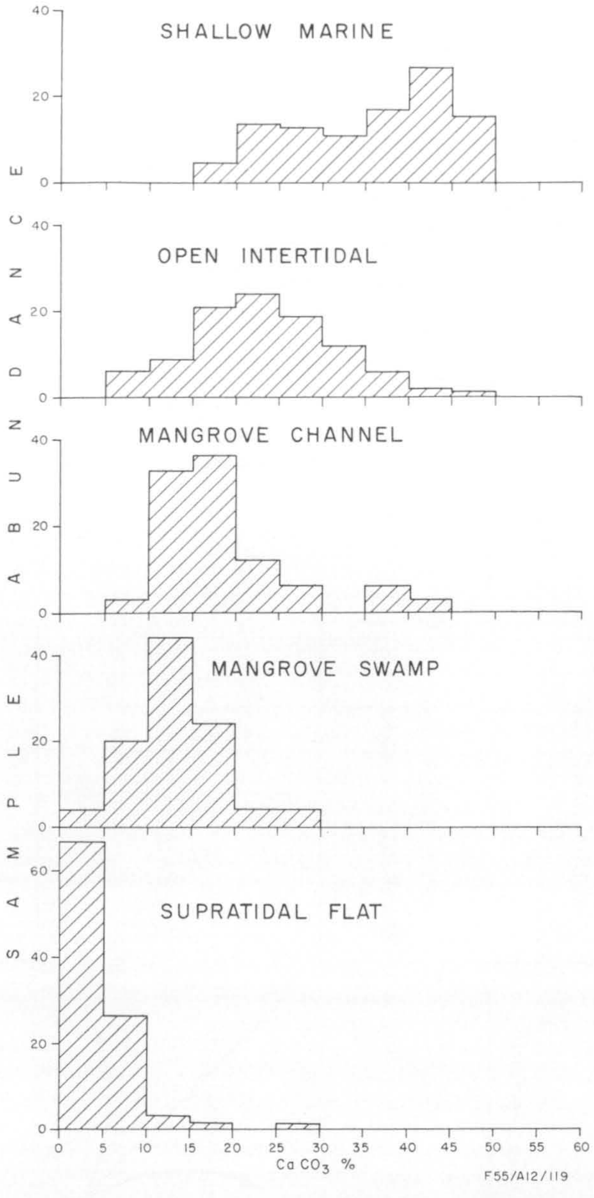


Figure 59. c. Histograms to illustrate the variation of calcium carbonate content in sediments of the various depositional environments.

current-orientated sandbanks overlying the relict Pleistocene and early Holocene sediments.

3. Silt and clay winnowed from the incoming sediments and mixed sediments, as well as that already in suspension, are redeposited mainly in the supratidal zone (sorted mud sediments) and to a lesser extent in the subtidal zone.

4. Mixing of the sorted sand and sorted mud sediments takes place continuously in the mangrove channels and at the mangrove swamp/open intertidal boundary.

5. Some of the biogenic material in the estuary is in situ shell material; the majority is derived from the marine shelf and intermixed with the locally-derived terrigenous material.

An idealized diagram of this model is shown in Figure 59a; 59b summarizes the sediment interchange between the sedimentary units and indicates the link between these units and the sedimentary environments.

In contrast to the genetic classification which is essential for unravelling the geochemical interrelations within each sedimentary unit, this model will be useful when the geochemical relations between the units are being studied.

Conclusions

1. The two grainsize distribution parameters, mean and standard deviation, successfully classify the Broad Sound samples into four main sedimentary units, viz. the sorted sand unit, sorted mud unit, unsorted gravel unit, and unsorted muddy sand unit. Each unit reflects a distinct combination of sedimentary processes in Broad Sound. The two distribution parameters or other grainsize parameters may be used to further subdivide the units.
2. The geological interpretations of changes in the mean and standard deviation values are different in the four sedimentary unit. These interpretations may be useful when geochemical relations within each unit are determined.
3. The sedimentation model links the major sedimentary processes in Broad Sound with the sedimentary units and may aid in determining their geochemical relations.

PETROLOGY AND MINERALOGY

The two basic components in the Broad Sound sediments are the terrigenous fraction which is composed mainly of light minerals such as quartz and feldspar, and the biogenic component which is predominantly calcareous. The abundance of $CaCO_3$ in Broad Sound which caries markedly in the depositional environments (Fig. 59c) the relative abundance of biogenic and terrigenous material, and calcareous material becomes increasingly abundant to the north as conditions become more marine (Figs. 31 and 61). Nevertheless this does not show the source of the material, particularly the non-calcareous fraction. It has been shown by Bird (1964) that much of the material in modern estuaries on the southeast coast of Australia was derived not from a nearby fluvial source but from the shelf. This is also believed to be the case for many of the world's estuaries. During the Holocene transgression, terrigenous material which had accumulated on the shelf during the last Glacial and perhaps other Pleistocene low sealevel episodes was swept across the shelf towards the land.

By examining the varying proportions of minerals in the non-calcareous fraction it was hoped to clarify the immediate provenance of the terrigenous material. In addition, knowledge of the abundance of heavy minerals helps delineate areas with potentially economic heavy-mineral accumulations such as exist off the Queensland coast south of Broad Sound. Subsidiary aims of the study included the nature of the biota of the region and its use in delineating sedimentary environments, and the presence of any early diagenetic changes in the calcareous and non-calcareous fractions.

Petrology

The relative abundance of the various biogenic components was estimated using a binocular microscope. Sprinkle mounts were prepared of the terrigenous sand-size fraction (after acidulation to remove any calcareous material) of all samples, which were examined with a petrological microscope to determine roundness and sphericity. An estimate was made of the relative abundance of the various quartz types. Thin sections of a set of impregnated sediments (representative of each depositional environment) were prepared for petrological examination. Thin sections were prepared of the various nodules and concretions.

Biogenic sediments

Most calcareous material is biogenic, except some calcareous nodules (Pl. 12, fig. 2). Most biogenic material is calcareous with a few exceptions such as sponge spicules, crab fragments, and diatoms. A wide range of biogenic material is present, particularly in the shallow marine and open intertidal sediments. Material recognized consisted of whole and fragmentary corals, coralline algae, bryozoans, gastropods, pelecypods, brachiopods, foraminifers, diatoms, serpulid worm casts, sponge spicules, crabs, and plant material. Despite this range, few living forms were observed. This could be in part due to recent changes in environmental conditions such as the waters now being muddy or locally more saline. Long-term changes of this type are indicated by patches of dead recrystallized corals with a minimum radiocarbon age of about 30 000 years B.P. at the mouth of the Styx River near Charon Point, whereas the nearest living coral is 16 km to the northeast at the southern end of Long Island. However, there is no evidence to suggest that any drastic changes in environmental conditions have occurred within the last few hundred years. Consequently, much of the biogenic material may be swept into the southern end of Broad Sound by tidal currents, as suggested by the progressive increase in carbonate content to the north, although the same distribution may also result from the dilution of calcareous

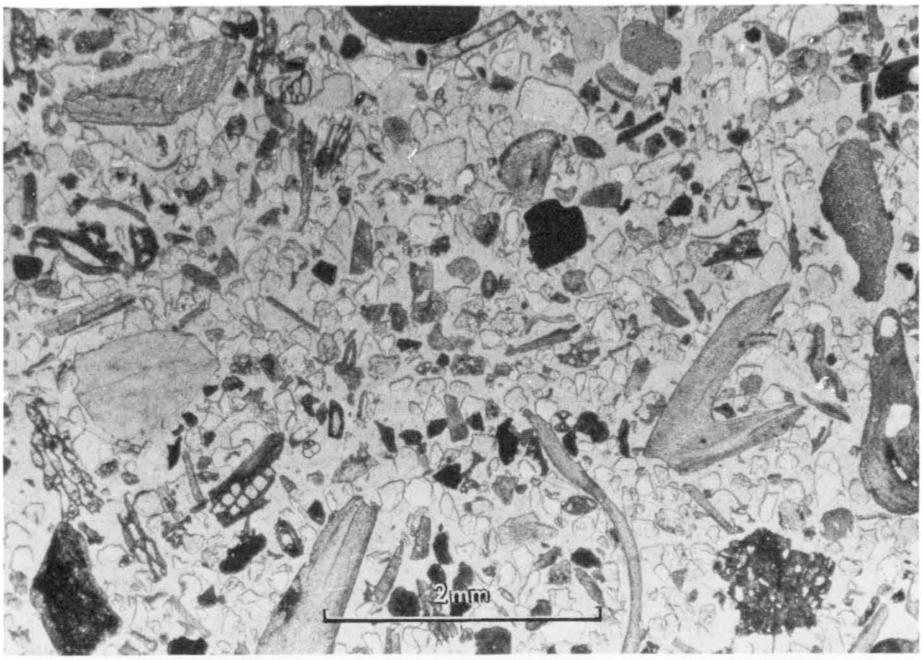


Plate 38, fig. 1. Poorly sorted sand from the Styx River estuary, containing coarse calcareous biogenic fragments and fine terrigenous grains. Sample 70636811. (M/1377/18)

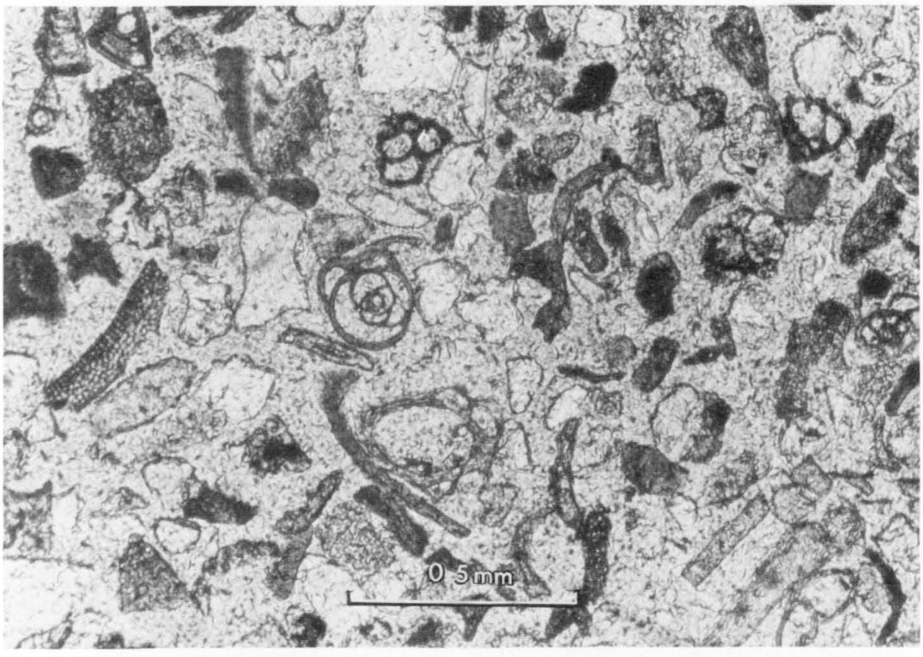


Plate 38, fig. 2. Moderately sorted sand from the upper reaches of the Styx River estuary. Biogenic fragments and detrital grains (mainly quartz) are approximately the same size. Sample 70636834, from the northern part of the study area. (M/1377/9)

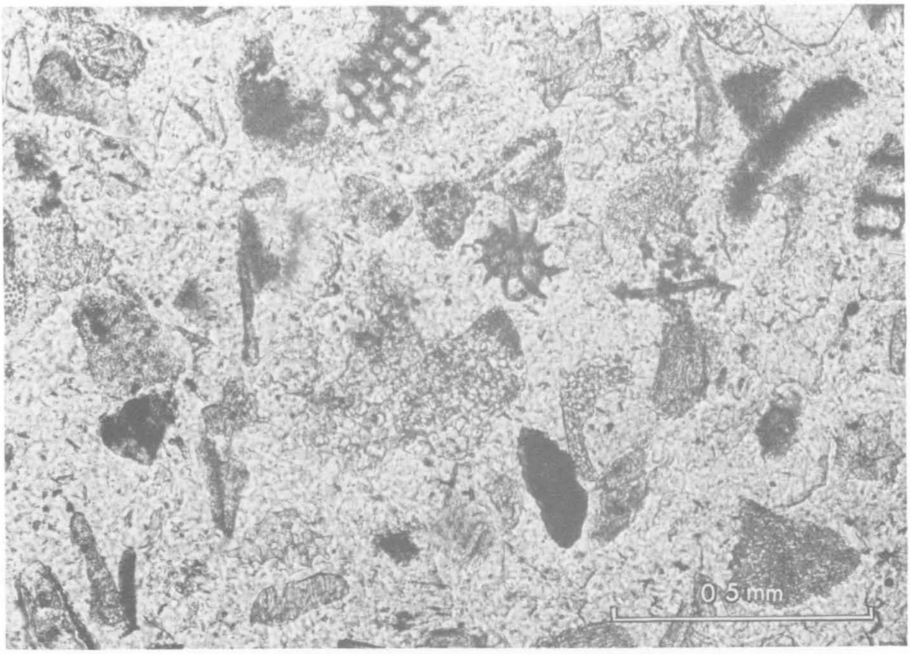


Plate 39, fig. 1. Fine sand fraction in supratidal flat sediments, composed mainly of angular fragments of biogenic material. Sample 70636020, from the upper part of Herbert Creek. (M/1571/26)

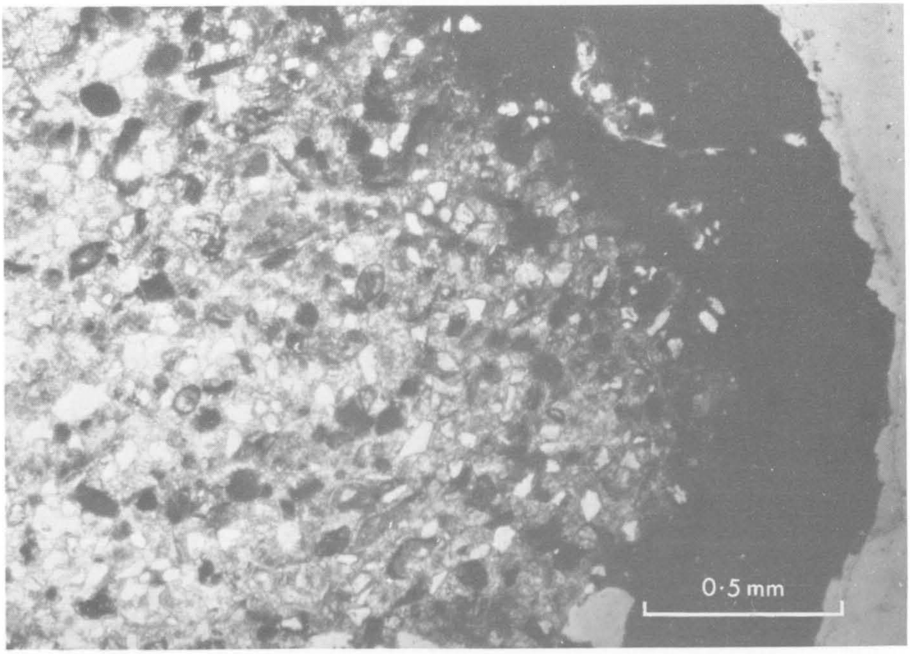


Plate 39, fig. 2. Sandy calcareous nodule, with a dark micritic rim, believed due in part to algal boring. Sample 70636295N.(M/1571/3)

J

material by the influx of terrigenous sediment from the south and west.

The biogenic material is generally coarser than the associated terrigenous fraction (Pl. 38, fig. 1), but some samples have similar grainsize (Pl. 38, fig. 2). This may be partly because the larger, though platier carbonate grains are the hydraulic equivalent of smaller, more equant terrigenous grains, although the carbonate assemblage is biocoenosic in places. The high-velocity currents are also able to move gravel-size material which is available in the biogenic material, whereas generally only sand-size material is available in the terrigenous material. In places, the biogenic material is well rounded and abraded, suggesting extensive transport; however, generally the biogenic material has a significantly lower roundness and sphericity than the terrigenous grains, except for the calcareous nodules which commonly show substantial rounding and sphericity (Pl. 13, fig. 1).

Estimates of the relative abundance of the various biogenic components revealed that the proportions vary both with the depositional environment and also within the same environment. All phyla are relatively abundant in the sand facies of the open intertidal environment, but whereas thin-shelled and thick-shelled foraminifers are present in about equal amounts in this environment, thin-shelled forms predominate in the supratidal flats and the shallow marine zones. This is probably a reflection of the low-energy conditions prevailing in these two environments compared with the open intertidal area. Similarly, forms such as corals, echinoderms, bryozoans, sponges, and bivalves are much less abundant in the supratidal zone than the intertidal, infratidal, and subtidal zones (Pl. 39, fig. 1).

The data are insufficient to plot the regional variation of the various phyla in all the depositional environments. However, it has been attempted for the shallow marine and open intertidal environments. These are shown in a series of maps (Figs. 60-67). For some, such as the relative abundance of pelecypods (Fig. 60), there is no

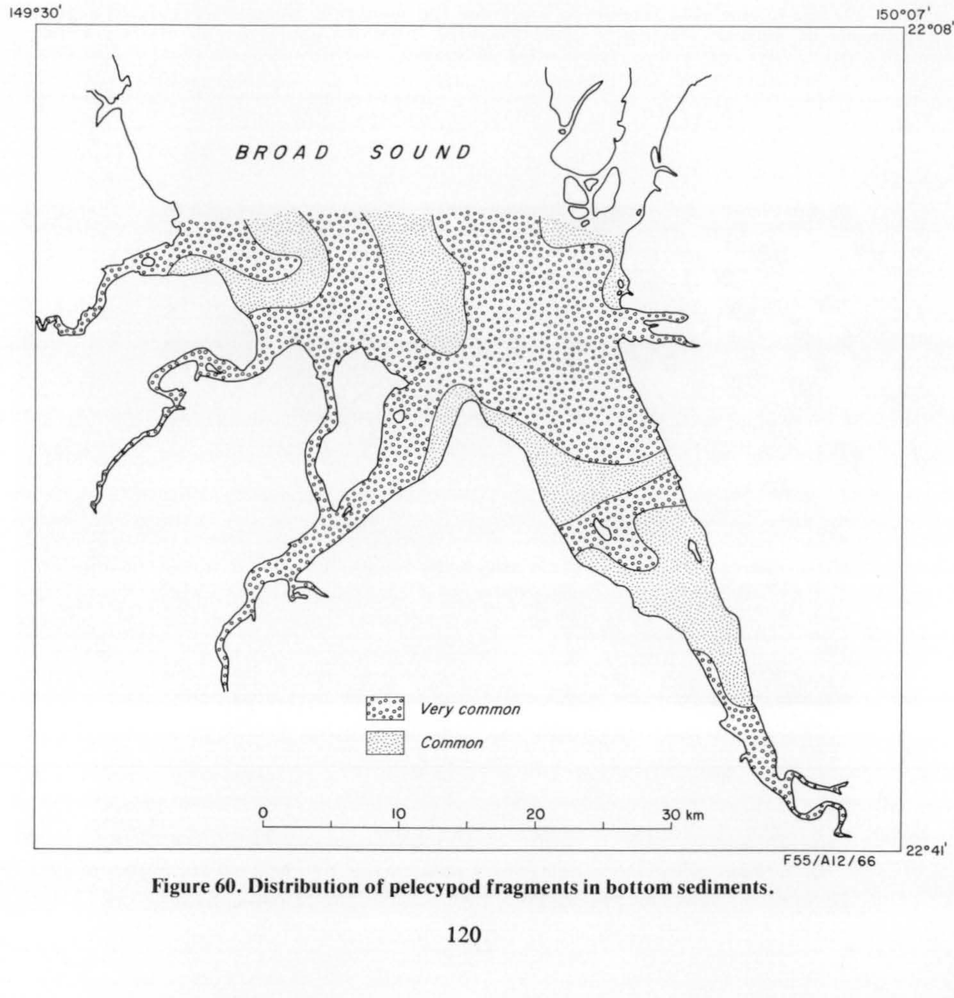


Figure 60. Distribution of pelecypod fragments in bottom sediments.

ready explanation. Other phyla show quite logical trends of increasing relative abundance to the north, i.e. towards more congenial marine conditions. Distribution of this type include corals plus coralline algae (Fig. 61), gastropods (Fig. 62), and bryozoans (Fig. 63). Diatoms on the other hand show a tendency to become less abundant seawards (Fig. 64). Hyaline foraminifers (Fig. 65) show a similar trend of decreasing abundance seawards, but porcellanous foraminifers appear to become more abundant seaward (Fig. 66). If the abundance of the two foraminiferal types are compared (Fig. 67) it is apparent that hyaline are more abundant than porcellanous in the more estuarine parts of the Sound and porcellaneous are more abundant in the more marine parts.

Whether this distribution is the result of the ecology of the foraminifers or whether it is a sorting effect such as the hyaline being lighter and therefore more easily swept into the upper reaches of the estuary by tidal currents is not certain. Many other biogenic distribution patterns may be a reflection of the effects of sorting by estuarine currents. Therefore, although the ecological significance is unknown, these data indicate that relative biogenic distribution patterns may be an additional tool to use in estuarine sequences in order to gain an insight into the palaeogeography of ancient estuarine sequences, indicating in particular the seaward and landward directions.

Calcareous nodules. Calcareous nodules are common in many parts of Broad Sound, particularly in the subtidal and intertidal zones. Dolomite nodules are present in the supratidal zone, and pedogenic nodules are found in the extratidal zone within the soil profile in a few places.

The external morphology of the marine calcareous nodules has been discussed previously, and some of the nodules are illustrated in Plates 14 and 15. Externally it is evident that at least some nodules are composed primarily of calcareous biogenic material which has been abraded. They may consequently be regarded as intraclasts. In thin section they have a variety of

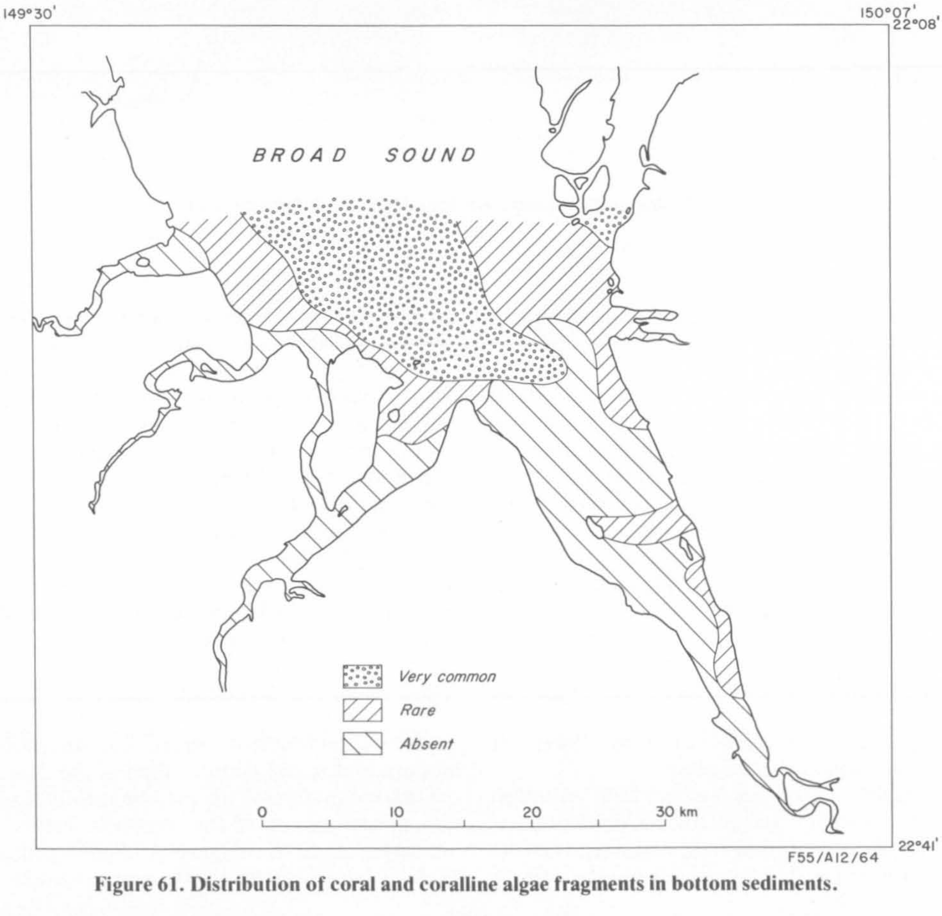


Figure 61. Distribution of coral and coralline algae fragments in bottom sediments.

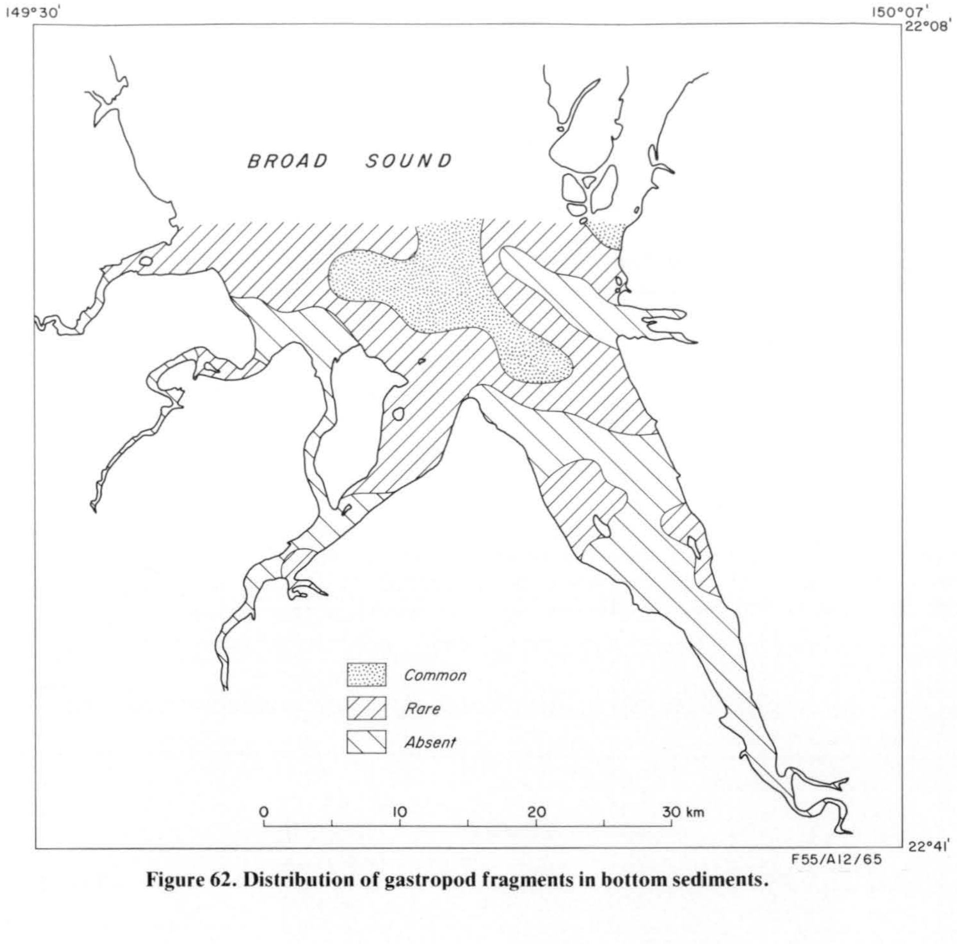


Figure 62. Distribution of gastropod fragments in bottom sediments.

internal textures. Most are sandy, with abundant detrital grains and shell fragments scattered throughout the nodule (Pl. 39, fig. 2). The matrix is commonly micritic (Pl. 40, figs. 1 and 2) or composed of a grain-growth mosaic (Bathurst, 1958). Marginal replacement of detrital grains by calcite is a common feature, and recrystallization textures are also abundant (Pl. 40, fig. 2). Iron staining is common. Some nodules show well defined bedding which is terminated by the external margin of the nodule. This indicates that the nodules are intraclasts, resulting from the break-up and subsequent rounding of bedded calcareous deposits. Other nodules have an external concentric micrite envelope (Pl. 39, fig. 2), suggesting a further period of carbonate deposition or, alternatively, algal burrowing subsequent to the formation of the intraclast.

Van Andel, Curray, & Veevers (1967) showed that these nodules are restricted to depths of about 100 m or less, and they suggested that the nodules formed within calcareous kunkar soils as a result of late Quaternary weathering. It seems probable that some of the calcareous marine nodules at Broad Sound have a similar origin. This is supported by the fact that calcareous pedogenic nodules are present within the soil profile in the Broad Sound region e.g. the Marlborough area. A number of these undoubted pedogenic nodules were examined in thin section. Like the marine nodules, they commonly show iron staining; a few contain shell fragments (Pl. 41, fig. 1) where they have formed close to the present-day shore line. Some shells were probably incorporated into marine muds before marine regression or, alternatively, the shell was transported into the area by water or wind and then incorporated in the soil profile. However, shells are undoubtedly much less abundant in modern pedogenic nodules than is the case with the marine nodules. This may be merely a reflection of the nature of the 'bedrock' rather then indicating a different genesis. Some pedogenic nodules have veins of coarse-grained calcite run-

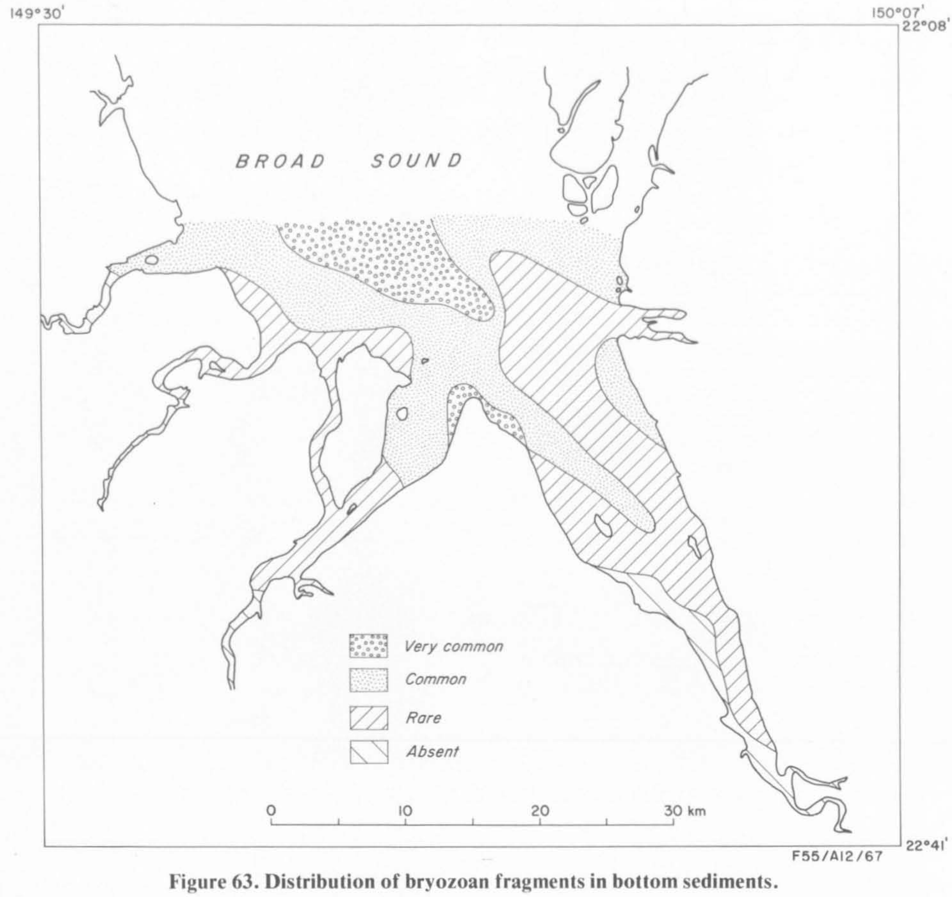


Figure 63. Distribution of bryozoan fragments in bottom sediments.

ning through them (Pl. 41, fig. 2) but the majority appear to be micritic, as are many of the marine nodules. Thus, texturally there are some similarities between the two types of nodules.

Further evidence that the marine nodules have formed as a result of, or have been subjected to, subaerial weathering comes from the results of radiocarbon dating of the nodules (Table 13). Composite nodule samples from two localities gave ages of 16 140 ± 180 years B.P. and 16 150 ± 260 years B.P. If 16 000 years B.P. is the age of formation of the nodules then this corresponds to a time when sea level was considerably below that of the present day and consequently the areas now covered by these carbonate nodules would have been subaerially exposed at the time. It therefore appears that at least some and perhaps most nodules are of pedogenic origin. However, some material is clearly of biogenic origin (see Pl. 13, fig. 2) and has been abraded. It is unnecessary to invoke subaerial soil-forming processes for this type of clast as subaqueous or strand-line processes would be equally effective in producing them.

A different type of nodule composed of dolomite and calcite is found in the supratidal zone. These nodules are known to occur only in the Charon Point area, but as comparable conditions prevail elsewhere they are likely to be more widespread. They are highly variable in form although most are elongate, ranging in length from 1 to 20 cm and in width from 0.5 to 10 cm. Many have a spherical, platy, or nodular habit (Pl. 42, fig. 1), and some have a distinctive cylindrical form (Pl. 42, fig. 2). In thin section they consist of a calcareous micritic groundmass with inclusions of shell fragments (Pl. 43, fig. 1), detrital quartz and feldspar and gypsum (Pl. 43, fig. 2). No dolomite rhombs are evident, and it is only by X-ray diffraction that the dolomitic nature is apparent. These nodules and concretions appear to have formed in situ, and are clearly not of intraclastic origin. They are believed to have formed by precipitation and

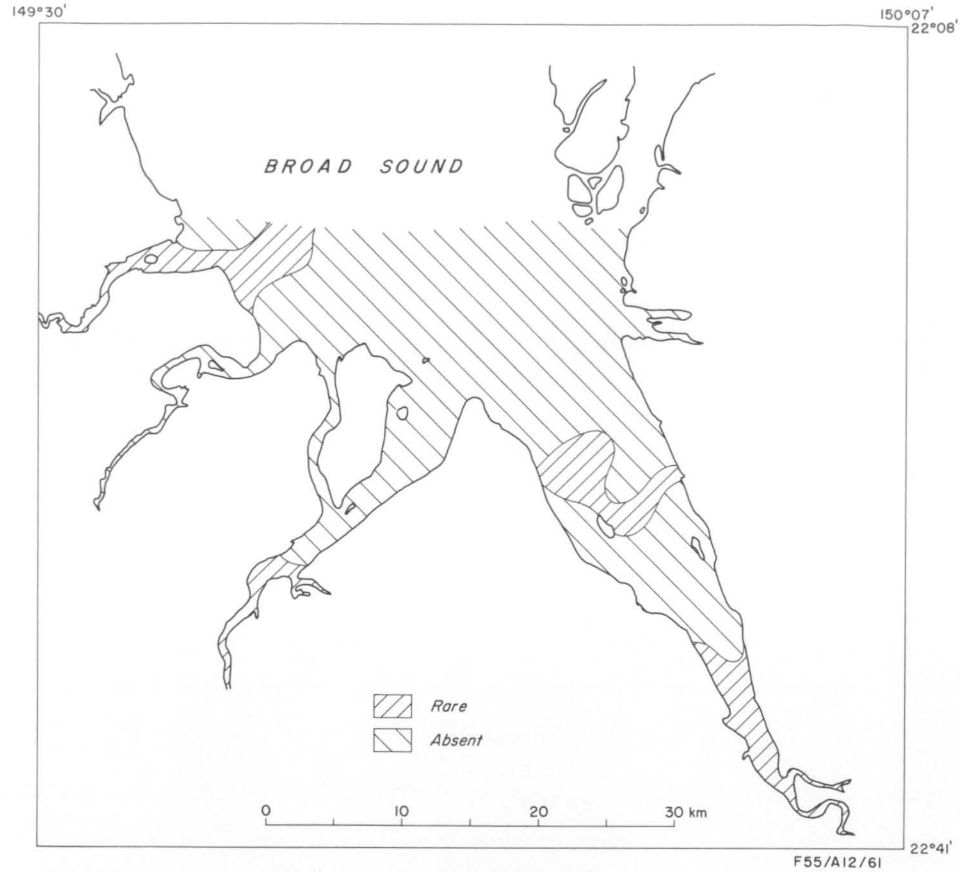


Figure 64. Distribution of diatom fragments in bottom sediments.

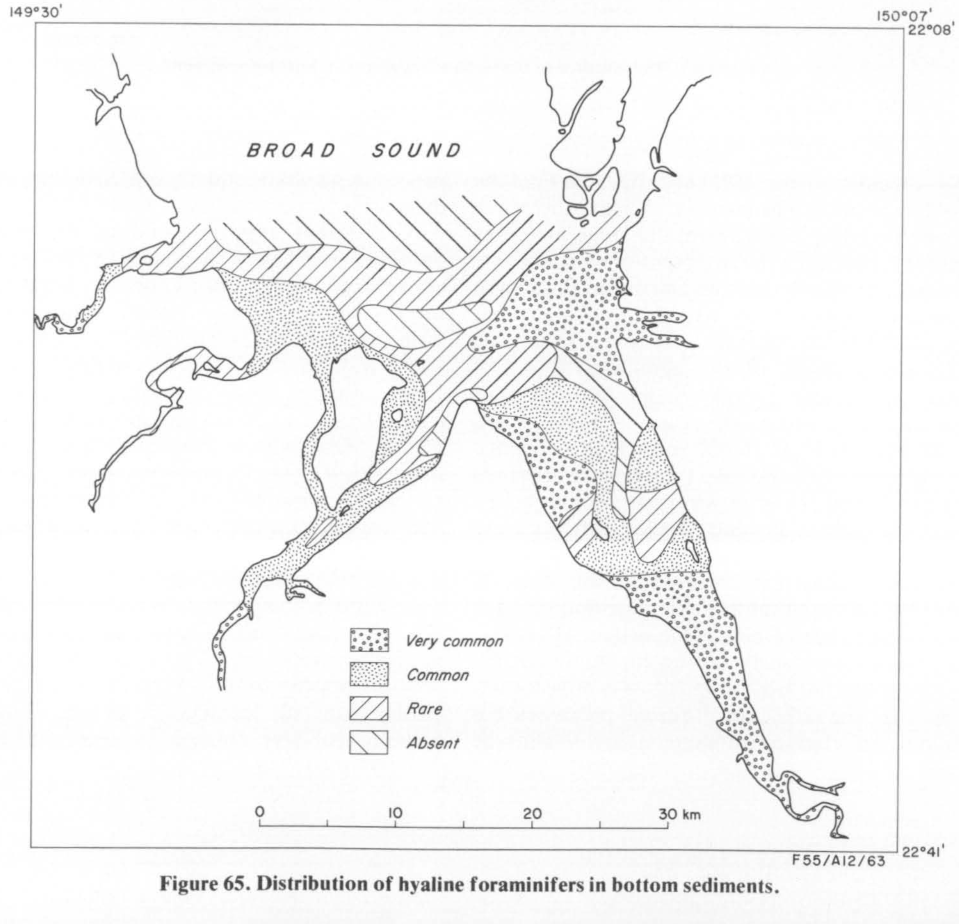


Figure 65. Distribution of hyaline foraminifers in bottom sediments.

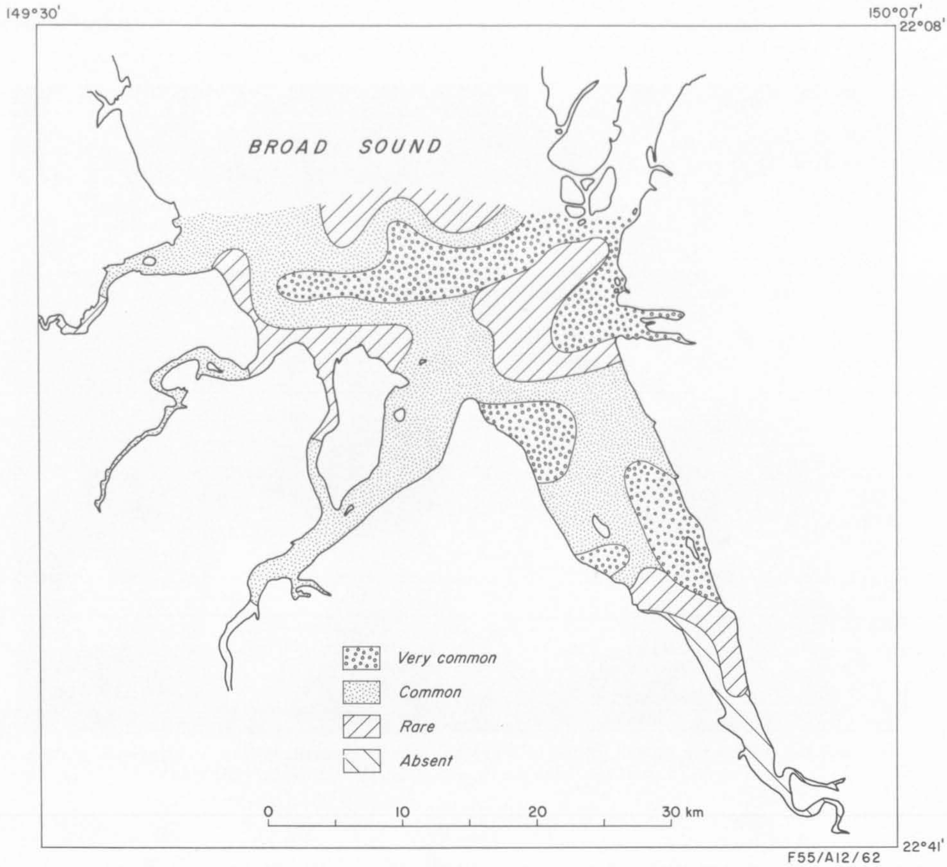


Figure 66. Distribution of porcellanous foraminifers in bottom sediments.

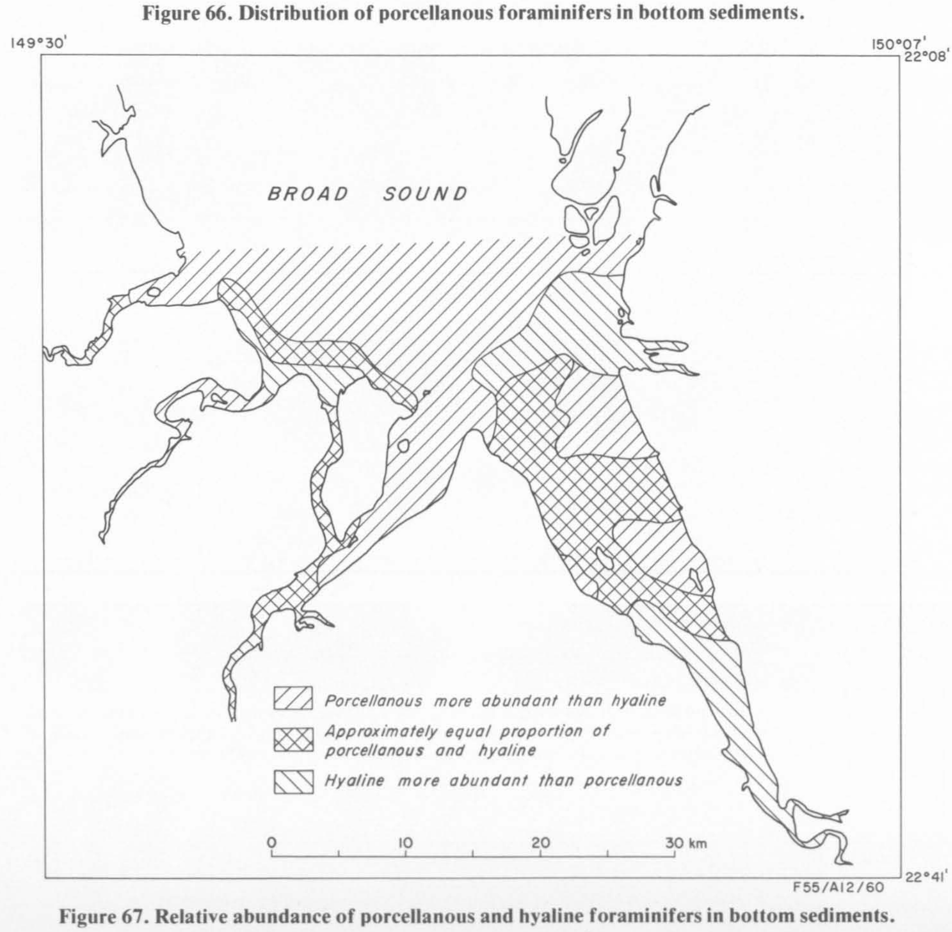


Figure 67. Relative abundance of porcellanous and hyaline foraminifers in bottom sediments.

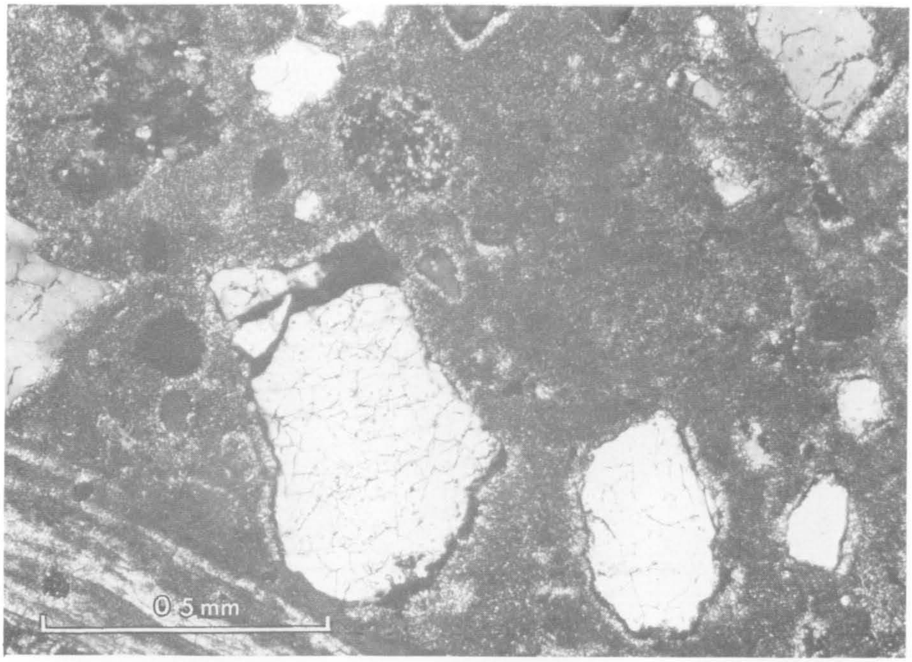


Plate 40, fig. 1. Coarse quartz grains in a calcitic micrite cement, within a calcareous nodule. Sample 70636216N, 2 km northwest of Turtle Island. (M/1571/14)

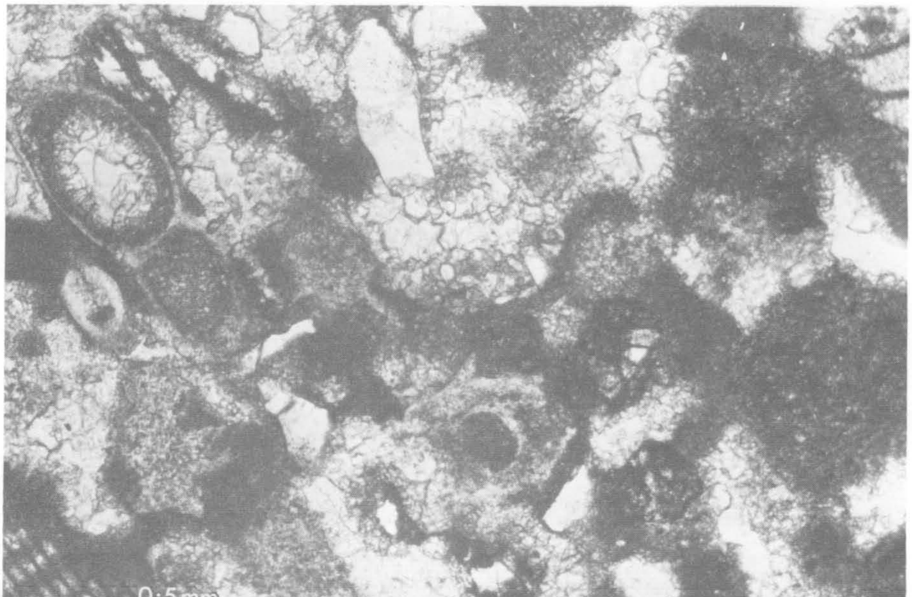


Plate 40, fig. 2. Calcareous nodule showing a grain-growth mosaic texture due to recrystallization of micrite. Abundant biogenic fragments and some terrigenous grains are present. Sample 70636268N, from the central part of Broad Sound. (M/1571/11)

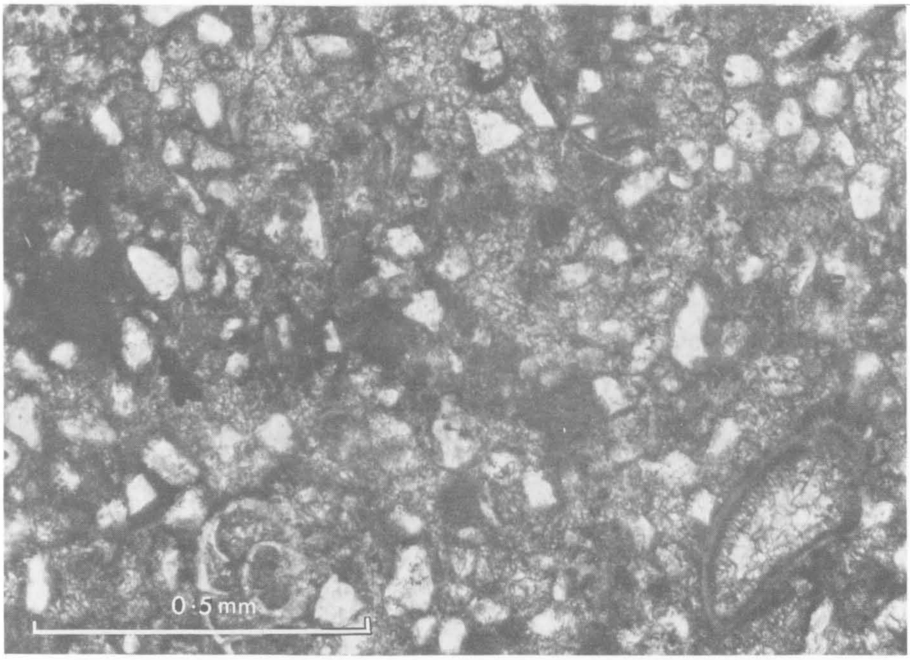


Plate 41, fig. 1. Internal structure in a sandy calcareous pedogenic nodule. Sample 70636003B, from the east bank of Marlborough Creek. (M/1571/20)

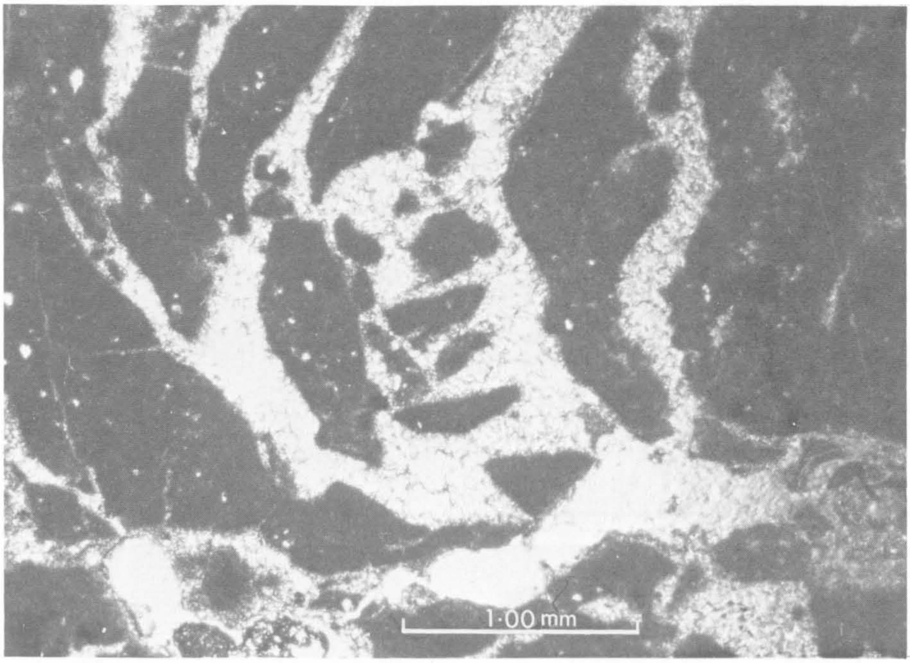


Plate 41, fig. 2. Calcareous pedogenic nodules, with veins of sparry calcite running through a micritic matrix. Sample 71636003A, from the east bank of Marlborough Creek. (M/1345/36)

Plate 42, fig. 1. Dolomite nodule from supratidal flats in the Charon Point area. The nodule is 9 cm long. Sample 70636720C. (GA/5769)

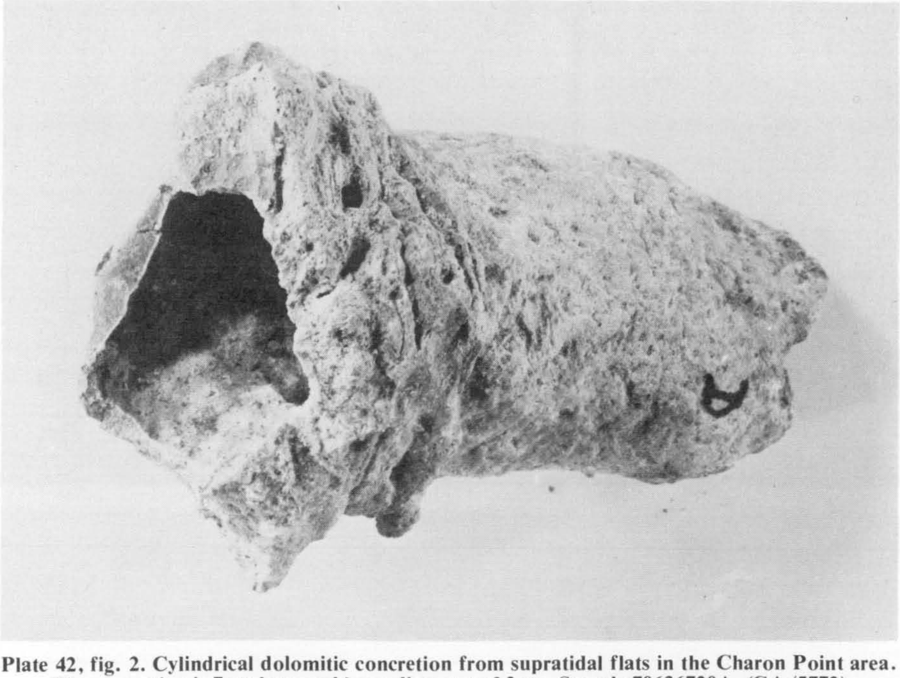


Plate 42, fig. 2. Cylindrical dolomitic concretion from supratidal flats in the Charon Point area. The concretion is 7 cm long and has a diameter of 3 cm. Sample 70636720A. (GA/5772)

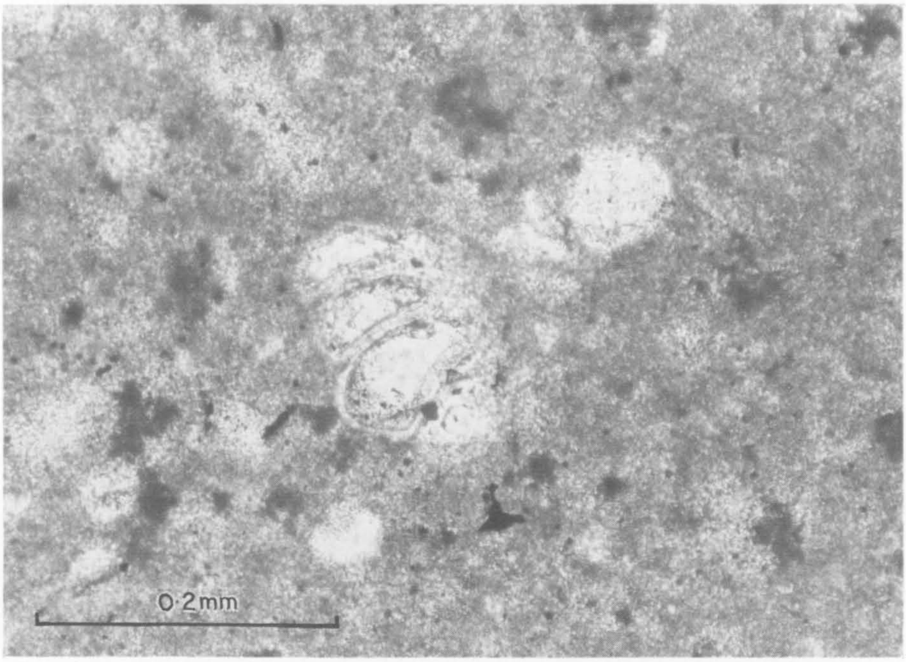


Plate 43, fig. 1. Dolomitic micrite with an included gastropod fragment. Sample 70636720, 1 km south of Charon Point. (M/1345/28)

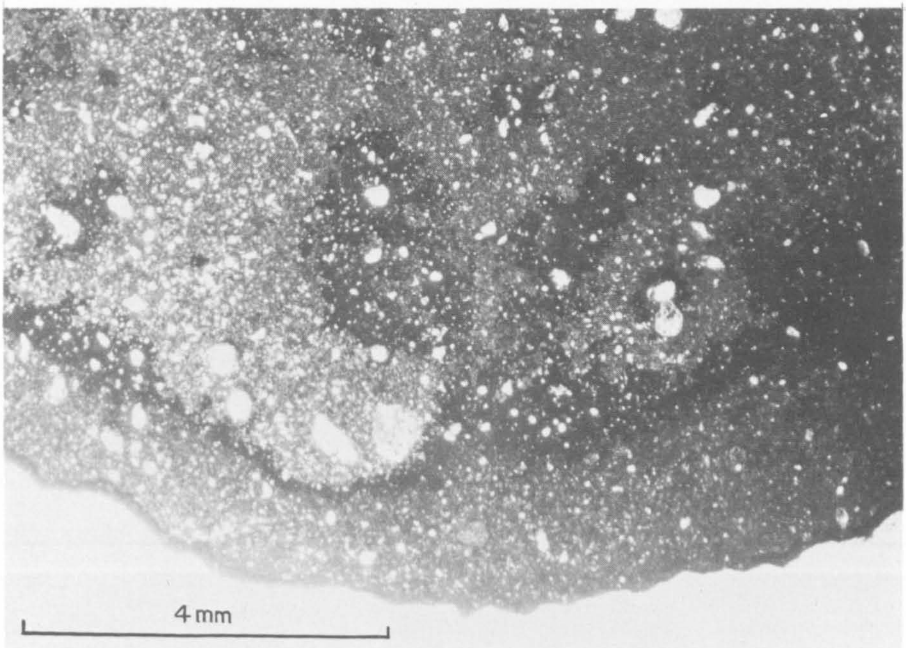


Plate 43, fig. 2. Dolomitic micrite with inclusions of detrital grains, biogenic fragments, gypsum inclusions, and voids. The darker areas of the concretion are more dolomitic than the lighter areas. Sample 70636720, 1 km south of Charon Point. (M/1350/4A)

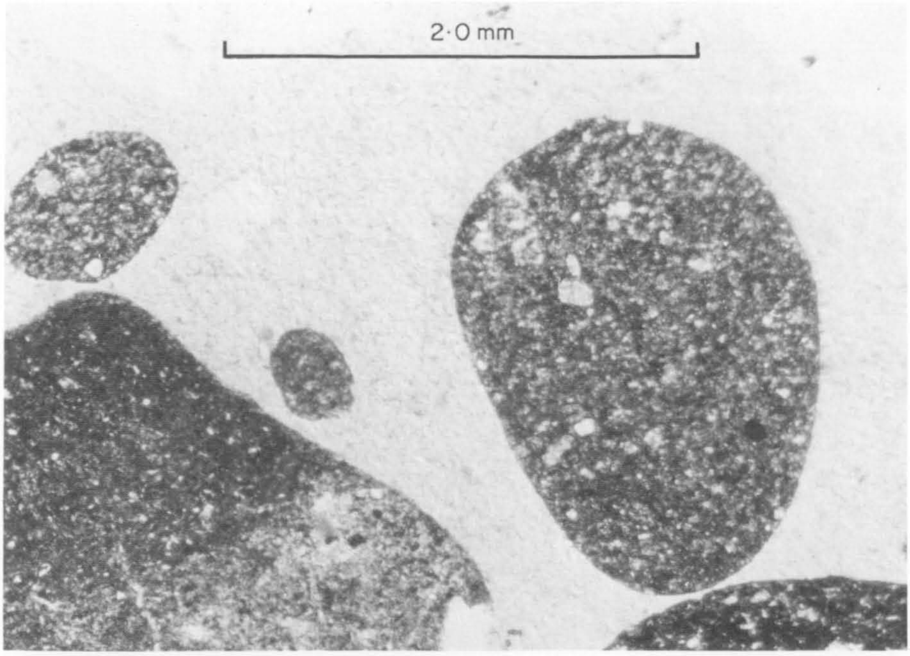


Plate 44, fig. 1. Coarse, well rounded rock fragments in the sand fraction of sediments of the upper part of the Styx River estuary. The matrix is of the mounting medium. Sample 70636843. (M/1377/3)

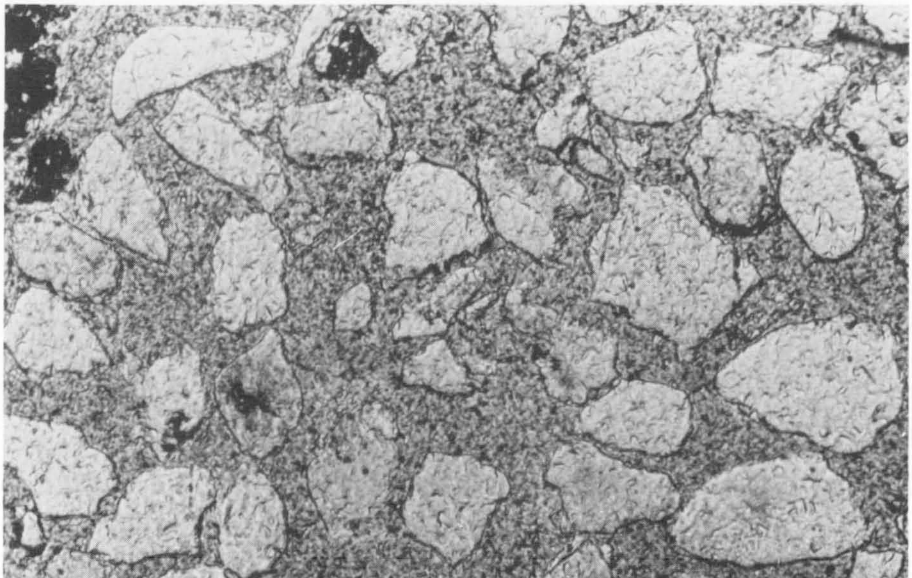


Plate 44, fig. 2. Typical terrigenous fraction of a marine sand showing moderate sorting and poor rounding. Sample 70636061, from the central portion of Herbert Creek. (M/1377/31) replacement processes within the supratidal flat environment in the presence of magnesium-rich pore waters. The formation of these concretions is discussed by Cook (1973) and Cook & Polach (1973b).

Terrigenous sediments

This discussion is concerned primarily with sand-size terrigenous material; silt-size and gravel-size grains are included to a limited extent, and clay-size material is dealt with later. Thin-section and sprinkle-mount examination reveals that the terrigenous assemblage is in general moderately mature, with quartz predominant, minor feldspar, and minor to very minor rock fragments.

Coarse, well rounded rock fragments (Pl. 44, fig. 1) are common in a few sands from the upper reaches of the estuary. Up to 20 percent rock fragments were noted in an immature sand from locality 151 (in the Styx River), putting it into the lithic arenite class of Crook (1960). However, the terrigenous component of most sediments falls into the quartzose arenite or feldspathic sublabile arenite classes. Although most sediments have a comparatively mature mineral assemblage in the terrigenous sand fraction, some may be texturally immature (Pl. 44, fig. 2) with moderate sorting but poor rounding, suggesting that some reworking of pre-Cainozoic sediments has taken place. This is supported by the occurrence in the same sediments of well rounded and poorly rounded grains (Pl. 45, fig. 1).

Variation in roundness and sphericity was determined for the sand-size terrigenous fraction. This showed that the shallow marine and open intertidal (sand facies) sediments have a significantly higher degree of rounding and sphericity than the mangrove swamp, mangrove inlet, and supratidal flat sediments. This is particularly apparent in the supratidal flat environment, where the sand fraction is unsorted and com monly contains many euhedral grains, including some double terminated quartz crystals. The regional variation in roundness and sphericity estimated using the Zingg Scale is illustrated in Figures 68 and 69. Degree of rounding shows a complex pattern although the less rounded grains are found mainly in the upper reaches of the estuaries (Fig. 68). Sphericity similarly increases seawards (Fig. 69). Therefore both these parameters are consistent with most of the terrigenous fraction having a fluvial source. This is supported by the distribution of quartz types in Broad Sound. Figure 70 shows that the less stable forms of quartz (composite quartz, metaquartzite, and chert) are more abundant in the upper parts of the estuaries. As the less stable forms probably become more abundant towards their source the implication is that much of the detrital quartz in Broad Sound has a local fluvial source. However, a source of common quartz moving landward from the shelf and progressively diluting the less mature present-day fluvial material is also possible.

MINERALOGY

Most of the Broad Sound mineralogical studies were undertaken by X-ray diffraction techniques. A Philips PW 10 diffractometer fitted with a spinning stage was used. A nickel filter and copper Kα radiation were employed, with settings of 40 kv and 24 MA and a slit width of ¼°. Samples were scanned initially at 1° per minute over the range 2° to 65°2θ, and then, from 2° to 32°2θ at a goniometer speed of ¼° per minute. At the slower speed, fluorite was used as an internal standard to correct peak positions.

The abundance of magnesium was determined using the peak position-magnesium substitution relation of Goldsmith & Graf (1958). A relative quantitative mineralogical determination was made using peak areas. Peak areas were determined by means of an MK electronic area calculator for the principal peaks of aragonite, low-magnesium calcite, high-magnesium calcite, dolomite, potassic feldspar, calcic feldspar, and quartz (Fig. 71). In the case of quartz, some difficulty was experienced in measuring the main 101 peak at 26.65°2θ because the amplitude of the peak was too great. Consequently it was necessary to measure the area of the subsidiary 100 quartz peak at 20.80°2θ, and then multiply this value by 2.322 to convert it to the area of the 101 peak. Apart from this, loadings were not applied to any of the peak areas. Although a number of authors have suggest that loadings are necessary to obtain absolute values, it was considered that only the relative values are important in the Broad Sound work.

Special techniques used for clay mineralogy are discussed later.

Carbonate mineralogy

Aragonite, calcite (both high-magnesium and low-magnesium forms), and dolomite are the only important carbonate minerals in the Broad Sound sediments. In the marine environment, carbonate mineralogy depends primarily on the biotic forms supplying the carbonate. Consequently,as the biota varies from one environment to the next and also within the same environment, it is reasonable to expect carbonate mineralogy to do the same. The Broad Sound environments may be regarded as three-component systems comprising low-magnesium calcite, high-magnesium calcite and aragonite. Dolomite is found only in the supratidal flats. It is apparent

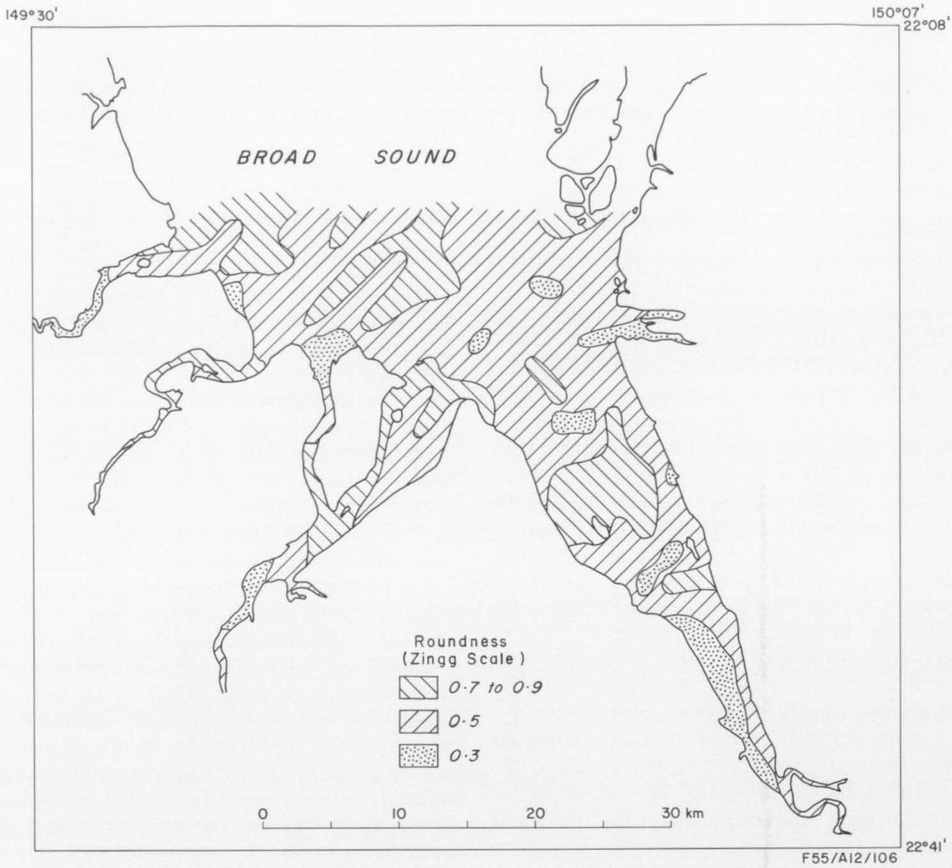


Figure 68. Degree of rounding of terrigenous sand grains in Broad Sound sediments.

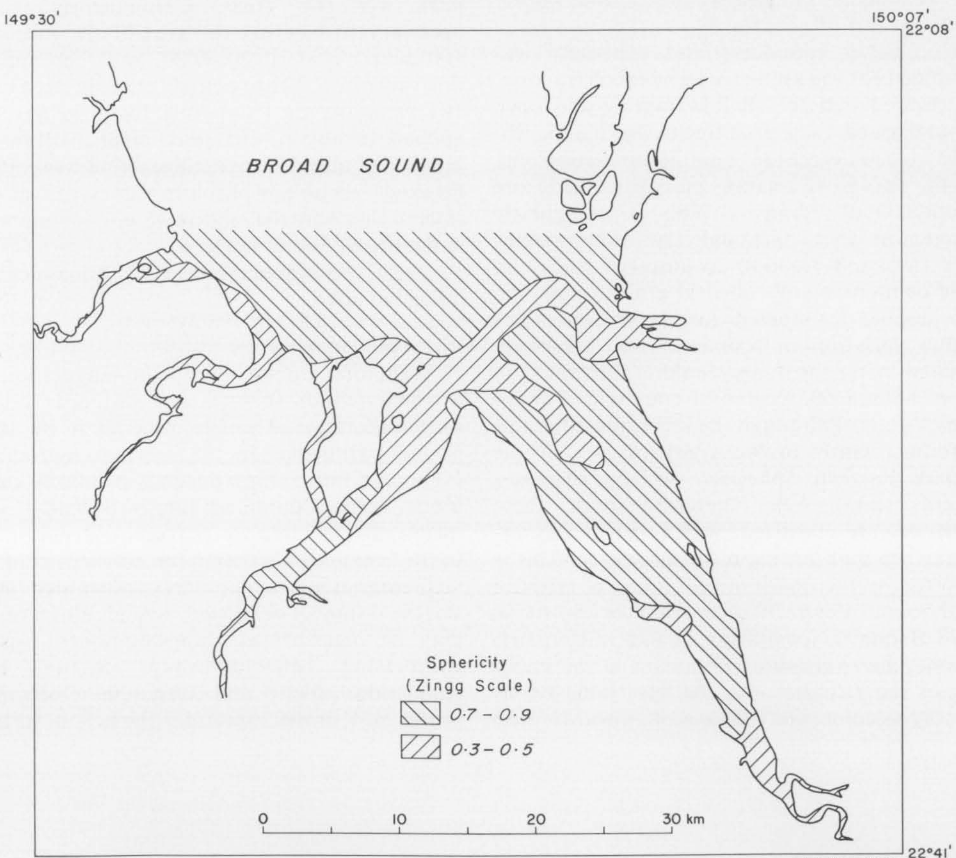


Figure 69

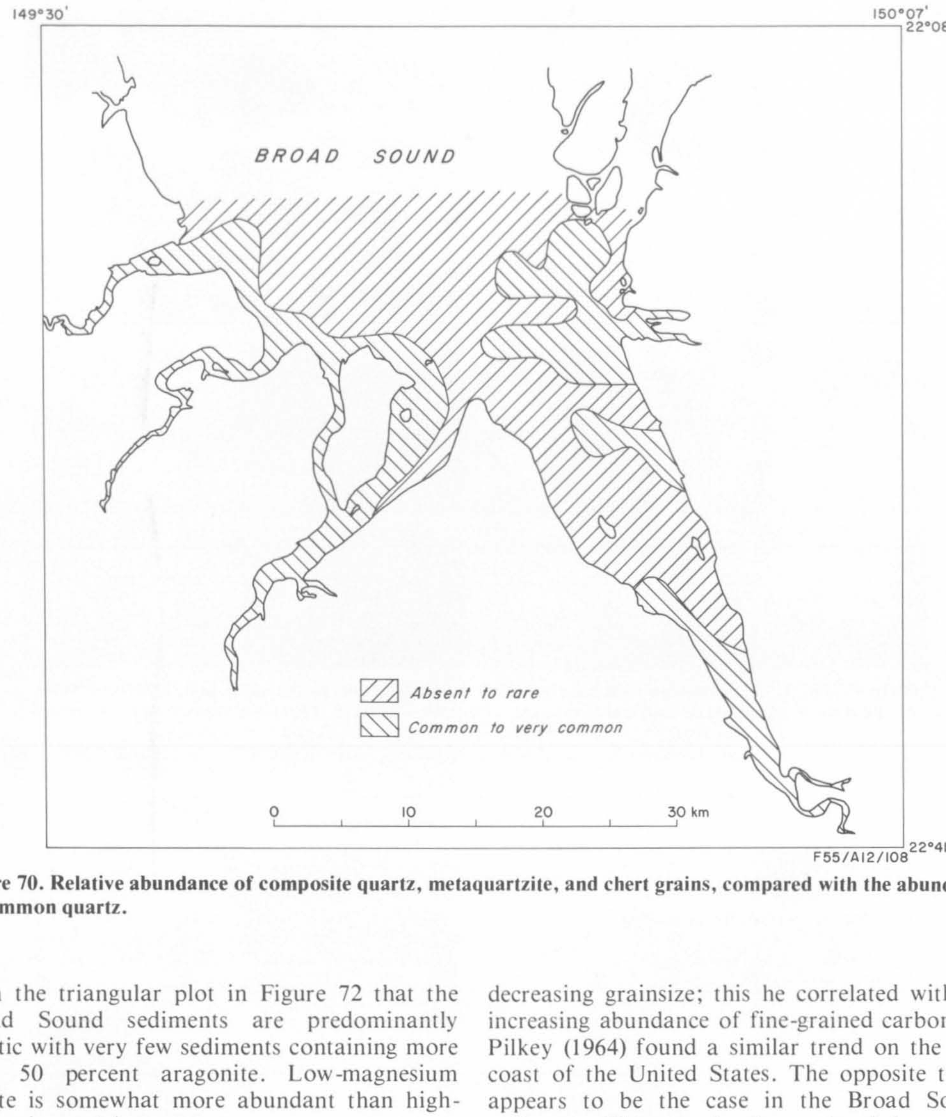


Figure 70. Relative abundance of composite quartz, metaquartzite, and chert grains, compared with the abundance of common quartz.

from the triangular plot in Figure 72 that the Broad Sound sediments are predominantly calcitic with very few sediments containing more than 50 percent aragonite. Low-magnesium calcite is somewhat more abundant than high-magnesium calcite.

Aragonite. In general the Broad Sound sediments are low in aragonite (Fig. 73). This is consistent with the regional pattern already determined by Maxwell (1968) of low aragonite values in the nearshore zone, in marked contrast to the high aragonite values in sediments of the reefal zone. Maxwell found that the main source of aragonite was coral, halimeda, and molluscs.

The overall trend in relative abundance of aragonite (Fig. 73) is a seaward decrease, whereas there is a regional pattern of increasing seaward abundance as the reef is approached. However, Broad Sound is too far from the reef for this regional pattern to assert itself.

Chave (1962) reported a decrease in aragonite in the Bahamas and Campeche Bank areas with decreasing grainsize; this he correlated with an increasing abundance of fine-grained carbonate. Pilkey (1964) found a similar trend on the east coast of the United States. The opposite trend appears to be the case in the Broad Sound sediments. This may be the result of decreasing seaward abundance of molluscs, but the more probable reason is that it is a reflection of relict pre-Holocene sediments in the subtidal zone. As a result of subaerial weathering, extensive recrystallization of aragonite to calcite is likely to have taken place.

Calcite. Calcite contains varying amounts of magnesium, which substitutes for calcium in the lattice. There is thought to be a gap in the solid solution series at about $Ca_{0.90}Mg_{0.10}CO_3$; consequently the boundary between low-magnesium and high-magnesium calcite is usually taken at this point. As the position of the 104 peak is proportional to the amount of magnesium in the lattice, the molar proportion could be determined from the X-ray diffraction pattern. In the Broad

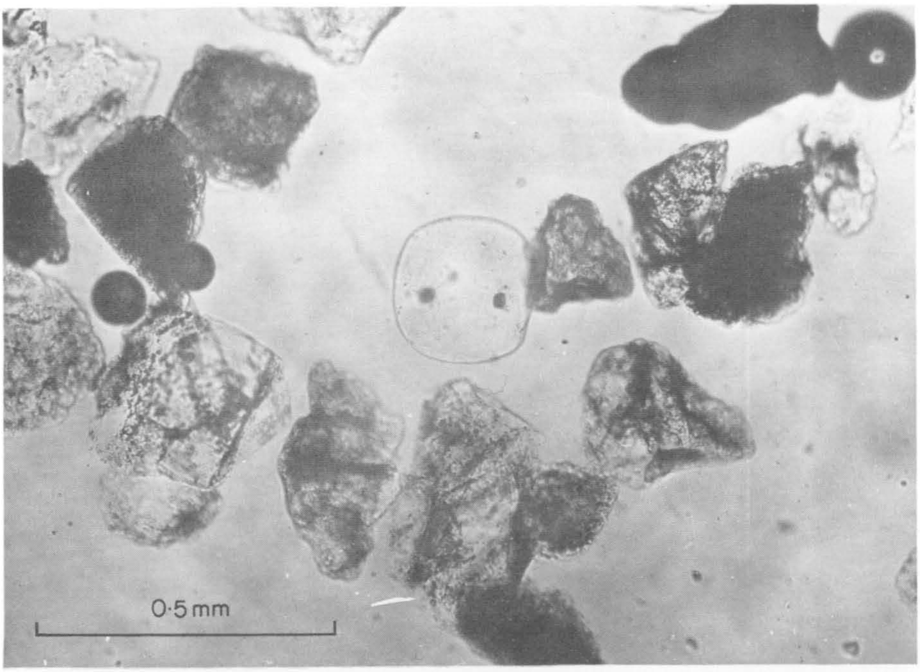


Plate 45, fig. 1. Well rounded and poorly rounded quartz grains in the same light fraction. Some of the darker grains have iron oxide coatings. Sample 70636270, from the central part of Broad Sound. (M/1366)

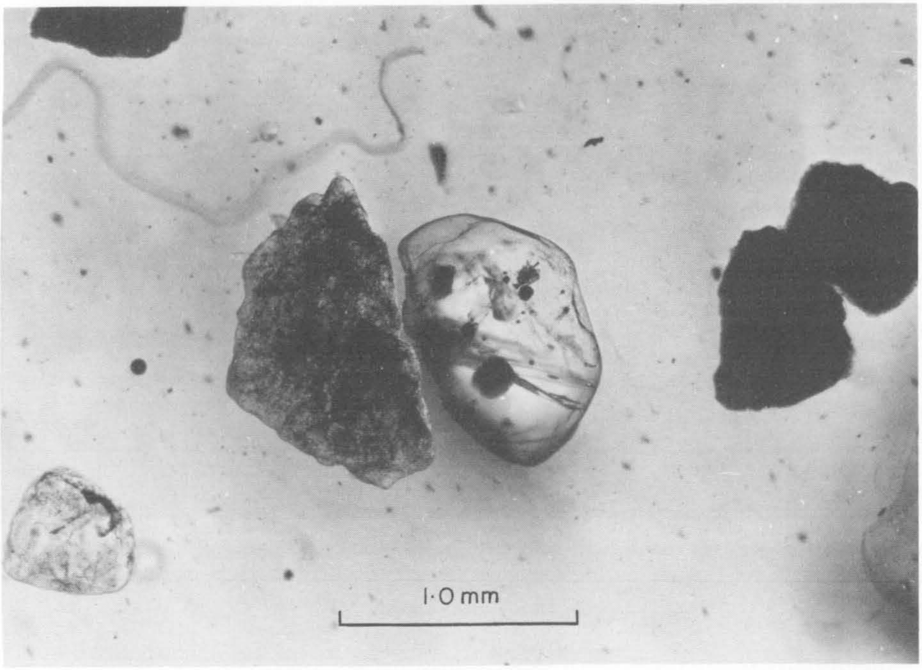


Plate 45, fig. 2. Clear volcanic quartz in shallow marine sediments. Sample 70636217, 2 km north of Turtle Island. (M/1366/27)

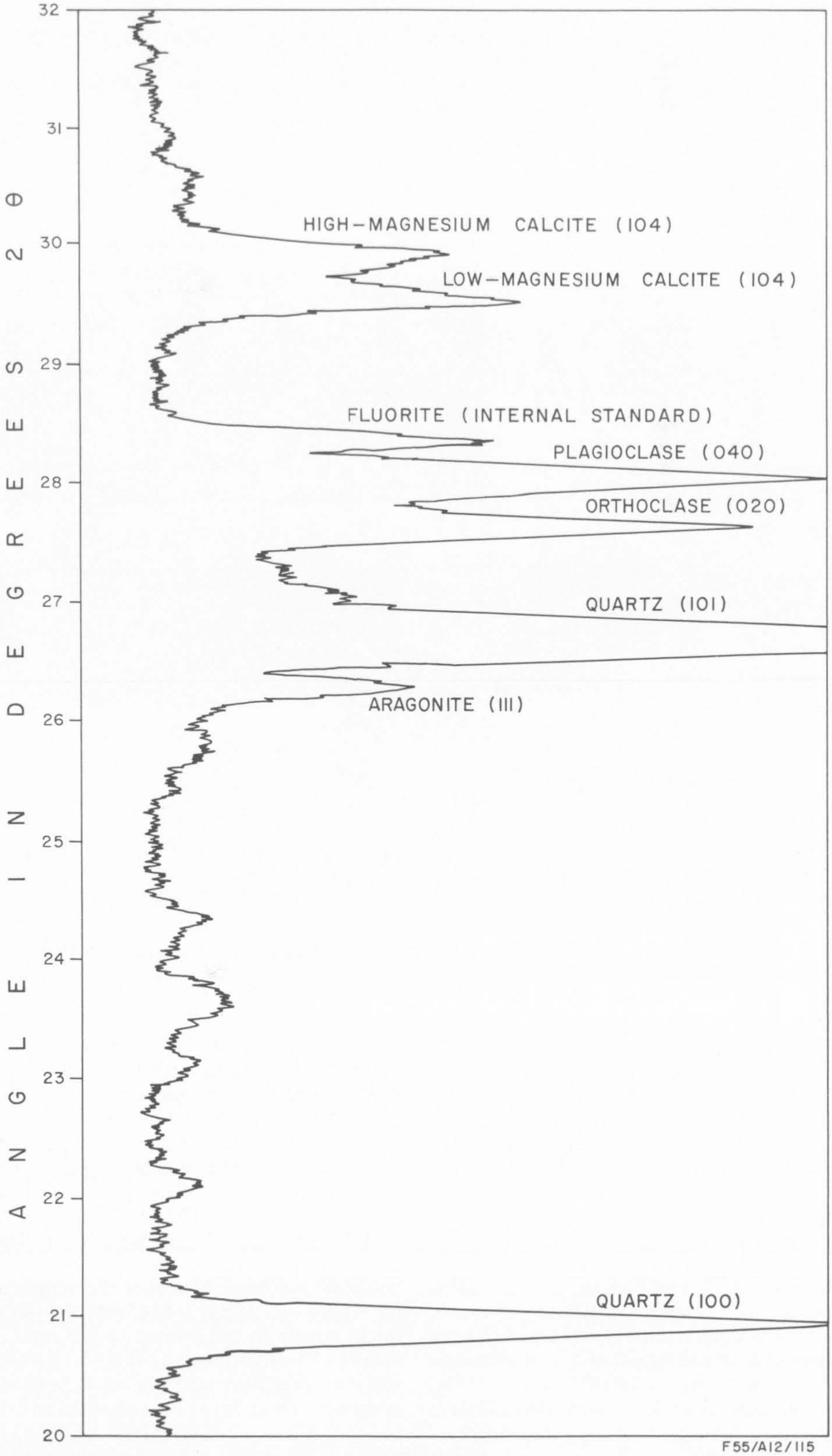


Figure 71. Typical X-ray diffraction chart (sample 70636282) showing the principal peaks used for semi-quantitative mineralogical analysis.

K

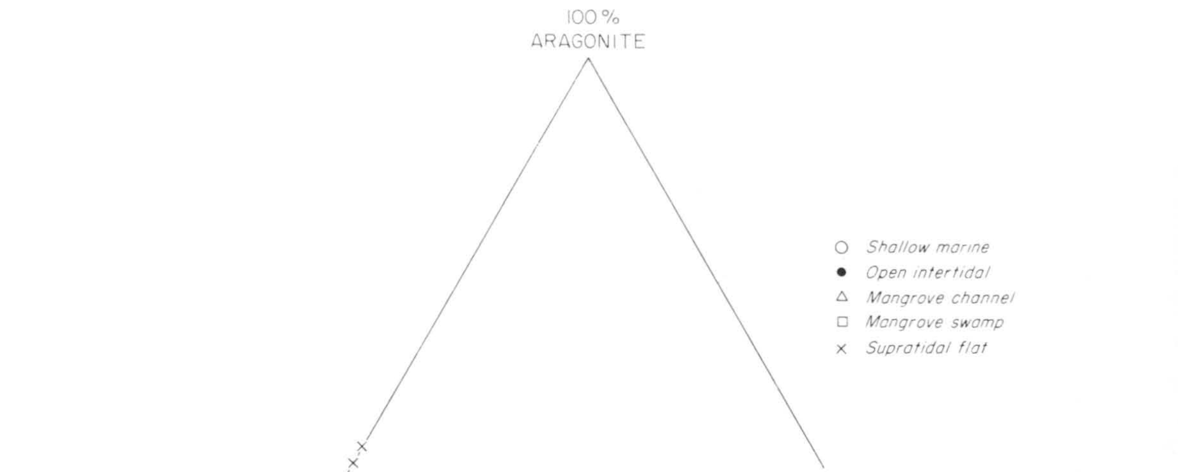


Figure 72. Ternary plot showing the variation in carbonate mineralogy with the depositional environments.

Sound sediments the average formula for high-magnesium calcite is approximately $Ca_{0.850}Mg_{0.150}CO_3$, and $Ca_{0.965}Mg_{0.035}CO_3$ for low-magnesium calcite. Differences in molar proporations between the various environments are small (Table 6) and are not considered significant.

The differences in relative abundance of high-magnesium and low-magnesium calcite in the various environments are fairly marked. It is evident from Figure 72 that high-magnesium calcite is abundant in the open intertidal sediments, somewhat less abundant in the supratidal flat and mangrove swamp sediments, and least abundant in the shallow-marine sediments. Siesser (1971) pointed out that 'since high-magnesian calcite is the least stable carbonate mineral, it should be the first, if not the only, mineral in an unconsolidated sediment mass to show evidence that diagenetic alteration has occurred'. Thus the relative abundance of high-magnesium calcite in the open intertidal sediments suggests that they have undergone less diagenesis than those of other environments. The fact that the intertidal environment appears to have undergone less diagenesis than the supratidal environment suggests that the degree of subaerial exposure may be an important factor. The subtidal sediments might appear to run counter to this trend, but it should be remembered that most subtidal sediments are believed to be relict pre-Holocene sediments which have been subjected to extensive

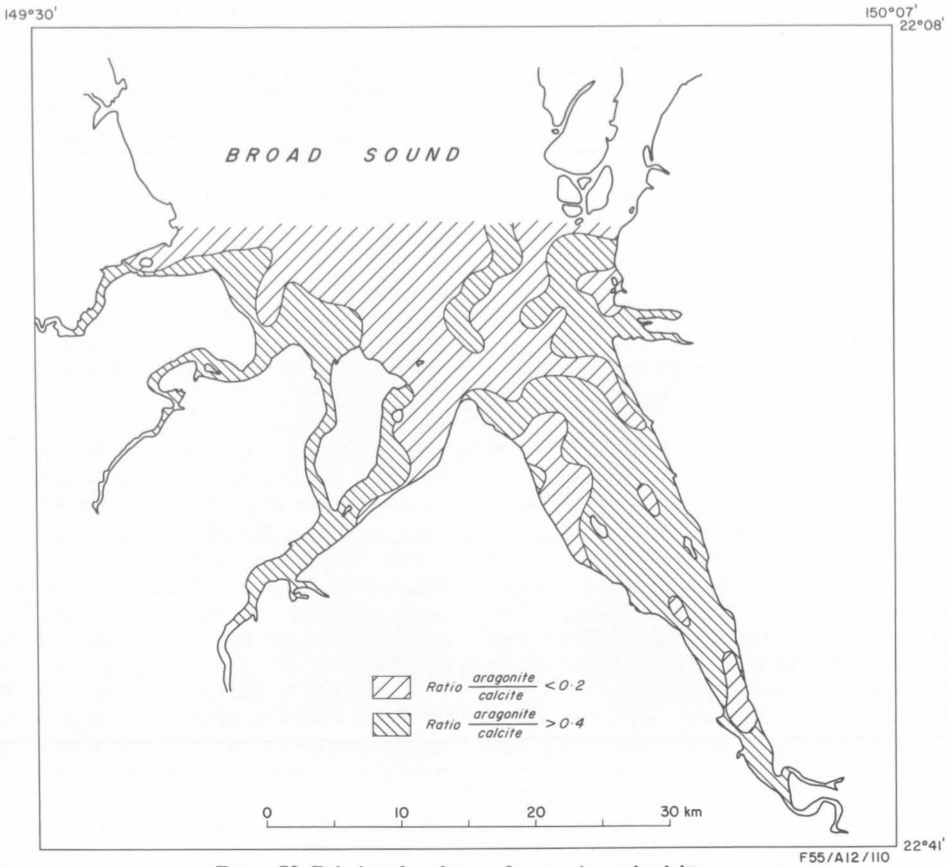


Figure 73. Relative abundance of aragonite and calcite.

pre-Holocene and early Holocene subaerial weathering. Siesser also found on the South African continental shelf that there was removal of high-magnesium calcite as a result of subaerial exposure of the continental shelf sediments during Pleistocene low sea-level stands. This same feature is illustrated by Figure 74, which shows a seaward increase in the relative abundance of low-magnesium calcite. Maxwell (1968, p. 223) stated that 'low-magnesium calcite may be a useful indicator of the relative contributions of detritus from dead reef and living reef, since the ratio of low-magnesium calcite to the lithothamnoid-foraminiferal content is greater for material derived from old reef surfaces where subaerial weathering results in the conversion of the originally high-magnesium calcite of the organisms to the low-magnesium form'. It is possible that some of the differences in Broad Sound result from faunal changes, but the relativity would not be between old reefal and modern reefal material but between old partly reefal material and modern non-reefal material. Again, this is probably the result of subaerial exposure and the preferential replacement of metastable high-magnesium calcite.

Dolomite. Dolomite is found only in the supratidal flat sediments. The supratidal flats contain on average only 4.3 percent $CaCO_3$, which is made up of approximately equal quantities of aragonite, low-magnesium calcite, and high-magnesium calcite. In addition, trace amounts of dolomite were detected by X-ray diffraction in a number of samples. It was only in the muds of the Charon Point area that the dolomite phase could be isolated. There, it exists as nodules and concretions (see earlier). Detailed X-ray diffraction (Cook, 1973) showed that these nodules are formed of low-magnesium calcite and calcian (or magnesium-deficient) dolomite ranging in composition from $Ca_{0.65}Mg_{0.35}CO_3$ to $Ca_{0.59}Mg_{0.41}CO_3$. Both aragonite and high-magnesium calcite are absent. The X-ray diffraction pattern for the dolomite ranged from a low diffuse hump to a sharp, well defined peak, but no ordered peaks (100,221,111) were evident.

TABLE 6. MOLAR PROPORTION OF MAGNESIUM IN CALCITE IN SEDIMENTS OF THE BROAD SOUND ENVIRONMENTS

Environment	*Molar percentage of Mg*	
	High-Mg calcite	*Low-Mg calcite*
Supratidal flat	16.0	3.0
Mangrove swamp	15.1	2.6
Mangrove channel	15.0	3.7
Open intertidal	15.2	3.7
Shallow marine	15.8	3.9

Radiocarbon dating (Cook & Polach, 1973b) showed that the dolomite is about 3000 years old.

There are several significant features of the Broad Sound dolomite: its nodular and concretionary form is unlike any previously described from Holocene sediments, although comparable dolomitic features have been described from Devonian sediments by Read (1973), and Wright et al. (1972) found similar calcitic concretions around mangrove roots in the Ord River region. Secondly, all other known occurrences of Holocene dolomite have been described from calcareous sequences such as those of the Caribbean (Deffeyes, Lucia, & Weyl, 1965) or the Persian Gulf (Illings, Wells, & Taylor, 1965; Kinsman, 1969), whereas the Broad Sound dolomites are from essentially terrigenous sediments with a low carbonate content. Finally the dolomite mineralogy is somewhat unusual in that the Goldsmith & Graf (1958) relationship indicates a dolomite composition (molecular ratio of Mg ranging from 0.35 to 0.41) which falls within the range of the inferred 'miscibility gap' thought to exist between dolomite and high-magnesium calcite (Schroeder, Dwornik, & Papike, 1969).

TERRIGENOUS COMPONENT MINERALOGY

Only the more abundant terrigenous components could be quantitatively determined by X-ray diffraction. Clay minerals were separated and analysed separately. Of the light minerals, only feldspar and quartz were present in sufficient abundance to enable semi-quantitative analysis by X-ray diffraction. It was necessary to separate heavy minerals with bromoform, and use optical methods of identification. The three groups: light minerals, heavy minerals, and clay minerals will be dealt with separately.

Light minerals

Quartz is the most abundant light mineral of the terrigenous fraction, comprising 70 to 100 percent of the light fraction (excluding clay minerals) in most Broad Sound sediments. The ratio of quartz to total feldspar (Q/F ratio) has been used as a maturity index for sands by a number of workers including Russell (1937) and Hsu (1960). They found that the relative abundance of quartz increases with distance from the source owing to the less resistant nature of feldspar.

Most Broad Sound sediments have a Q/F ratio of about 4 which corresponds to the 'average' sandstone of Pettijohn (1957). The light fraction mineralogy is similar for all the depositional environments (Fig. 75), but the mangrove channel, mangrove swamp, and supratidal flat sediments are somewhat more feldspathic than the shallow marine and open intertidal sediments. Throughout Broad Sound, quartz becomes more abundant seawards, although there is no clear trend (Fig. 76). However, if the four estuaries are considered individually the Herbert, Styx, and St Lawrence estuaries have significantly more feldspathic sediments in their upper reaches than in the lower reaches. No such trend is apparent in Waverley Creek but data there are sparse. A prominent 'plume' of feldspathic sediment is apparent at the mouth of Wadallah Creek. A further feature evident from Figure 76 is that the areas of relict sediments in the shallow marine environment are relatively low in feldspar. Thus, the Q/F maturity index suggests that there is an overall trend of increasing maturity seawards, and also that the pre-Holocene sediments are more mature than the Holocene sediments. This pattern becomes obscured in the northern part of Herbert Creek where there is a large area with a high maturity index.

The ratio of potassic to calcic feldspar may similarly be used as a maturity index (Fig. 77), but trends are less defined than those using the Q/F index. The region of high-maturity sediments at the northern part of Herbert Creek

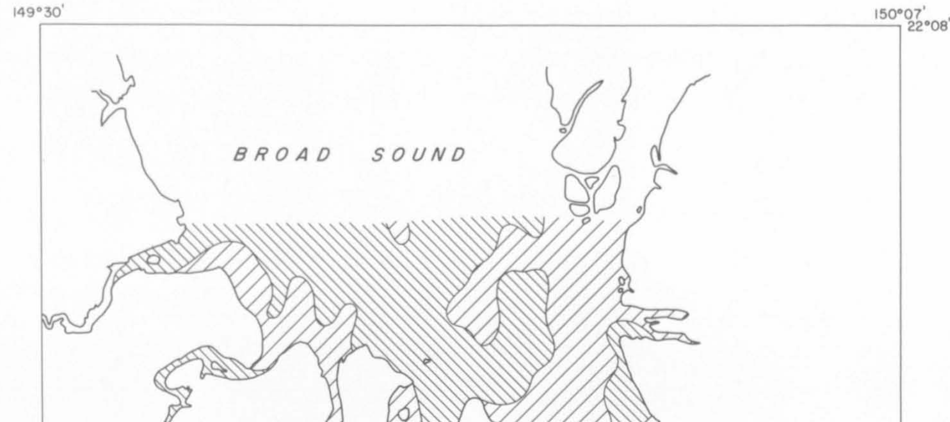


Figure 74. Relative abundance of high-magnesium and low-magnesium calcite.

is again delineated in Figure 77 and there is a poorly defined trend of increasing feldspar maturity seawards. There is, however, no high feldspar maturity in the pre-Holocene relict sediments.

If the mineral stability series proposed by Goldich (1938) is accepted, then using both K-feldspar and Ca-feldspar and Q/F maturity indices, there appears to be increasing maturity seawards and perhaps also a trend of increasing maturity with increasing age. The first feature could perhaps be taken to indicate that as grains are subjected to chemical weathering during transport, the less stable grains are progressively removed. The distance involved would appear to be too small (a maximum of 30 km) for such marked changes in maturity to take place; although the actual distance travelled is much greater owing to tidal oscillations. The possibility of a sorting effect whereby feldspar becomes concentrated in the fine fraction may be discounted because the X-ray analyses were undertaken on the whole sediment and not on the sand fraction, and also because of the lack of a correlation between grainsize and the quartz and feldspar maturity indices. In addition, it is uncertain what affect provenance has on the maturity index. A high percentage of the Waverley Creek catchment is made up of sandstones of the Styx Basin. This appears to be reflected in the fact that the Waverley sediments are more mature than sediments in some of the other estuaries. The occurrence of well rounded and poorly rounded quartz grains in the light fraction of the same sediment (Pl. 45, fig. 1) suggests that some quartz grains are reworked. Similarly, the more feldspathic nature of the Wadallah Creek sediments may be a reflection of the granitic nature of part of the catchment, whereas the mature sediments at the northern end of Herbert Creek (Fig. 77) are possibly the result of the adjacent strongly lateritized metasediments.

It is apparent from Figures 76 and 77 that some immature sediments with a fluvial source are

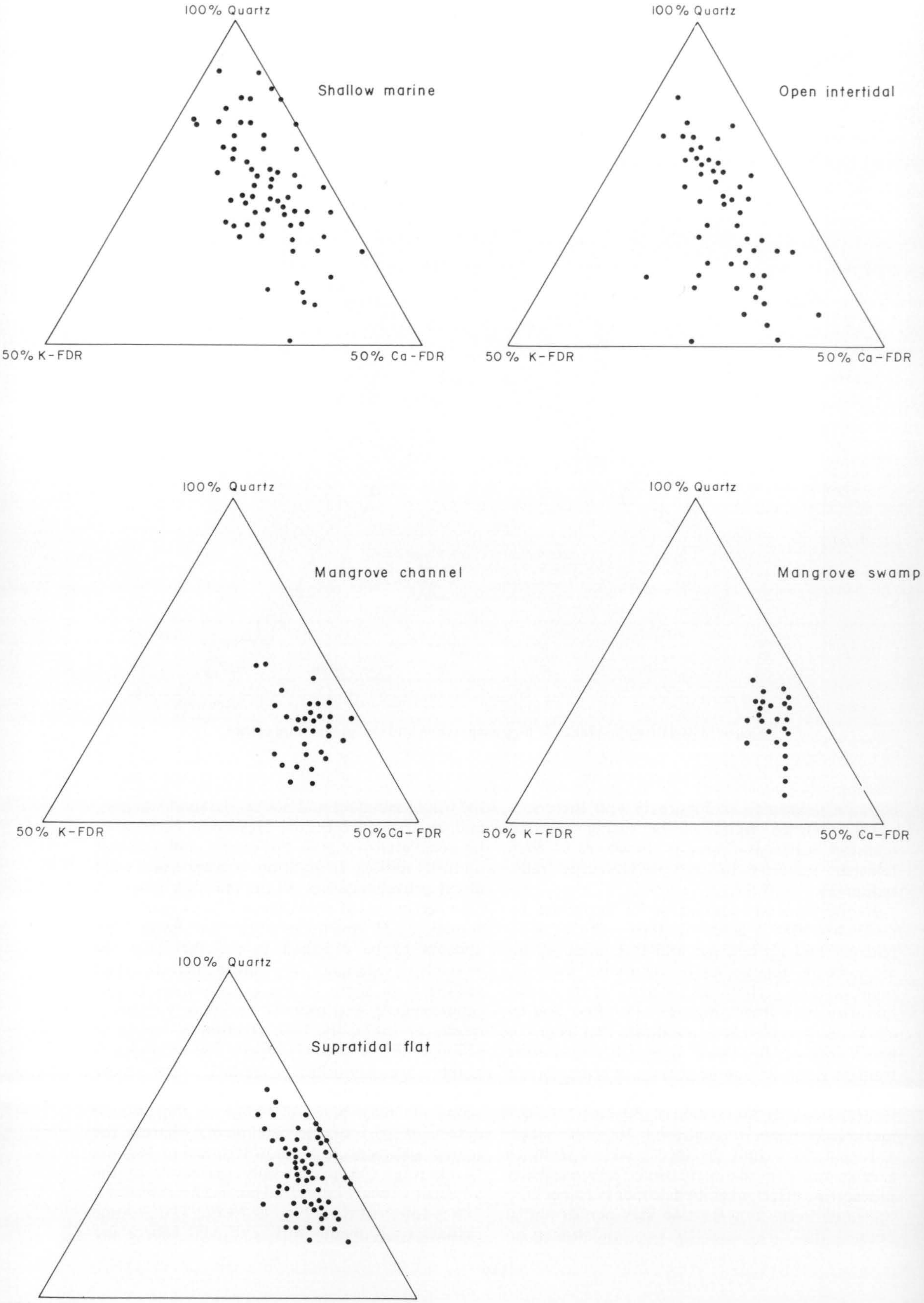


Figure 75. Ternary plots for the light-mineral fraction in the various depositional environements.

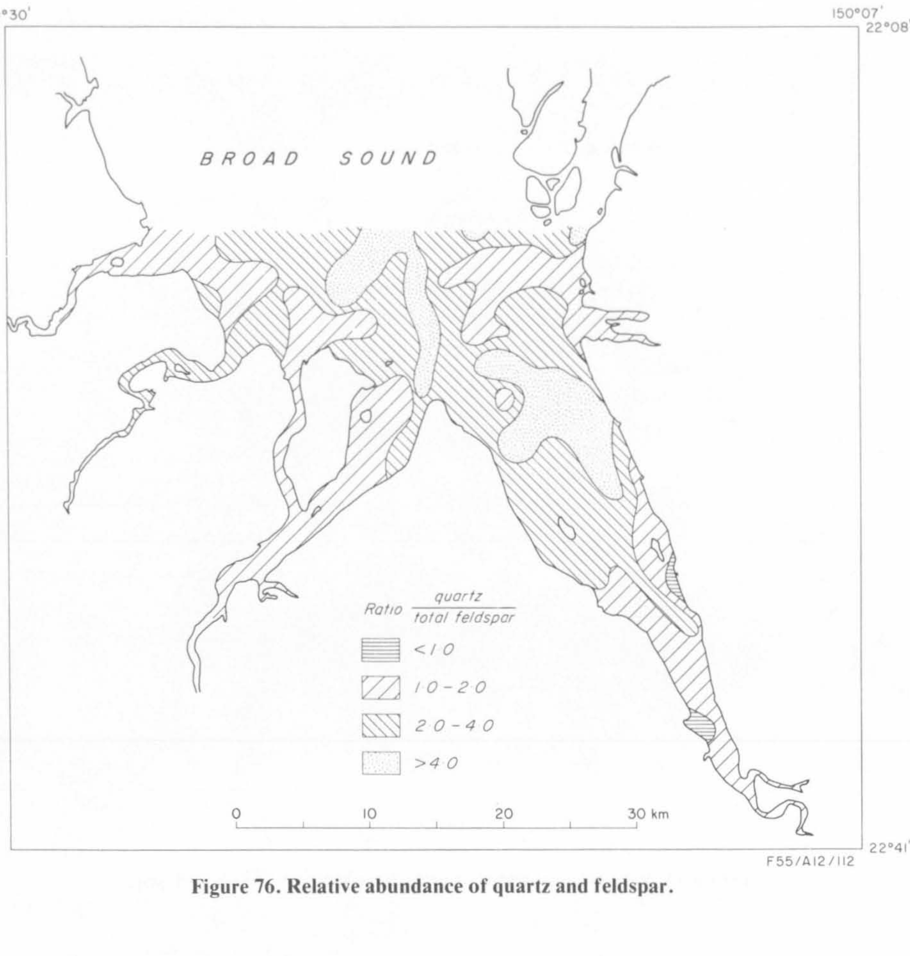


Figure 76. Relative abundance of quartz and feldspar.

entering the Broad Sound estuarine complex. It is possible that the increasing seaward maturity is more the result of dilution of seaward-moving immature sediments by landward-moving mature sediments, rather than the result of chemical weathering and removal of less stable sedimentary components. As much of the sediment derived from the shelf is probably relict, this picture would be consistent with the more mature nature of the pre-Holocene sediments. It is uncertain whether the maturity of these sediments is due to post-depositional diagenesis or to a different provenance. The abundance of subeuhedral grains of volcanic quartz (Pl. 45, fig. 2) in the pre-Holocene sediments compared to the Holocene sediments suggests that the provenance may have been somewhat different, but diagenesis is also likely to have significantly modified the Q/F maturity index as a result of weathering of less stable feldspar.

It is difficult to determine the relative abundance of the terrigenous continental shelf contribution compared with the terrigenous fluvial contribution: The sediments may undergo rapid maturation; alternatively the configuration of the maturity indices may indicate that the fluvial source of quartz and feldspar is important up to the estuarine mouth in the case of the Styx River, and for up to 2 or 3 km beyond the mouth in the case of the Waverley and St Lawrence Creeks. Similarly in Herbert Creek the large area of mature sediments in the northern half of the estuary may be taken as evidence that fluvial influences do not extend out of the southern half.

Conversely, fluvial outflow from Wadallah Creek extends for about 5 km out to sea. However, in the more seaward parts of the open Sound the evidence from the distribution of quartz and feldspar shelf suggests that the fluvial input is probably subordinate to the continental input of relict terrigenous sediment.

Heavy minerals

Heavy-mineral grain mounts were prepared by

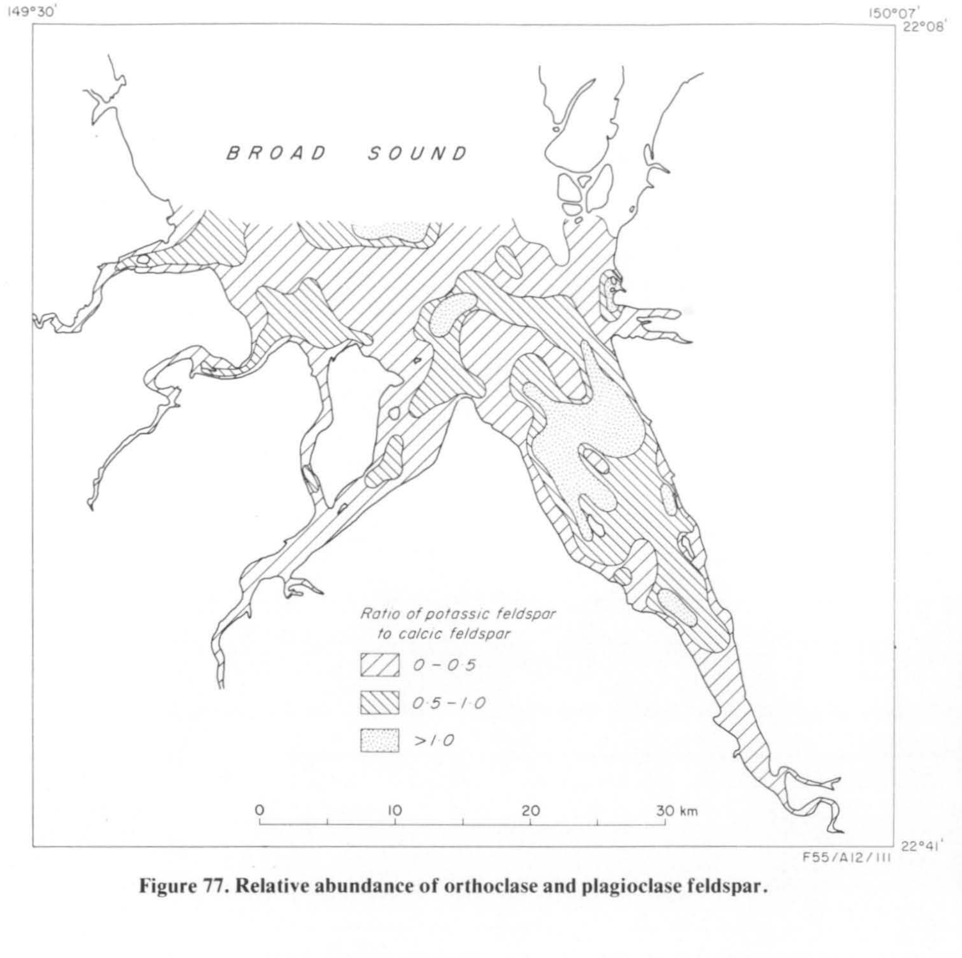


Figure 77. Relative abundance of orthoclase and plagioclase feldspar.

wet-sieving about 25 g of the original sediment to remove the mud fraction, and the calcareous component of the sand fraction was then removed with dilute hydrochloric acid.

Heavy minerals were separated using bromoform, and the heavy-mineral residue mounted onto a glass slide. Grain counts of about 200 grains per sample were then made on 195 samples. Most samples were shallow marine and open intertidal sediments; the muddier sediments of the mangrove swamp and supratidal flat environments seldom contained sufficient heavy-mineral grains to count.

The distribution of heavy minerals illustrated in Figure 78 shows that few samples contain more than one percent heavy minerals.

The apparent importance of Wellington Creek (the main tributary on the east side of the Styx River) as a contributor of heavy minerals is marked by the 'plume' of sediments comparatively rich in heavy minerals. Elsewhere the rivers appear to be making little contribution of heavy minerals. Herbert Creek sediments in particular contain a low percentage of heavy minerals.

If the heavy minerals are considered as a percentage of the non-carbonate fraction, the same basic trends may be discerned but the pattern becomes somewhat modified (Fig. 79). The greatest concentration of heavy minerals is in the Styx River system, with a contribution from this source possibly extending south into the mouth of Herbert Creek and north towards Long Island.

Some of the catchment of the Styx River is located in Lower Palaeozoic ultrabasic rocks, which may explain the abundance of heavy minerals. However, much of the Herbert Creek catchment is composed of lateritized Pyri Pyri Granite and consequently heavy minerals are sparse in its upper reaches.

The heavy-mineral assemblage is composed of approximately equal proportions of opaque and non-opaque minerals. The mineralogy of the opaque mineral assemblage was not determined.

Figure 78. Percentage of heavy minerals in Broad Sound sediments.

The ratio of opaque to non-opaque grains may give an approximate measure of the maturity of the assemblage. The percentage of opaque grains in the various environments is given in Table 7, the greatest abundance being in the supratidal and subtidal zones. In the supratidal zone, subaerial weathering processes predominate and it is possible that many opaque grains are iron oxides or grains coated with iron oxides. Similarly, much of the sediment in the shallow marine environment was subjected to subaerial weathering during the Pleistocene and iron oxide coatings are common. Thus the abundance of opaques is considered to be the consequence of subaerial weathering.

The non-opaque assemblage consists of varying proportions of 'stable' minerals such as zircon, tourmaline, and rutile and 'unstable' minerals such as epidote, zoisite, amphiboles, pyroxenes, and garnets. In general, unstable minerals are common, and the Broad Sound heavy-mineral suite is immature. The relative abundance of the stable and unstable minerals (commonly referred to as the ZTR index) is illustrated in Figure 80, from which it is apparent that the assemblage becomes more mature seawards. Figure 81 also indicates that the sediments of the shallow marine environment have a more mature assemblage than the adjacent open intertidal environment.

The most common minerals of the unstable assemblage are epidote, pyroxenes, amphiboles, and minor garnet. There appears to be little variation in the unstable assemblage for the various environments (Fig. 82) except for the suggestion of a greater relative abundance of amphiboles in the sediments of the supratidal flats although the heavy-mineral data are sparse for this environment.

The seaward increase in stability of the heavy-mineral assemblage is accompanied by a decrease in total heavy-mineral content. This trend cannot be reasonably ascribed to simple hydraulic sorting as in a unidirectional fluvial system, as

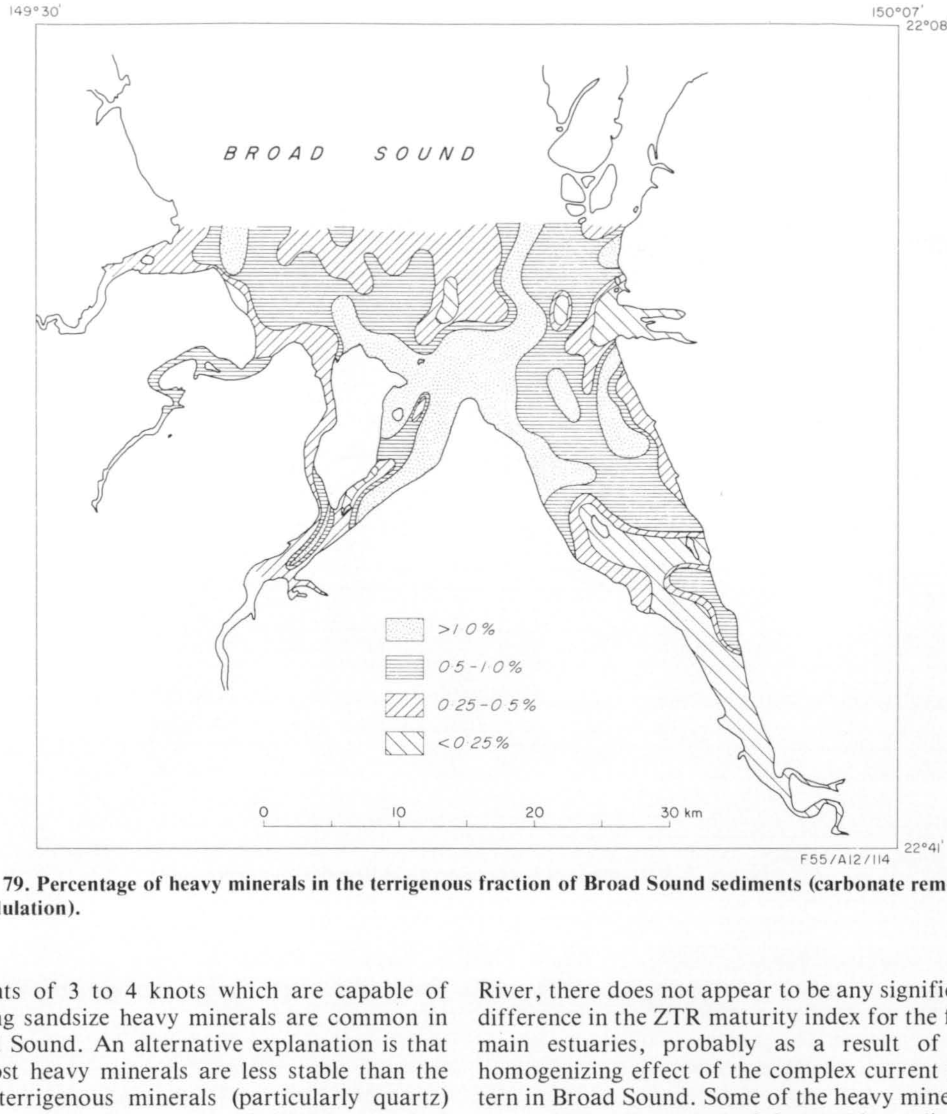


Figure 79. Percentage of heavy minerals in the terrigenous fraction of Broad Sound sediments (carbonate removed by acidulation).

currents of 3 to 4 knots which are capable of moving sandsize heavy minerals are common in Broad Sound. An alternative explanation is that as most heavy minerals are less stable than the light terrigenous minerals (particularly quartz) they are progressively removed either by chemical action or by abrasion. This mechanism could be used to explain the seaward increase in the ZTR index (Fig. 80). Undoubtedly this process occurs in Broad Sound to some extent; unstable grains such as hypersthene have corroded boundaries (Pl. 46), whereas stable grains such as zircon are commonly euhedral. This process is likely to result in a greater abundance of unstable heavy minerals in the mud fraction but this cannot be confirmed as only the sand fraction was separated.

Provenance of the present and relict sediments is also important to the heavy-mineral suite. Although the granitic Herbert Creek catchment contributes fewer heavy minerals than the volcanic (and ultrabasic) catchment of the Styx River, there does not appear to be any significant difference in the ZTR maturity index for the four main estuaries, probably as a result of the homogenizing effect of the complex current pattern in Broad Sound. Some of the heavy minerals are undoubtedly reworked from older sedimentary sequences, as exemplified by well rounded zircon grains. Other euhedral grains are clearly primary grains derived from nearby igneous or metamorphic rocks.

The sediments of the shallow marine environment of the subtidal zone are believed to be mainly relict pre-Holocene sediments. They have the most mature heavy-mineral assemblage, possibly the result of extensive (mainly pre-Holocene) subaerial weathering. Subaerial weathering is known to remove the less stable heavy minerals in a comparatively short time (Walker, 1967). Thus, in some circumstances weathering alone may produce a mature mineral assemblage. Whether the amount of time available for subaerial weathering was sufficient

TABLE 7. PERCENTAGE OF OPAQUE AND NON-OPAQUE GRAINS IN THE HEAVY-MINERAL FRACTION

Environment	*% Opaques*	*% Non-Opaques*
Shallow marine	53.2	46.8
Open intertidal	44.9	55.1
Mangrove channel	43.7	56.3
Mangrove swamp	49.0	51.0
Supratidal flat	56.9	43.1

to account here for the mature assemblage is uncertain. It is also possible that the pre-Holocene sediments had a different provenance to the Holocene sediments; Maxwell (1968) suggested that the Pleistocene Fitzroy River entered the ocean via Broad Sound, although we found no evidence for this. Despite the uncertain genesis of the pre-Holocene mineral assemblage, there is no doubt that the pre-Holocene sediments have a more mature heavy-mineral assemblage than the Holocene sediments.

From the short distance travelled by the grains, and the brief time interval involved, it seems that the seaward increase in maturity cannot be due solely to chemical action and mechanical abrasion; some of it must result from the less stable seaward-moving fluvial assemblage progressively diluting the more stable marine

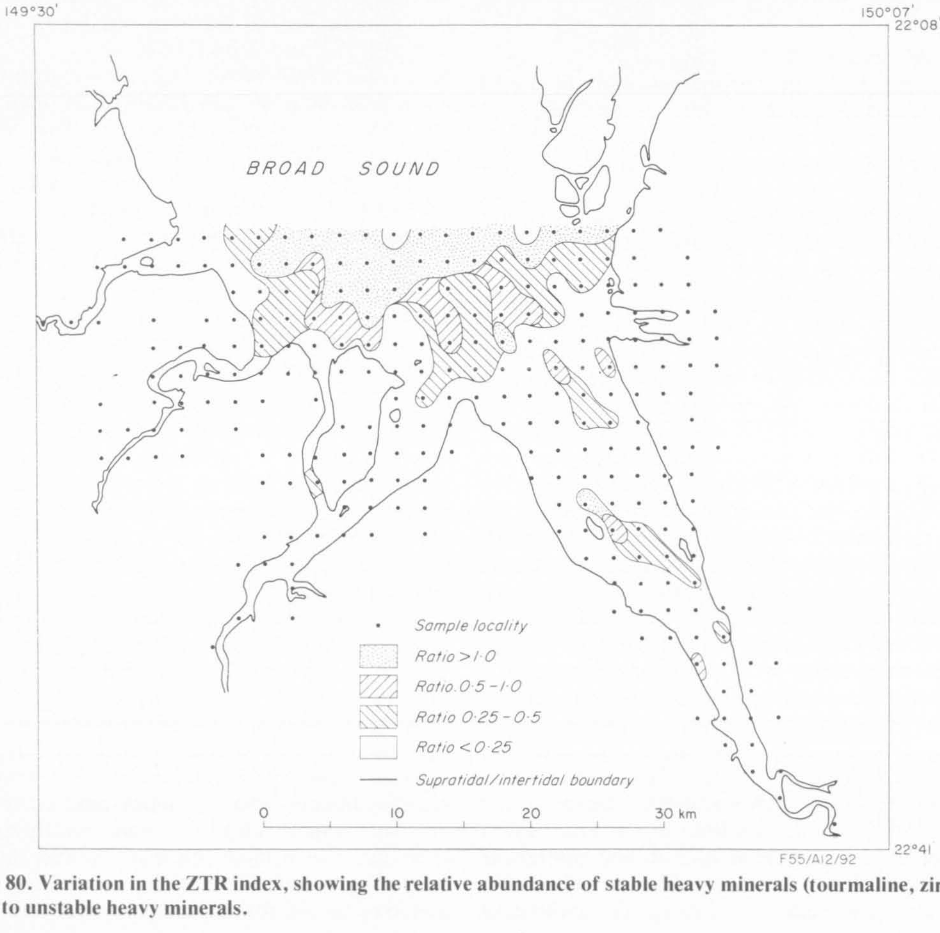


Figure 80. Variation in the ZTR index, showing the relative abundance of stable heavy minerals (tourmaline, zircon, rutile) to unstable heavy minerals.

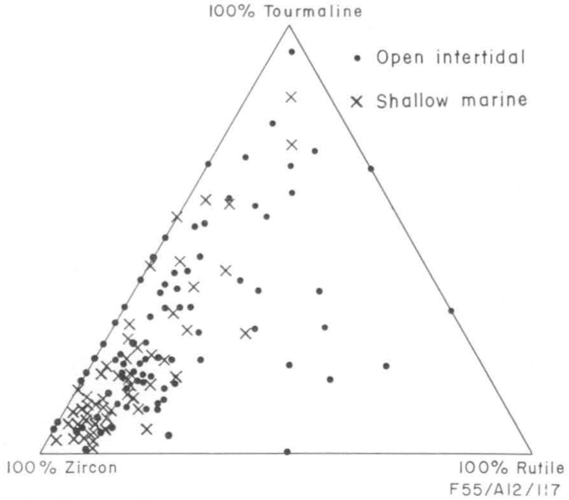


Figure 81. Variation in the stable heavy-mineral composition of Broad Sound sediments.

assemblage derived from relict pre-Holocene sediments.

Clay Minerals by D. L. Gibson

Samples from the localities shown in Figure 83 were selected for clay mineral analysis, and minus-two-micrometer fraction was separated by settling and decantation. A veneer of clay material was mounted on small ceramic tiles using a suction method similar to that of Kinter and Diamond (1955) to give maximum orientation of the clay particles.

X-ray diffractograms were made of the tile after each step:- it was (i) drying at room temperatures, (ii) placing in a glycol atmosphere at 60 °C for at least 24 hours, and (iii) heating at 300 °C for at least two hours.

Some tiles were also X-rayed after being heated at 600 °C for at least two hours. All heated tiles were X-rayed to 15 °2θ, the glycolated tiles to 15 ° to 30 °2θ, and the untreated tiles to 15 ° to 40 °2θ. The clay samples were not treated to remove organic matter, calcium carbonate, amorphous iron, etc., nor were they saturated with any ions (calcium, magnesium, etc.) in the laboratory.

Mineral identification. The clay mineral groups dealt with here were recognized by their characteristic basal spacings, corresponding to X-ray diffraction maxima, and the behaviour of these maxima after glycolation and heating. Nickel filtered copper Ka radiation with a stabilized power supply was used. Minerals of the kaolinite, illite, and montmorillonite groups and mixed-layer clays were identified, and quartz was detected in all samples X-rayed beyond 25 °20. No attempt was made to identify the individual mineral or minerals in each group. The identification scheme set out below is similar to that of Carrol (1970) and Grim (1968).

Kaolinite. Members of the kaolinite group have a basal spacing of 7 °A followed by a rational sequence of secondary diffractions. They are not affected by glycolation or heating to 300 °C.

Illite. Members of the illite group have a basal spacing of 10 °A followed by a rational sequence of secondary diffractions. They are not affected by glycolation or heating to 300 °C.

Montmorillonite. Clays which have a basal spacing of 12.4 °A to 15 °A when untreated, and 17 °A to 18 °A after glycolation, belong to the montmorillonite group. The basal spacing collapses to 10 °A after being heated at 300 °C.

Mixed-layer clays. In this study the only mixed-layer clays identified were irregularly interstratified montmorillonite-illite. These are identified by their basal spacing of 10 °A to 15 °A when untreated and 10 °A to 16 °A when glycolated. They collapse to 10 °A when heated at 300 °C.

Chlorite. Chlorite was identified only in soil samples from the Styx River catchment. The 14 °A basal spacing is unaffected by glycolation or heating at 600 °C, and the second-order diffraction at 7 °A is not affected at 300 °C.

Other minerals. Quartz was identified by a diffraction peak corresponding to a spacing of 4.26 °A. In many charts, a small peak corresponding to a spacing of 13.6 °A was encountered. A chart made of a blank tile also showed this diffraction maximum, and it was concluded that it was due to the material in the tile itself or a

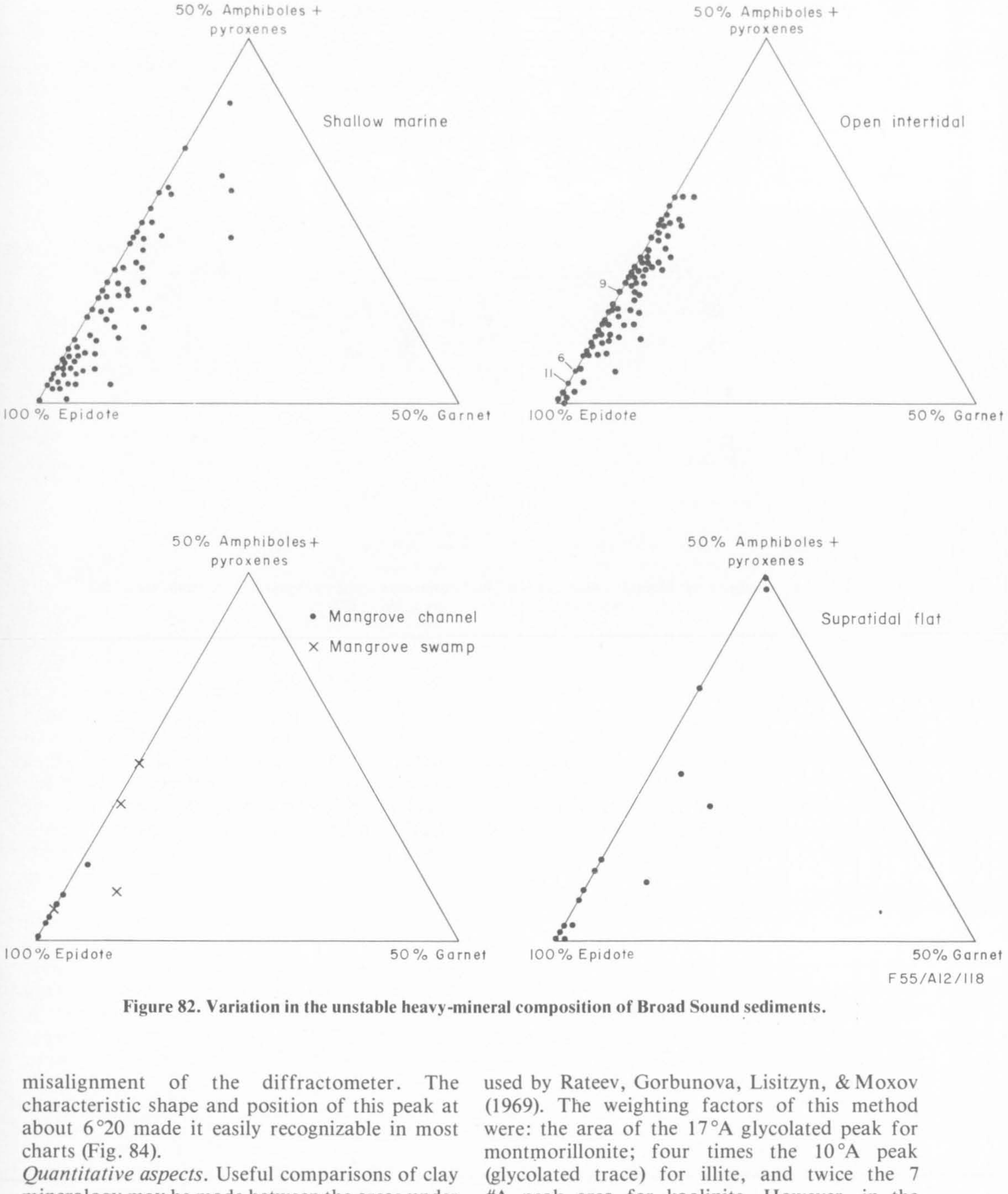


Figure 82. Variation in the unstable heavy-mineral composition of Broad Sound sediments.

misalignment of the diffractometer. The characteristic shape and position of this peak at about 6°2θ made it easily recognizable in most charts (Fig. 84).

Quantitative aspects. Useful comparisons of clay mineralogy may be made between the areas under the basal diffraction peaks of the different clay groups. Many authors have devised empirical correction factors for peak areas; a popular method seems to be that of Biscaye (1965), which was a development of the method of Johns, Grim, & Bradley (1954) and was subsequently used by Rateev, Gorbunova, Lisitzyn, & Moxov (1969). The weighting factors of this method were: the area of the 17°A glycolated peak for montmorillonite; four times the 10°A peak (glycolated trace) for illite, and twice the 7 #A peak area for kaolinite. However, in the charts obtained in this study, it was impracticable to measure the area of the 17°A peak on the glycolated chart as the trace in the 2-4°2θ region was very poor.

Consequently the method suggested by Schultz (1960) was used for all estuary and creek samples.

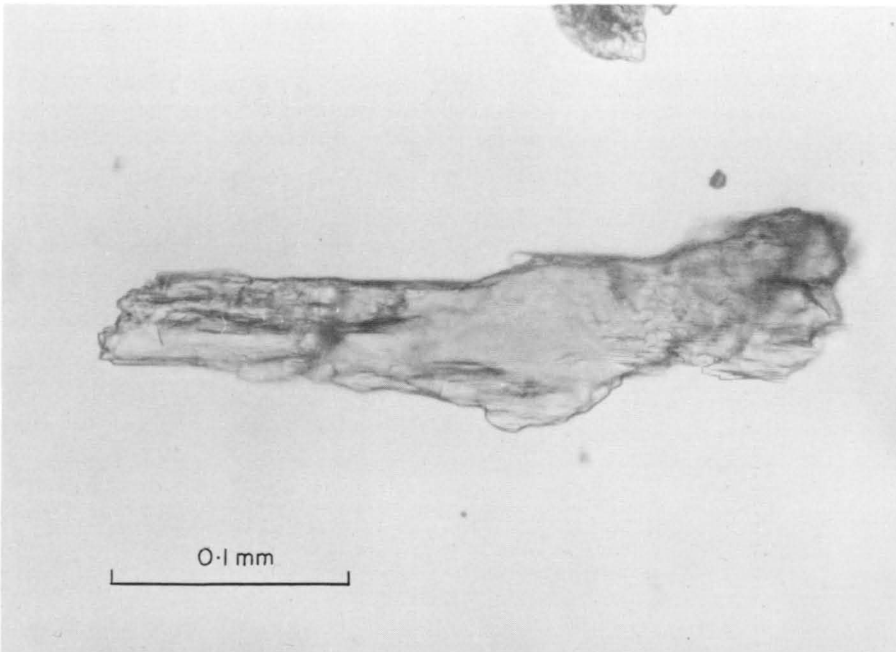


Plate 46. Grain of hornblende, showing marginal corrosion features. Sample 70636026, from the upper part of Herbert Creek. (M/1387/5)

In this method, the collapsed montmorillonite peak and the illite peak areas have the same weighting, and the weighting of the kaolinite peak with respect to them varies according to the crystallinity of the kaolinite. Schultz's chart shows that the 80 percent confidence interval for the kaolinite weighting factor for the kaolinite of Broad Sound is 1.2 to 1.6. Rather than use a non-integral factor, it was decided not to apply any correction factors. Hence the areas under the 7°A and 10°A peaks on the charts of the glycolated material were used as a measure of the amount of kaolinite and illite, and the increase of the 10°A peak after the sample had been heated to 300°C was used as a measure of the montmorillonite and mixed-layer clays, referred to hereafter as 'montmorillonite (plus m.l)'. The three areas were summed to 100 percent to give percent clay mineralogy.

No attempt was made to determine the clay mineralogy of the soil samples quantitatively as they either contained chlorite or the diffractogram traces were too poor to measure accurately. Biscaye (1964) suggested that the areas under the 3.5°A doublet (kaolin 002 and chlorite 004) are proportional to the amounts of each present, but this method was not attempted. A semi-quantitative mineralogy is given for the soil samples.

There are several possible sources of error in the quantitative determination of clay mineral components, including the difficulty of establishing where the background level is located on the chart, imperfect alignment of the X-ray machine, and determining the area under the curve. Despite this, repeat analyses of the same sample gave consistent results. Three typical diffractograms of Broad Sound clays are shown in Figure 84.

Clay minerals of the estuary. The summarized percentage clay mineralogy for the estuary samples shown in Table 8 indicates that kaolinite, illite, and montmorillonite (plus mixed layer) are present in approximately equal amounts. A similar assemblage has been reported in recent sediments by many workers, including Grim, Dietz, and Bradley (1949) in the Gulf of California and off the Californian coast, and Oinuma, Kobayashi, and Sudo (1959) in the western Pacific. Prior and Glass (1961) found a similar assemblage in Cretaceous and Tertiary sediments deposited in an inner neritic environment in the Mississippi Embayment.

Rateev et al. (1969) did not give data for most of the eastern coast of Australia and the area for several hundred kilometres to seaward in their maps of the worldwide distribution of clay minerals, but it is evident that kaolinite, illite,

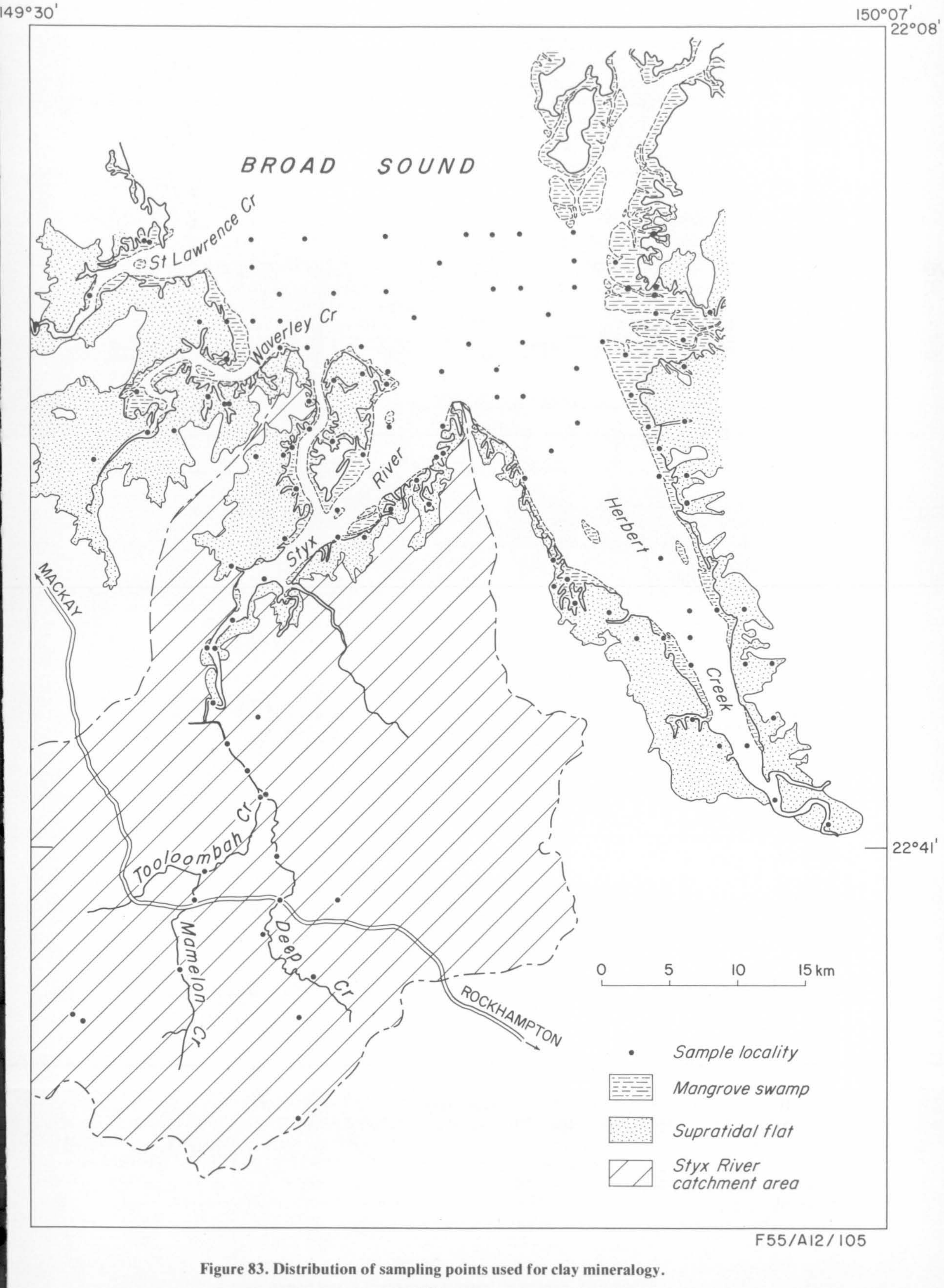


Figure 83. Distribution of sampling points used for clay mineralogy.

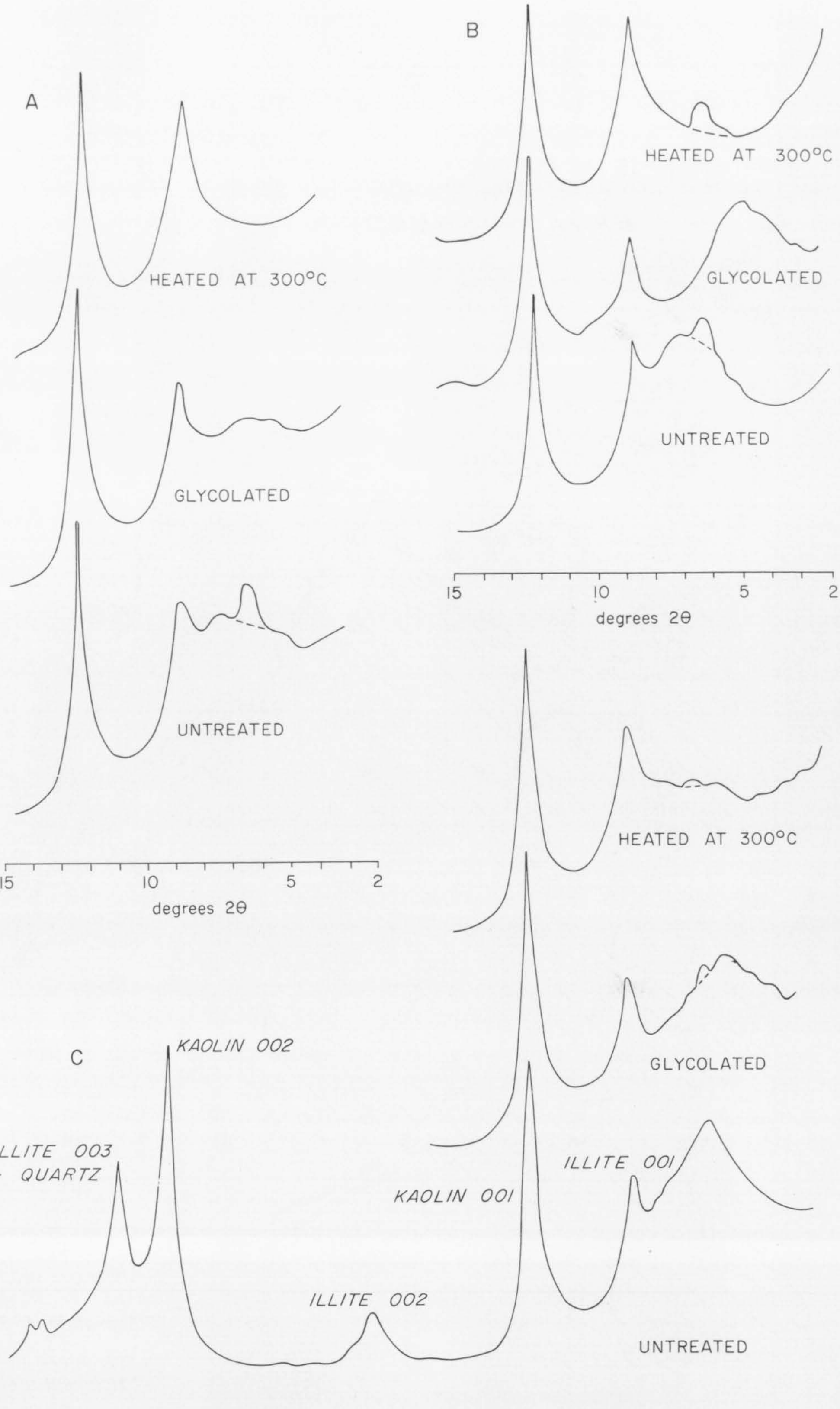


Figure 84. Typical diffraction patterns of Broad Sound clays.

TABLE 8. CLAY MINERALOGY OF CREEK-BANK SAMPLES FROM THE STYX RIVER CATCHMENT

Sample No.	*% Kaolinite*	*% Illite*	*% Montmorillonite (plus m.l.)*
70639-308	84	16	
335	69	31	0
341	33	29	38
349	33	27	40
350	29	25	47
360	32	26	41
367	28	28	45
376	21	44	35
474	22	24	53

and montmorillonite each generally constitute 20 percent to 40 percent of the clay fraction at latitudes around 20 °S. Hence it appears that the clay minerals in Broad Sound represent a common assemblage.

Table 9 gives the mean and unbiased standard deviations of the mineralogy of samples from each depositional environment. Figure 85 shows the statistically significant differences in mineralogy between the five main environments. A Student's *t* test shows there is no significant difference in the clay mineralogy between the intertidal sands and muds or between the shallow marine muds, sands, and gravels.

To account for the variation in clay mineralogy between the environments, the sources of the sediment in each environment (as well as the interchange of sediment between environments) need be known). Our studies indicate that:

1. Mangrove muds are being both deposited and eroded at the present time. The mangrove swamp deposits seem to be sometimes only a temporary store of fine sediment.
2. There is sediment interchange between the shallow marine and open intertidal environments.
3. Some of the mud in the open intertidal environment is derived from erosion of mangrove swamp deposits.
4. Eroded supratidal flats and mangrove swamps supply fine detritus to the mangrove channels.
5. High spring tides supply most of the sediment to the supratidal flat environment. During the wet season sediment is also supplied from the land, generally from nearby soils. Some ponding occurs in this area, preventing total drainage and causing high salinity. Coastal grasslands flanking the supratidal flats are also being eroded in places.

Consequently, there appears to be a continual interchange of sediment between the shallow marine and open intertidal, and to a lesser extent

TABLE 9. MEAN AND UNBIASED STANDARD DEVIATIONS OF THE CLAY MINERALOGY OF SAMPLES FROM THE FIVE BROAD SOUND DEPOSITIONAL ENVIRONMENTS

Environment	*Number of samples*	*Kaolinite mean*	*st.dev.*	*Illite mean*	*st.dev.*	*Montmorillonite (plus m.l.) mean*	*st. dev.*
Supratidal flats	27	36.11	3.21	34.74	4.74	29.22	6.22
Mangrove swamp	20	32.00	3.24	31.40	2.46	36.65	4.03
Mangrove channel	20	36.20	2.86	30.55	2.98	33.35	4.45
Open intertidal	27	31.78	4.16	32.70	3.71	35.63	5.44
Shallow marine	26	31.96	4.86	30.08	3.40	38.04	5.51
All environments	120	33.57	4.28	32.02	3.97	34.50	6.12

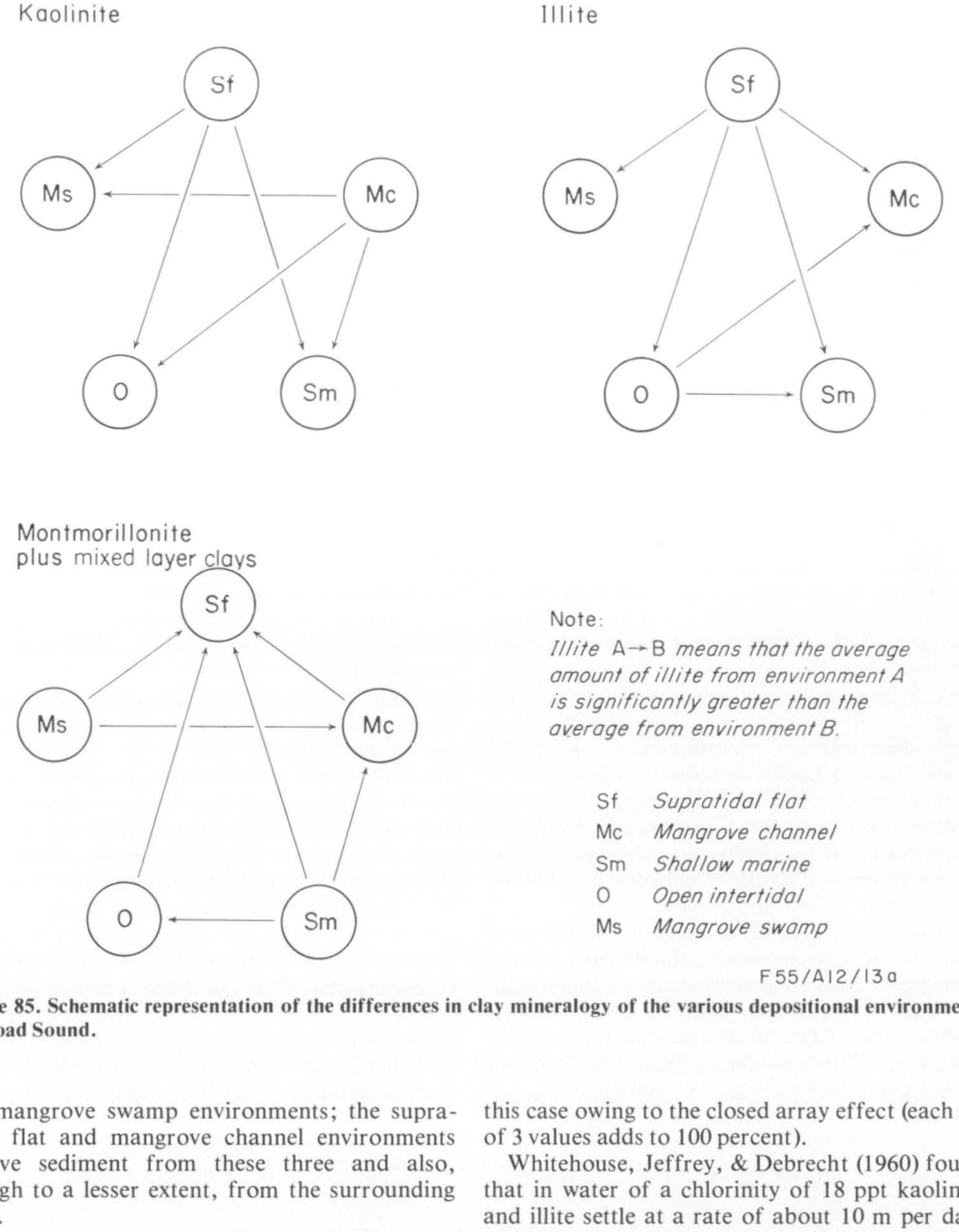
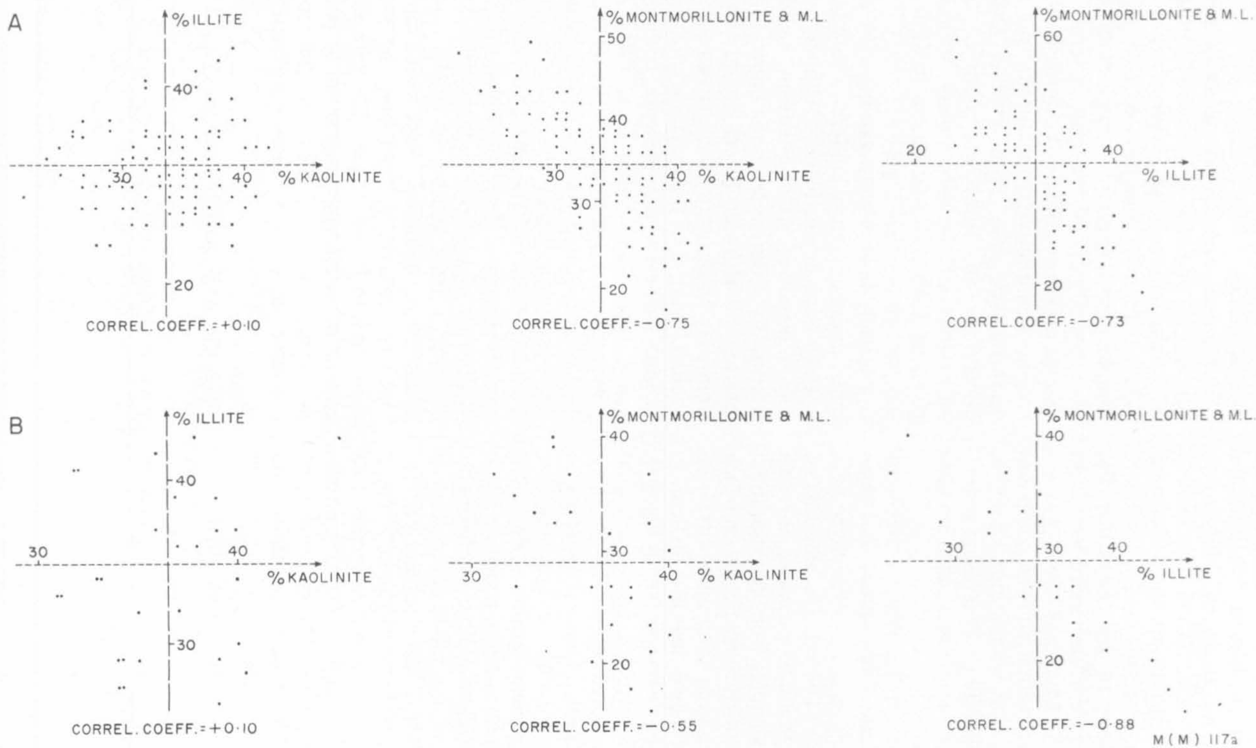


Figure 85. Schematic representation of the differences in clay mineralogy of the various depositional environments at Broad Sound.

the mangrove swamp environments; the supratidal flat and mangrove channel environments receive sediment from these three and also, though to a lesser extent, from the surrounding land.

In an attempt to ascertain interrelations between various clay fractions, scattergrams of the percentages of the three minerals analysed were plotted by computer (GESTAT program by Garrett, 1967) and are shown in Figure 86. There are good inverse relations between the amount of montmorillonite (plus m.1.) and the amounts of kaolinite and illite in the estuary as a whole; there is no correlation between kaolinite and illite. Interpretations within an unknown system based on correlation coefficients alone are difficult enough, but they are made even more difficult in this case owing to the closed array effect (each set of 3 values adds to 100 percent).

Whitehouse, Jeffrey, & Debrecht (1960) found that in water of a chlorinity of 18 ppt kaolinite and illite settle at a rate of about 10 m per day, which is about ten times as fast as montmorillonite. Whitehouse (1952) and Whitehouse & Jeffrey (1955) also reported a much slower settling rate of montmorillonite. Montmorillonite settles more slowly because it usually has a smaller grainsize, flocculates more slowly, and forms smaller floccules. The slower settling rate of montmorillonite (and no doubt mixed-layer montmorillonite-illite) would result in varying amounts of these minerals settling in different environments as well as within one environment, according to the depth and movement of water.



M. L. (mixed layer clays)

Figure 86. Scattergrams of percentage clay mineralogy, with axes through the sample means. A — all estuary samples; B — supratidal samples.

Since much of the water entering the supratidal flat environment cannot escape because of ponding, the supratidal flat deposits should generally reflect the mineralogy of the suspended clay load of the water of Broad Sound mixed with a little clay from nearby soils. However, the supratidal flat relations shown in Figure 85, plus the variability of the mineralogy (17-40% montmorillonite) and the inverse relation between illite and montmorillonite in the supratidal flat zone indicate that another process is occurring. Figure 86 shows scattergrams of the supratidal flat samples. A single sample of suspended load from near the mouth of St Lawrence Creek was examined by X-ray diffraction. It was composed predominantly of quartz with minor kaolinite, illite, and montmorillonite (in decreasing order). Because only a single sample was taken no conclusion can be drawn.

Examination of the diffractometer traces of clays from the supratidal flat shows that these sediments usually contain more mixed-layer clays than montmorillonite. The relative amounts of the two minerals could not be measured but, as a guide, 21 of the 27 samples from the supratidal flat environment give a glycolated chart on which the basal peak of the expanding mineral(s) is so close to the 10°A illite peak that it is difficult to resolve the two peaks (see sample 003 in Fig. 84). The curve must be corrected to a horizontal background to determine the drop in X-ray intensity between the two peaks. Hence it appears that either less montmorillonite is reaching the supratidal flat environment (which is unlikely), or that montmorillonite is being transformed to mixed-layer montmorillonite-illite, or the montmorillonite content of the mixed-layer clays is being decreased. The high salinities and desiccation in the supratidal flat environment could substantially affect the montmorillonite and could convert some of it to illite, forming mixed-layer montmorillonite-illite. The conversion of montmorillonite to illite in saline conditions has been noted by several clay mineralogists and sedimentologists: Dietz (1941) and Milne & Earley (1958) reported a transformation of montmorillonite to illite, and Grim & Vernet (1961) reported a change from montmorillonite through mixed-layer montmorillonite-illite to illite in the Mediterranean.

Clay minerals from the Styx River catchment. Six soil samples and nine of alluvium from the banks of creeks in the Styx River catchment were analysed for clay minerals. As four of the soil samples gave very poor traces (probably owing to poor crystallinity of the clay minerals present) and the other two contained chlorite (which could not be quantitatively measured), no accurate quantitative data are given. Qualitative mineralogy of these six samples and the mineralogy of the streambank sediments are given in Tables 10 and 8; the localities of the samples are shown in Figure 83.

The soils have widely varying clay compositions, and many more analyses would be needed to carry out a detailed study. Although the mean clay mineralogy of the stream sediments is statistically different from the mineralogy of the marine sediments of Broad Sound, no conclusions may be drawn as these streams drain only about 12 percent of the total catchment of Broad Sound. However, the presence of montmorillonite is of some importance. Prior & Glass (1961) reported that montmorillonite is absent in the Cretaceous and Tertiary fluvial sediments of the Upper Mississippi Embayment, but forms from 20 percent to 80 percent of the clay from the inner neritic zone. They attributed this variation to the fine grainsize of montmorillonite, which prevents it from settling in fluvial conditions. Clearly, some unknown factor allows montmorillonite to settle in at least some of the creeks draining into Broad Sound. The expanding clay mineral in the alluvium appears to be pure montmorillonite, whereas there is commonly appreciable mixed-layer montmorillonite-illite in

TABLE 10. QUALITATIVE CLAY MINERALOGY OF SOIL SAMPLES FROM THE STYX RIVER CATCHMENT

Sample No.	*Mineralogy in order of decreasing amount in sample*
70639-229	Kaolinite
310	Illite, kaolinite
409	Chlorite, kaolinite, montmorillonite
410	Chlorite, kaolinite
516	Kaolinite, illite
614	Kaolinite

sediments from all environments of Broad Sound. If the samples studied are typical of the sediment coming into Broad Sound, slow conversion of some of the montmorillonite to illite to give irregularly stacked mixed-layer montmorillonite-illite may be occuring as the sediment enters saline water.

Therefore, it may be concluded from the clay mineralogy that

(1) The general assemblage of clay minerals in Broad Sound (kaolinite, illite, montmorillonite, and mixed-layer montmorillonite-illite) is normal when compared with assemblages in ocean sediments at a similar latitude to Broad Sound. (2) Sediments of the supratidal flat and mangrove channel environments have less montmorillonite plus mixed-layer clays and more kaolinite and illite than does sediment of the shallow marine, mangrove swamp, and open intertidal environments. This may be explained by the conversion of montmorillonite to illite via irregularly stacked mixed-layer montmorillonite-illite in the highly saline and commonly desiccated supratidal flat environment, and the erosion of this sediment into mangrove inlets. (3) Minor variations in clay mineralogy between the shallow marine, open intertidal, and mangrove swamp environments may be explained by the slow settling rate of montmorillonite when compared with kaolinite and illite. (4) There may be some conversion of montmorillonite to illite via irregularly stacked mixed-layer montmorillonite-illite as sediment from the catchments enters the saline water of Broad Sound. This process would be much slower than the conversion taking place in the supratidal flat environment.

HOLOCENE STRATIGRAPHY AND DEPOSITIONAL HISTORY

In order to understand the sedimentology of Broad Sound fully, it is necessary to understand not only present-day depositional processes, but also processes which have occurred during the Holocene. The Holocene history of Broad Sound has profoundly influenced the morphology, mineralogy, grainsize, and geochemistry of the sediments and for this reason was studied in some detail.

As part of these Holocene studies a comprehensive program was undertaken to determine the onshore and offshore stratigraphy by seismic profiling, coring, and drilling. The stratigraphic information was put into a chronological framework by the extensive use of radiocarbon dating.

Offshore Seismic Survey

Offshore seismic work was undertaken in Broad Sound in 1966, 1970, and 1971, and a total of about 800 km of continuous profiles obtained (Fig. 87). The 1966 survey was carried out by the United Geophysical Corporation for Ampol Exploration Limited using the M.V. *Unitedgeo I*. A 16 000-joule sparker unit was used, with a sparking interval of 4.5 seconds and a hydrophone streamer approximately 50 m in length. The 1970 survey was undertaken by BMR first in the M.V. *Bali Hai* and subsequently in the M.V. *San Pedro Strait*. A 1000-joule 3-electrode Sparkarray sound source was used in conjunction with a 30-element MP 7 hydrophone and an Ocean Sonics GDR-T recorder; the sparking interval was 1 second. In 1971 the seismic work was undertaken for BMR by Laser Electronics Pty Ltd using their 'mini-sparker' system and an Ocean Sonics recorder. A Raytheon DE119 echo-sounder was used throughout this program because of the difficulty in determining the depth of the sea-floor from the seismic records.

The quality of data obtained from the three seismic surveys ranges from good to poor, with the average quality only moderate. This is primarily the consequence of very shallow water and the nature of the sub-bottom. The very shallow water resulted in numerous multiples in the record which made the recognition of genuine reflections generally difficult and frequently impossible. The sandy nature of the sediment-water interface together with the presence of an underlying indurated horizon also resulted in poor records in many areas owing to excessive energy reflection. In addition, where megaripples were present there was a total loss of reflection, presumably because the megaripples randomly scattered the sound.

Pre-Cainozoic reflectors

Palaeozoic basement is recognized in a number of seismic lines, particularly those of the 1966 survey. Three of these lines are reproduced in Figures 88, 89, and 90. Figure 88 shows that the depth to basement shallows towards the northern end of Broad Sound, where Palaeozoic rocks crop out on most of the islands. At the southern end of the Sound the seismic picture becomes too confused for basement to be recognized but the presence of outcropping basement onshore in-

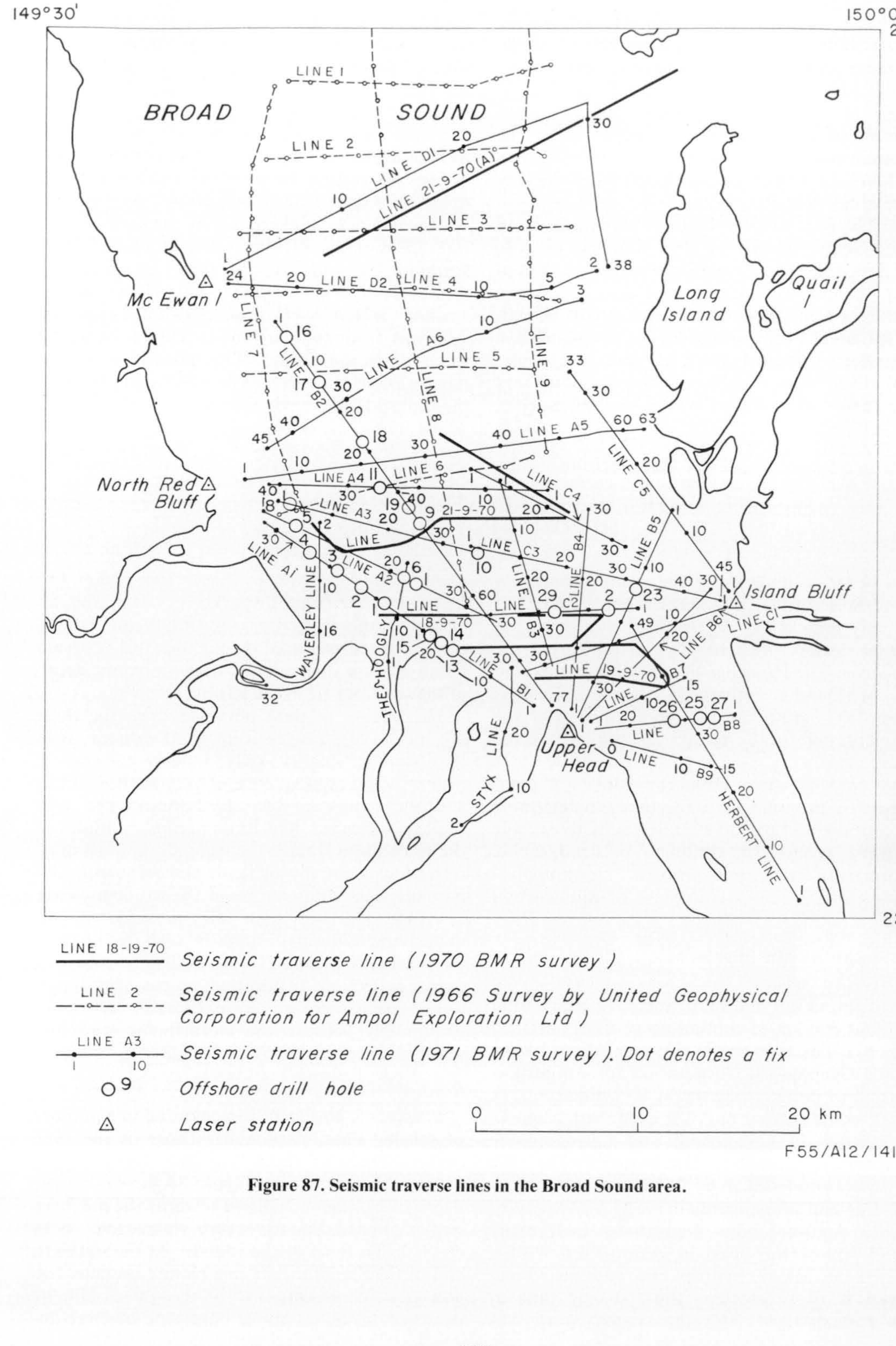


Figure 87. Seismic traverse lines in the Broad Sound area.

dicates that it must also shallow considerably there. The east-west traverses (Figs. 89 and 90) reveal a narrow trough in the basement in which about 500 m of sediments has accumulated (Fig. 91). The trough is interpreted by Roosjen (1966) as being downfaulted on its west side, with a vertical displacement of about 400 m. This inferred fault runs parallel to numerous other normal faults which have been mapped onshore. The youngest episode of faulting recorded by Kirkegaard et al. (1970) in the Broad Sound area is ?mid-Tertiary, although they also suggested that there may have been Quaternary northwest-trending faulting along the west side of Shoalwater Bay. It would seem reasonable to assume that the Broad Sound Fault (Fig. 5) is of Mesozoic-Cainozoic age, with much of the sediment in the trough being downfaulted Cretaceous Styx Basin sediments. There is no clear reflector separating ?Cretaceous sediments from ?Cainozoic sediments although Roosjen (1966) suggested that there is some truncation of sediments in the shallow portion of the trough, which may represent the contact between consolidated Cretaceous and unconsolidated Cainozoic sediments.

Cainozoic reflectors

The primary aim of the two BMR seismic surveys was to help delineate the stratigraphy of the younger sediments, with the 1970 survey having a maximum sub-bottom penetration depth of about 200 m and the 1971 survey about 80 m.

The 1970 work showed that sediments ranging in age from ?Tertiary to Recent are flat-lying to very gently dipping on the east side of Broad Sound but are folded on the west side (Fig. 92). It is uncertain whether this folding is the effect of draping and compaction of sediments over older structures or whether it is the consequence of early Cainozoic tectonic activity. The latter suggestion is supported by the fact that some folding occurs near the inferred fault. The consistent dips to the north and west in the eastern half of the basin may also be tectonic and are possibly the result of downwarping associated with the development of the trough. Alternatively, some of the dips may be depositional, as large-scale cross-beds with dips to the northwest are a feature of some modern sand bodies on the east side of Broad Sound.

Several shallow sedimentary features were revealed by the 1971 seismic survey. Traverses

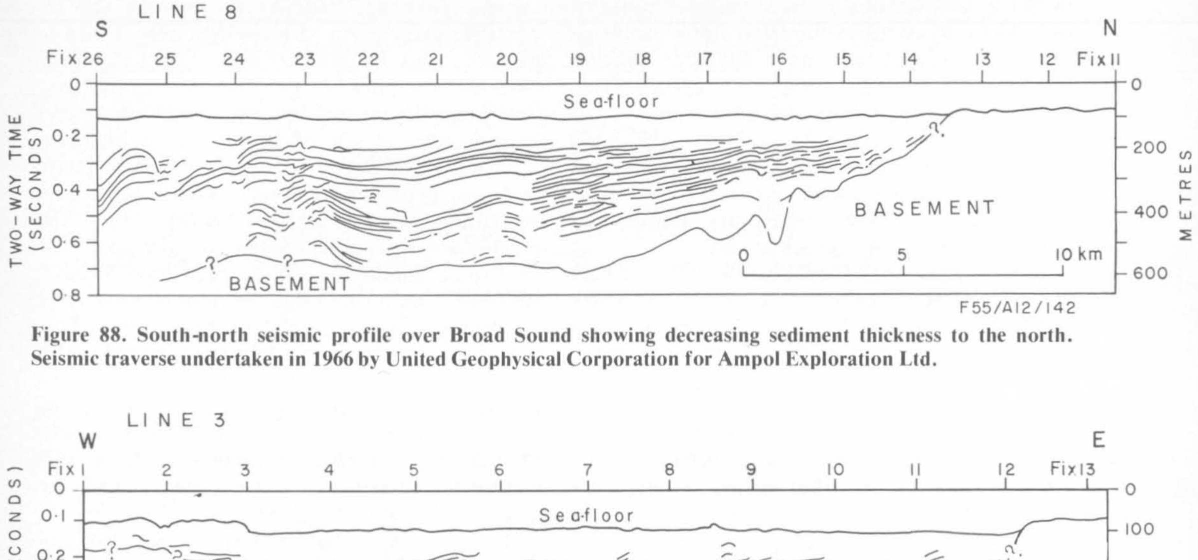


Figure 88. South-north seismic profile over Broad Sound showing decreasing sediment thickness to the north. Seismic traverse undertaken in 1966 by United Geophysical Corporation for Ampol Exploration Ltd.

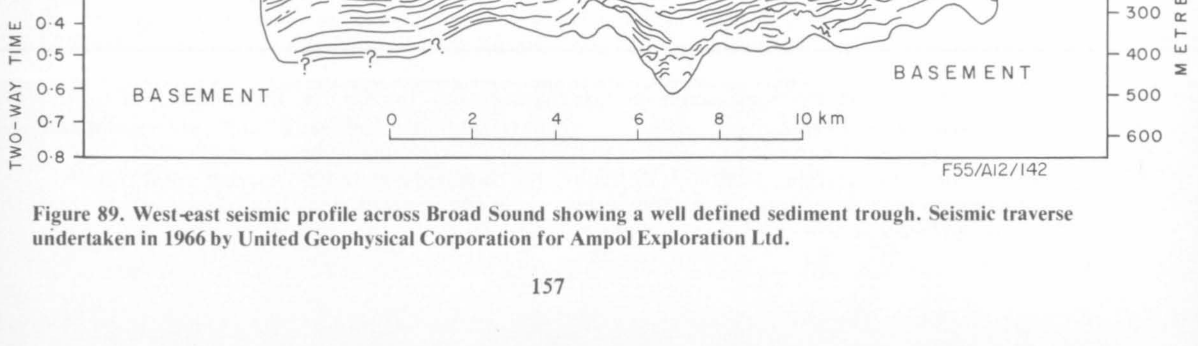


Figure 89. West-east seismic profile across Broad Sound showing a well defined sediment trough. Seismic traverse undertaken in 1966 by United Geophysical Corporation for Ampol Exploration Ltd.

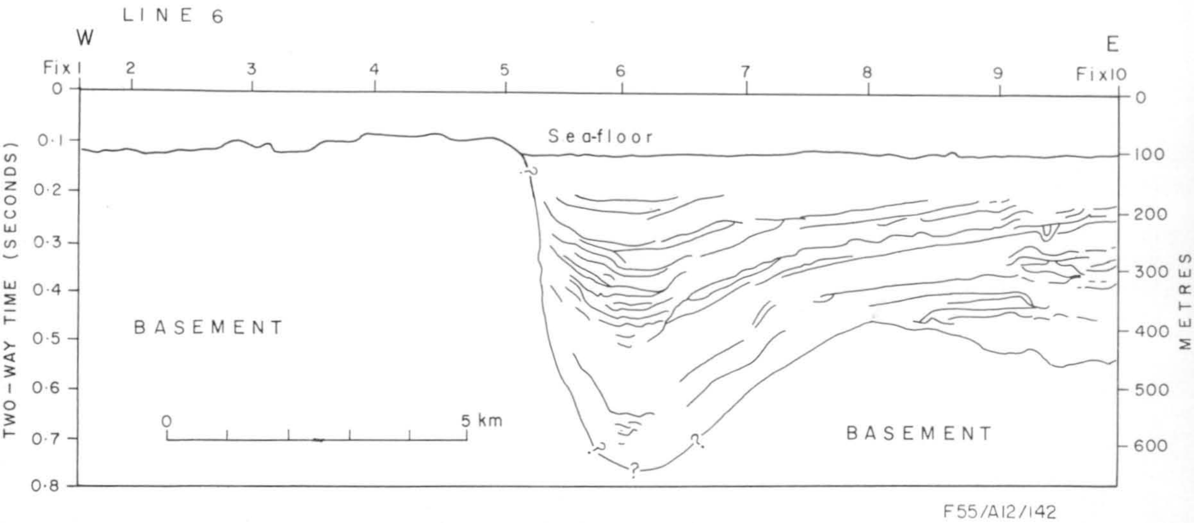


Figure 90. West-east seismic profile across Broad Sound showing a deep sediment trough on the west side of the Sound. Seismic traverse undertaken in 1966 by United Geophysical Corporation for Ampol Exploration Ltd.

up some of the river mouths (Figs. 93 and 94) indicated that at least 25 m of unconsolidated or poorly consolidated sediment is preserved in places in present-day river valleys. Some of this thickness could result from initial scouring during floods and subsequent infilling; however the 'over deepening' probably occurred during the late Wisconsin low sea-level stand. it is apparent from Figures 93 and 94 that the depth to basement varies markedly in the centre of the river channels, with basement becoming particularly shallow at the estuary mouth, and forming an outcropping rock in places.

Seismic data away from the estuaries indicate that the inferred ?Quaternary section gradually increases in thickness to seaward. Channel structures gradually increases in thickness to seaward. Channel structures are a particularly common feature of the sub-bottom profiles. Figure 95, which illustrates a traverse line in the southwest portion of Broad Sound, shows some of these channels. It is evident that buried channels are abundant near the mouths of some of the present-day estuaries. Sub-surface data obtained from offshore drillings are incorporated in Figure 96 and show that some of these channels contain gravels, possible of fluvial origin. These channels are believed to be of late Wisconsin age; they are overlain by up to 10 m of unconsolidated sands, suggesting that, there, Holocene sedimentation has been comparatively rapid.

A feature discussed elsewhere, an undurated surface within the Quaternary section, is difficult to recognize on the seismic records. Although the indurated surface was delineated at several places by drilling (Fig. 95) it is nevertheless impossible to positively identify in any of the seismic profiles. Many of the old channels revealed by seismic work are believed to underlie the indurated surface. An attempt has been made to plot the distribution of these ?pre-Holocene channels in Figure 96. The best developed channels, generally up to 5 m deep and 500 m across, are on the west side of Broad Sound (the area most subject to fluvial influences at present), with the most prominent channel system apparently emanating from the mouth of the Styx River. The pre-Holocene channel system on the east side of Broad Sound is considerably less defined, suggesting that there has been no major river system there, at least during the Quaternary. This is counter to the suggestion made by Maxwell (1968) that the Fitzroy River had a pre-Holocene drainage path north through Broad Sound. The deeper-penetration seismic work also failed to provide any evidence in favour of Maxwell's hypothesis. Seismic traverses made across a number of sandbanks and sand-ridges showed that in some of the banks there are large internal cross-beds, with sets of 5 to 10 m thickness and apparently dipping to about the northwest (Fig. 97); this dip direction is uncertain owing to the essentially two-dimensional picture obtained from a seismic line. It is also apparent from the sub-bottom profile that the sand-ridges are not overlying or following any older elongate bedrock structure. The unconsolidated sand of the ridge appears to be overlying a flat (Fig. 98), or in some instances a channelled, surface (Fig. 99). Drilling suggests that in some places this

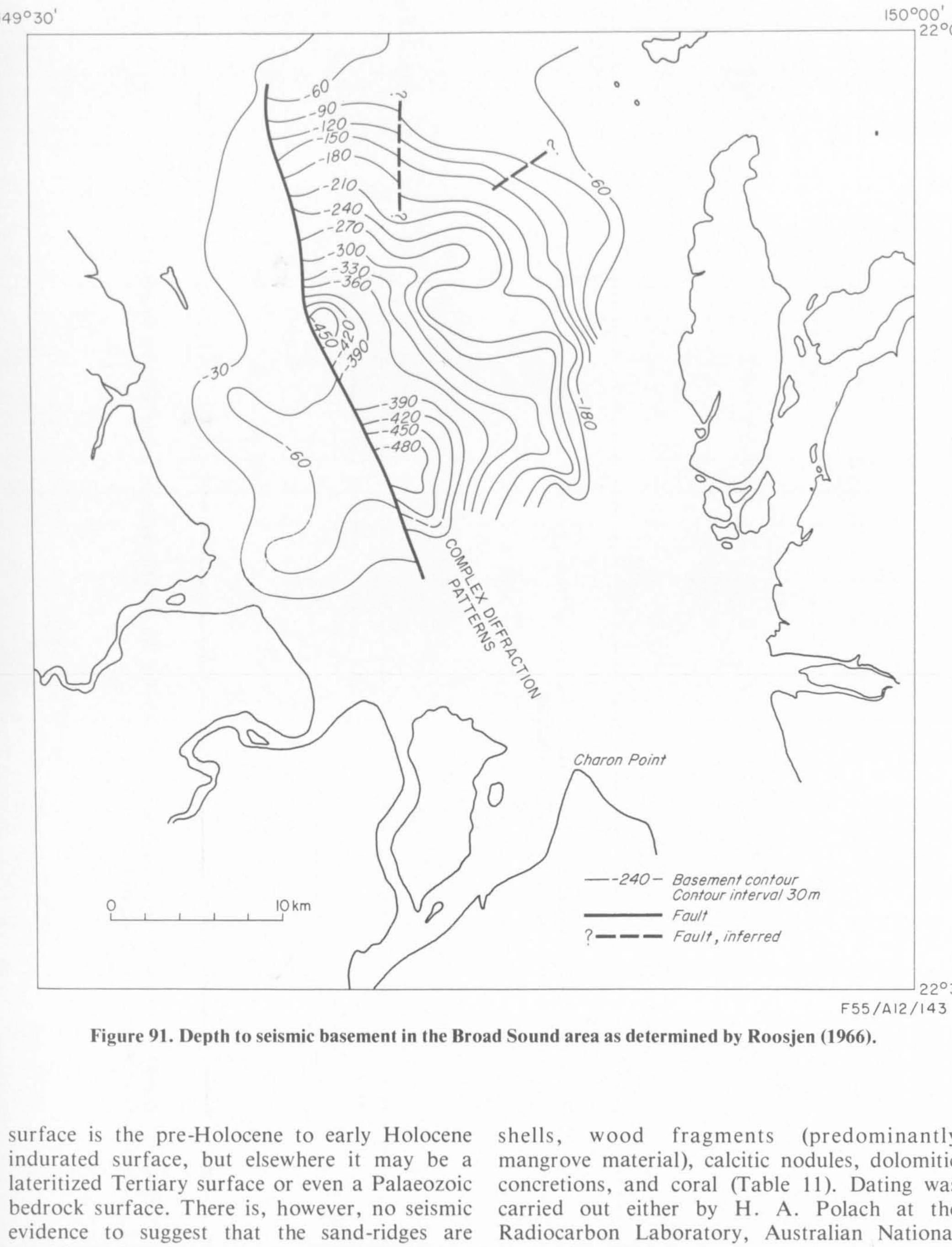


Figure 91. Depth to seismic basement in the Broad Sound area as determined by Roosjen (1966).

surface is the pre-Holocene to early Holocene indurated surface, but elsewhere it may be a lateritized Tertiary surface or even a Palaeozoic bedrock surface. There is, however, no seismic evidence to suggest that the sand-ridges are anything other than very young (late Holocene) features.

RADIOCARBON DATING

Radiocarbon dating was undertaken on 40 samples from the Broad Sound area in order to establish a chronological framework for the stratigraphic sequence. Material dated included shells, wood fragments (predominantly mangrove material), calcitic nodules, dolomitic concretions, and coral (Table 11). Dating was carried out either by H. A. Polach at the Radiocarbon Laboratory, Australian National University (sample numbers prefixed ANU-) or by Associate Professor R. B. Temple and Mr R. Gillespie at the Radiocarbon Laboratory of the University of Sydney (sample numbers prefixed by SUA-).

Calcareous material

Dating of calcareous material was undertaken

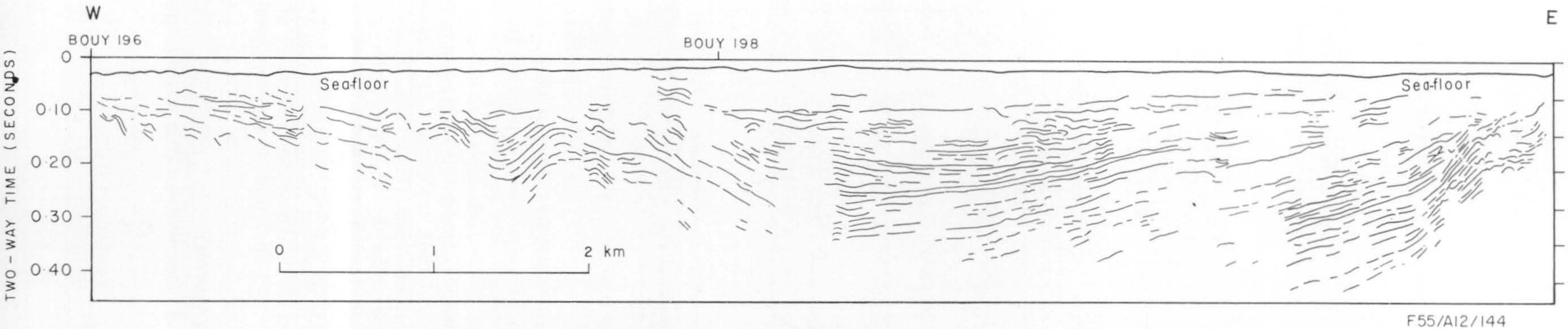


Figure 92. West-east seismic traverse across Broad Sound showing some folding of sediments on the west side of the Sound. Position of seismic traverse line indicated in Figure 88.

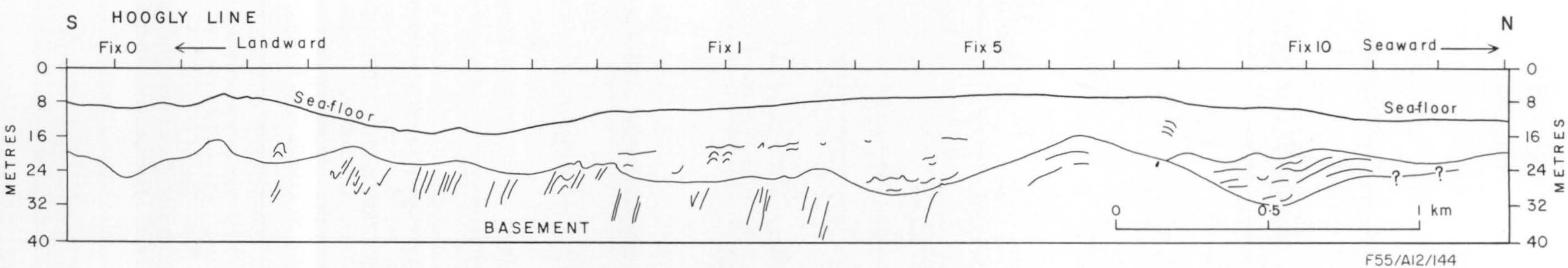


Figure 93. South-north seismic line down The Hoogly showing the marked variation in the depth to basement. Seismic traverse line indicated in Figure 88.

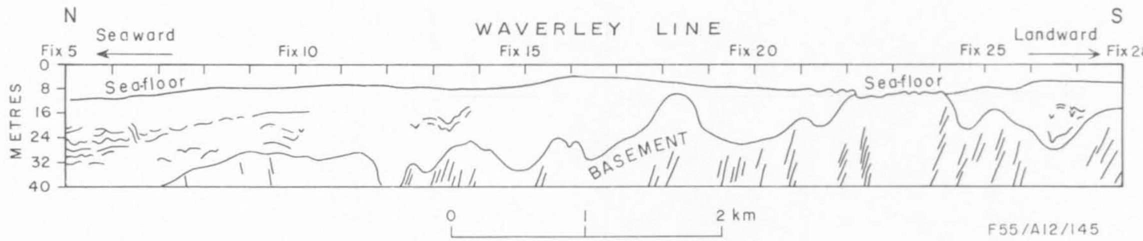


Figure 94. Seismic line up Waverley Creek showing the marked variation in depth to seismic basement. Traverse line indicated in Figure 88.

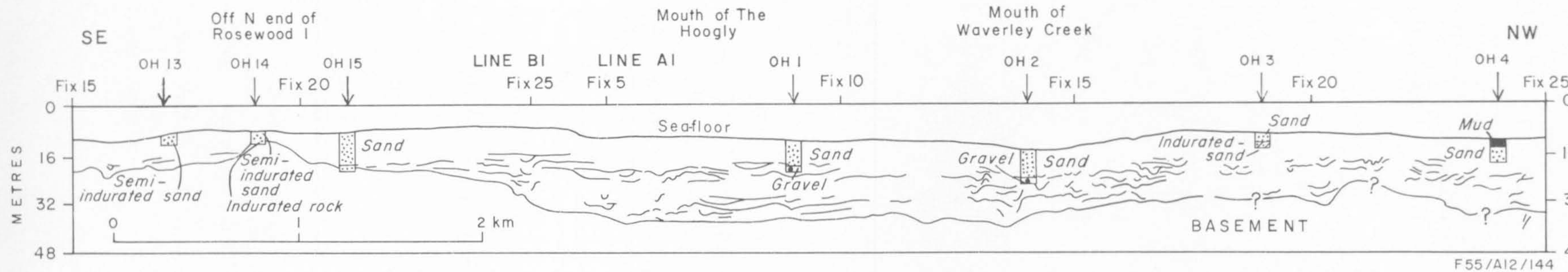


Figure 95. Seismic and drilling information in the southwest part of Broad Sound. Location of line indicated in Figure 88.

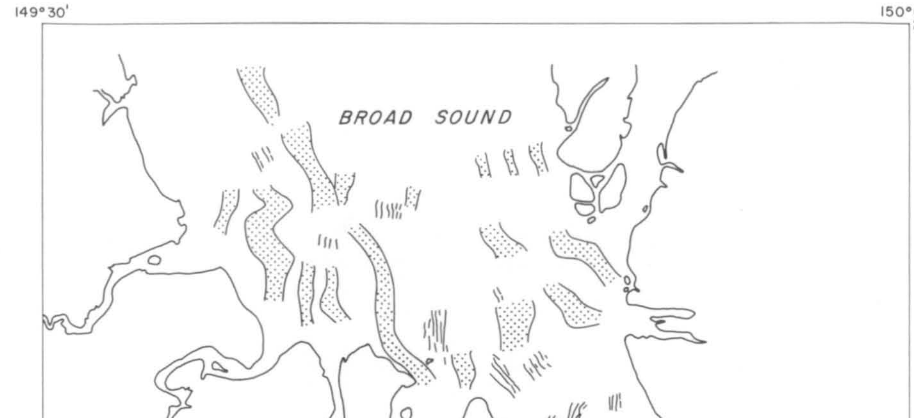


Figure 96. Pre-Holocene drainage channels in Broad Sound, as inferred from seismic information.

primarily on shells, particularly oyster shells, as it is believed that the dense calcitic structure of the shells minimizes post-depositional exchange of carbonate with the environment. The outer 10 percent of the shells was leached by dilute hydrochloric acid to remove any weathered material before acid evolution of CO_2. In order to test for weathering affects,the outer, middle, and inner fractions of shell sample ANU-903 were dated. All values were found to agree to within one standard deviation, suggesting that there has been no significant post-depositional modification of the radiocarbon content of shells by weathering. Most of the dated shell material is from cheniers and in every instance the date obtained was both sensible and consistent with dates obtained on adjacent cheniers. Consequently, it appears that reliable radiocarbon dates were obtained on shelly material from the Broad Sound area.

A number of dates for Broad Sound material have previously been published by Cook & Polach (1973a), but a re-evaluation of the radiocarbon modern reference standard values indicated that corrections were necessary for a number of dates. In addition, a minor change is necessary to the preliminary date given by Cook & Polach (1973b) to correct for weight loss. These corrections are given in Table 12.

Dates obtained on coral material are perhaps less reliable than those on shells. Chappell & Polach (1972) demonstrated that post-depositional conversion of the originally coralline aragonite to sparry calcite can substantially affect the apparent radiocarbon age of the material. Recrystallization of the coral (sample SUA-110, P. 47, Fig. 1) is evident both in thin section (Pl. 47, fig. 2) and from the predominantly calcitic nature of the coral as compared to its originally aragonitic nature. Consequently the age of 30700 ± 1200 years B.P. obtained on SUA-110 can be regarded only as a minimum age.

The value of dates obtained on shallow

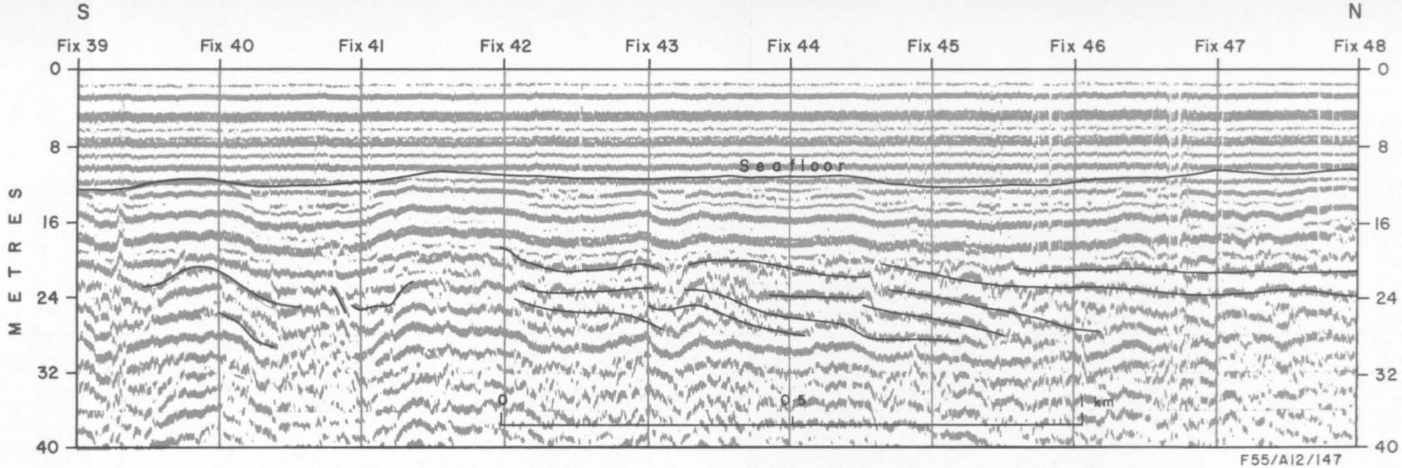


Figure 97. Inclined bedforms (?foresets) in sandbanks at the northern end of Herbert Creek.

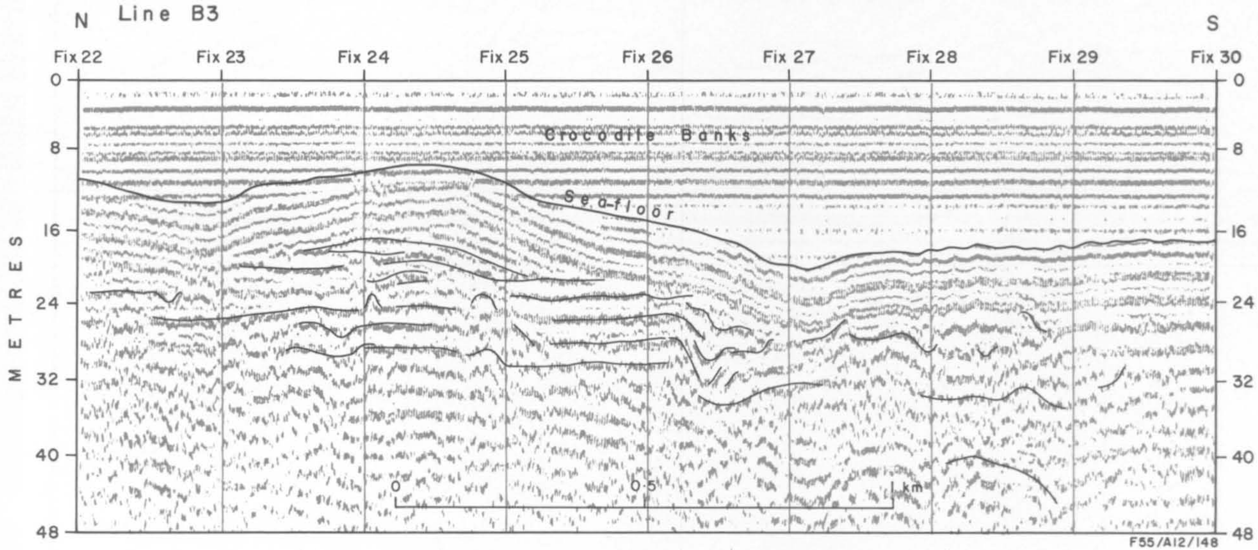


Figure 98. Seismic profile across Crocodile Banks, Line B3 (see Fig. 88).

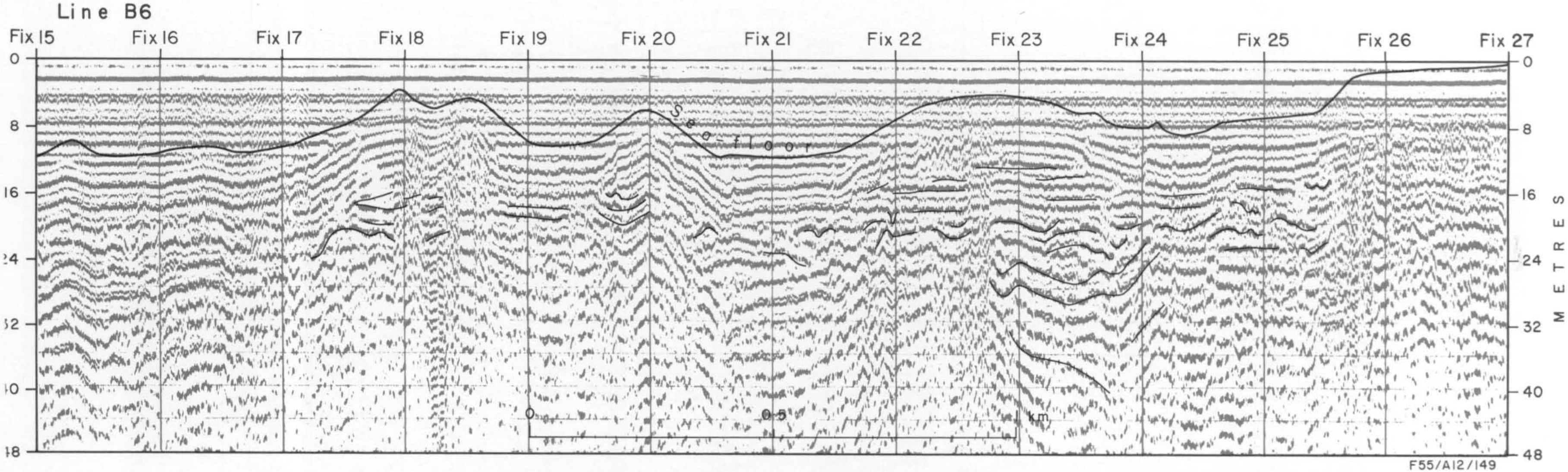


Figure 99. Seismic profile across sandbanks at the northern end of Herbert Creek; line B6 (see Fig. 88).

marine calcitic nodules is also somewhat uncertain. The fact that nodules from widely scattered localities give almost identical radiocarbon ages suggests that the dates obtained are probably reliable; however the significance of the dates obtained is less certain. The nodules are composed of abundant shell fragments (Pl. 40, fig. 2), some of which may have been originally aragonitic though there is now no aragonite present. Thus, any radiocarbon age is likely to give the age of formation of the calcite rather than the age of the shells. An additional complication results from presence of a thin micrite envelope on some of the nodules (Pl. 39, fig. 2), which is believed to be produced by boring algae. This process may also have affected the carbonate, giving a younger age. Despite these problems the closeness of the two ages for SUA 129 and SUA 130 suggests that the ages are significant and are believed to represent the approximate time of formation of the nodules, possibly within a soil profile.

A sample of dolomitic material (ANU-1037) was radiocarbon dated by CO_2 evolution and gave an age of 3070 ± 60 years B.P. (2860 ± 100 by Cook & Polach, 1973). This is regarded as a minimum age as the dolomitic material has a C^{13}/C^{12} ratio equal to -14.2 $°/_{00}$ compared to a normal value of SC^{13} value equal to -4 $°/_{00}$ to -7 $°/_{00}$ with respect to belemnite marine standard. This value may indicate the continuous post-depositional exchange of biogenic CO_2 with the concretionary carbonate. However, Rafter (1973) has found that C_{13} values of -10 $°/_{00}$ are found in estuarine carbonates; consequently the value obtained for Broad Sound material may also be the result of the prevailing estuarine environment. The radiocarbon age obtained, and the position of the concretions stratigraphically above shell material with an age of 3450 ± 90 years B.P. (ANU-967) suggest that the concretion has formed about 3000 to 3500 years ago.

Plant material

A number of mangrove wood samples (indicated in Table 11) were obtained from drill holes and auger-holes. In order to test for contamination, various organic fractions were obtained from the same wood sample, and dated separately. This was carried out with sample ANU-947. After treatment first with boiling 2% NaOH, then 2% HC1, three fractions were dated separately (ANU-947A, 947B, 947C). The wood, when free of humic acids, has a radiocarbon age of about 2950 years B.P., but both the humic acids and the fine wood fibres (free of humic acid) had radiocarbon ages of about 2200 years B.P. This young age is believed to be the result of contamination. A similar example of contamination is provided by sample ANU-966 (Table 11). Here too the wood (free of humic acid) gives a comparatively old age (2706 ± 190 years B.P.) whereas the contaminants are significantly younger; the fine plant material (free of humic acid) has an age of 2070 ± 160 years B.P. and the humic acids an age of 1360 ± 630 years B.P. Therefore it would seem that unless the humic-acid-free fraction of the coarse mangrove wood fragments are taken, the age may be too young owing to contamination by younger humic acids and younger fine intrusive plant material. Because of this, those ages obtained on wood samples which were not pre-treated with NaOH and HCL may only be minimal. Sample ANU-899, in particular, is regarded as being of uncertain significance. It was obtained from a depth of 1 m below the supratidal flat, yet has an essentially modern age (170 ± 110 years B.P.)

OFFSHORE STATIGRAPHY

A coring program with a small 20-kg gravity corer having a 50-cm barrel was used during the 1970 work. Few satisfactory cores were obtained and most were only 10 to 20 cm long. Subsequently a 300-kg piston corer was used. At a few localities, cores of up to 1 m were obtained but at most localities, owing either to the sandy indurated nature of the bottom, it was not possible to obtain a core. During 1971, offshore drilling was undertaken for BMR by Offshore Research and Development Pty Ltd at a number of sites in the hope of identifying reflecting horizons (Fig. 100). This program produced some interesting stratigraphic results, but was mostly unsuccessful in intercepting seismic horizons owing to the lack of prominent reflectors and the inability of the drilling system to penetrate indurated layers. Penetrations of up to 10 m were obtained and the drilling results are summarized in Appendix 3. It is evident from this that most drill-holes were terminated because of the presence of a hard layer. The drill-hole and coring locations are shown in Figure 100. During dredging operations, fine material may be washed out of the core dredge. However, comparison of the sediments obtained by coring and dredging showed that only minor amounts of mud were lost and that no modification to the facies distribution was necessary.

The vertical sequence varied from place to place. A number of drill-holes were sited on sand banks (021, 022, 024, 026 and 027, Fig. 100). These revealed a uniform sand, though with a greater abundance of gravel-size material (mainly carbonate nodules) and shells in the lower half of

TABLE 11. RADIOCARBON AGES OF BROAD SOUND MATERIALS

C^{14}Lab. No.	*BMR Reg. No.*	*Material dated*	*Locality*	*Radiocarbon age (years B.P.)*	*Remarks*
Beach ridges					
ANU-791	70636736	Mixed shell grit	Charon Point	4520 ± 125	
ANU-792	70636737	Mixed shell grit	Charon Point	3465 ± 110	
ANU-793	70636741	Mixed shell grit	Charon Point	2480 ± 100	Outer 10% of shell removed by dilute HCl before dating
ANU-900	71636103	Oyster shells	Hoogly-Waverley	2100 ± 70	
ANU-901	7163618	Oyster shells	Hoogly-Waverley	2140 ± 70	
ANU-902	71636139	Oyster shells	Hoogly-Waverley	2930 ± 70	
ANU-903A	71636141	Oyster shells	Charon Point	1640 ± 100	Outer one-third of shells dated
ANU-903B	71636141	Oyster shells	Charon Point	1410 ± 90	Middle one-third of shells dated
ANU-903C	71636141	Oyster shells	Charon Point	1430 ± 90	Inner one-third of shells dated
ANU-903C	71636141	Oyster shells	Charon Point	1430 ± 90	Inner one-third of shells dated
ANU-904A	71636100	Oyster shells	Hoogly-Waverley	1170 ± 70	
ANU-904B	71636100	Bivalve shells	Hoogly-Waverley	1020 ± 70	
ANU-905	71636107	Oyster shells	Hoogly-Waverley	4060 ± 80	
ANU-906	71636106	Oyster shells	Hoogly-Waverley	2960 ± 70	Outer 10% of shell removed by dilute HCl before dating
ANU-907	71636108	Oyster shells	Hoogly-Waverley	5450 ± 85	
SUA-127	71636039	Oyster shells	Torilla Plains	2950 ± 80	
Miscellaneous carbonate material					
ANU-967	71636150	Pelecypod shells	Charon Point	3450 ± 90	Shells from auger hole A19 (2.1 — 2.4 m)
SUA-110	71636140	Coral (calcitic)	Charon Point	30700 ± 1200	Dead coral (recrystallized) at L.W.M. tidal level
SUA-128	71636147 (S)	Shell fragments	Offshore	2430 ± 80	Shells from offshore drill hole 024 (7.9 — 8.5 m)
SUA-129	70636311	Carbonate nodules	Offshore	16190 ± 225	Nodules from water depth of 5.2 m (adjusted to L.W.)
SUA-130	71636147 (N)	Carbonate nodules	Offshore	16170 ± 400	Nodules from offshore drill hole 024 (7.9 — 8.5 m)
ANU-1037	70636720	Dolomitic concretions	Charon Point	3870 ± 60	Dolomitized concretions from the supratidal zone
Wood					
ANU-899	71636067	Mangrove wood	Torilla Plains	170 ± 110[1]	Wood from depth of 1 m — probably contaminated
ANU-908	71636143	Mangrove wood	Charon Point	2980 ± 95[1]	Wood from auger hole A23 (1.5 m)
ANU-909	71636144	Mangrove wood	Hoogly-Waverely	1280 ± 85[1]	Wood from auger hole A28 (2 m)
ANU-910	71636145	Mangrove wood	Hoogly-Waverley	3950 ± 125[1]	Wood from auger hole A29 (2.3 — 2.9 m)

ANU-912A	71636142	Mangrove wood	Charon Point	2060 ± 90 [1]	)	Wood from auger hold A18 (2.4 m)
ANU-912B	71636142	Wood (humic acid free)	Charon Point	2290 ± 80 [2]	)	
ANU-947A	71636148	Wood (humic acids)	Charon Point	2220 ± 110	)	
ANU-947B	71636148	Wood (humic acid free)	Charon Point	2950 ± 75	)	Wood from auger hole A19 (2.0 — 2.7 m)
ANU-947C	71636148	Wood (wood fibres free of humic acid)	Charon Point	2170 ± 80	)	
ANU-966A	71636149	Wood (humic acid free)	Charon Point	2760 ± 190	)	
ANU-966B	71636149	Wood (humic acids)	Charon Point	1360 ± 630	)	Wood from auger hole A18 (2.1 — 2.4 m)
ANU-966C	71636149	Mud & wood fines (humic acid free)	Charon Point	2070 ± 160	)	
SUA-126	71636059E	Wood	Torilla Plains	1720 ± 80		Mangrove stump partly buried by supratidal mud
SUA-131	71636206	Wood	Hoogly-Waverley	1335 ± 115		Wood from auger hole A28 (.9 m)
SUA-132	71636207	Wood	Hoogly-Waverley	1100 ± 110		Wood from auger hole A27 (1.8 m)
SUA-133	71636208	Wood	Torilla Plains	4125 ± 310		Wood from auger hole A11 (1.6 — 2.0 m)
SUA-134	71636209	Wood	Torilla Plains	1110 ± 250		Wood from auger hole A7 (.9 — 1.5 m)
SUA-136	71636211	Wood	Torilla Plains	2450 ± 210		Wood from auger hole A7 (1.8 — 2.1 m)
SUA-137	71636212	Wood	Torilla Plains	5850 ± 155		Wood from auger hole A11 (2.4 m)
SUA-138	71636213	Wood	Torilla Plains	5785 ± 550		Wood from drill hole Broad Sound No. 1 (2.4 — 2.7 m)
SUA-139	71636214	Wood	Torilla Plains	6000 ± 400		Wood from drill hole Broad Sound No. 4 (1.8 — 2.4 m)

Footnotes:

ANU — Radiocarbon Laboratory, Australian National University
SUA — Radiocarbon Laboratory, University of Sydney
[1]Treatment of wood before dating consisted solely of washing in distilled water

[2]Wood treated before dating by boiling first in 2% NaOH then in 2% HCl to remove humic acids.

TABLE 12. CORRECTIONS TO PREVIOUSLY PUBLISHED RADIOCARBON AGES FOR BROAD SOUND MATERIALS.

Publication 1 by Cook & Polach, 1973(a), Publication 2 by Cook & Polach, 1973(b).

Lab. No.	*Previous publication*	*Previously reported age (years B.P.)*	*Corrected age (years B.P.)*
ANU-907	1	5020 ± 90	5450 ± 85
ANU-905	1	3640 ± 80	4060 ± 80
ANU-906	1	2530 ± 70	2960 ± 70
ANU-902	1	2500 ± 70	2030 ± 70
ANU-901	1	1710 ± 70	2140 ± 70
ANU-900	1	1670 ± 70	2100 ± 70
ANU-904	1	740 ± 70	1170 ± 70
ANU-967	2	3020 ± 90	3450 ± 90
ANU-1037	2	2860 ± 100	3070 ± 60

the section. Shells obtained at a depth of approximately 8 m in offshore drill-hole 024 were found to have a radiocarbon age of 2430 ± 80 years B.P., (Table 11), indicating that locally there is a rate of sedimentation of about 3 m/1000 years. All drill-holes sited on sand-ridges terminated at a depth of 7 to 10 m in an indurated layer overlain by a thin conglomerate.

Drilling in deeper water, away from the intertidal sand bodies, revealed that this indurated material is present elsewhere. In some places it consists of alternating hard and soft bands (offshore drill-hole 014, Appendix B). Indurated bands are either siliceous or calcareous, and non-indurated bands are generally sandy mud and muddy sand.

The only area where offshore drill-holes failed to intercept an indurated layer was the west side of the Sound (offshore drill-holes 02, 04, and 06, Fig. 100). Seismic profiling in this area revealed several old river channels and consequently it is possible either that the indurated layer was removed by erosion in this area or, alternatively, that river channels and fluvial deposits precluded its formation. Sediments obtained during the offshore drilling contained abundant whole and fragmentary shell fragments and are probably predominantly of subtidal to intertidal origin. The sediments on the west side of the Sound contain a significantly greater proportion of mud than those of the east side, indicating that throughout the Holocene, fluvial influences have been greater on the west side. The only unit of uncertain affinities is the indurated surface. In places, particularly at the northern end of the study area, this surface is seen from the echogram to be rather irregular with jagged peaks rising several metres above the general level of the bottom. Dredging, coring, and drilling in this area were unsuccessful. It is believed that in this area there is early Holocene or pre-Holocene reefal material. Elsewhere, the indurated surface appears relatively flat and featureless; it is commonly overlain by a gravel composed of carbonate nodules. Conaghan (1966) described gravelly deposits from the floor of deep channels in Port Curtis estuary, about 150 km south of Broad Sound. He considered that 'rounded pebbles which comprise part of the bottom sediment in the channels probably represent reworked relict fluvial deposits which underlie marine sands in these localities'. Consequently these pre-Holocene gravels may be a common feature of this portion of the central Queensland coast. At both Broad Sound and Port Curtis it is necessary to invoke a non-marine origin for gravels and associated indurated sediments. The induration is believed to be the result of subaerial soil-forming processes in the late Quaternary. Using offshore and some onshore information it is possible to plot the elevation of the indurated surface (Fig. 101), and it is clear from this that the surface has a marked seaward dip.

Onshore Stratigraphy

Coring and augering at many localities on the coastal plain around Broad Sound, together with radiocarbon dating of samples, have made it possible to determine the onshore stratigraphic sequence. As in the offshore drilling, a number of drill holes bottomed in an indurated layer believed to represent in part a late Pleistocene to early Holocene weathering profile. This indurated layer becomes progressively shallower in a landward direction (Fig. 101) and is found up to several metres above present-day sea level in the Torilla Plains area on the east side of Broad Sound. It is possible that Holocene tectonic uplift (see later) is partly responsible for this shoreward shallowing. Overlying the indurated surface is a sequence of Holocene mud, sand, and gravel up to 5.5 m thick. An isopach map of the Holocene

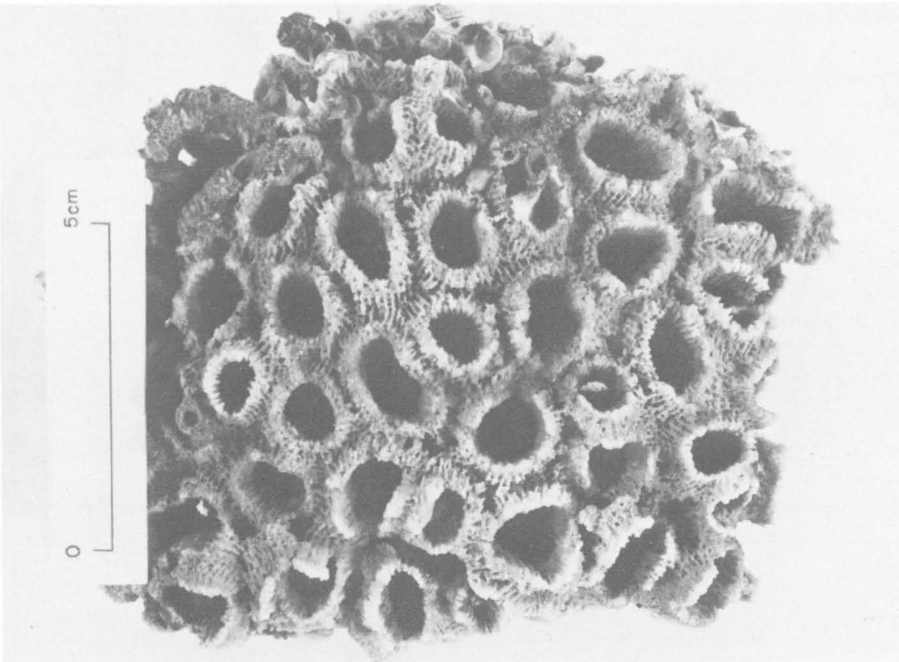


Plate 47, fig. 1. Dead coral (*Favia* sp.) from the L.W.S. tidal level in the Styx River near Charon Point. This specimen has a radiocarbon age of 30 700 ± 1200 years B.P. (GA/7839)

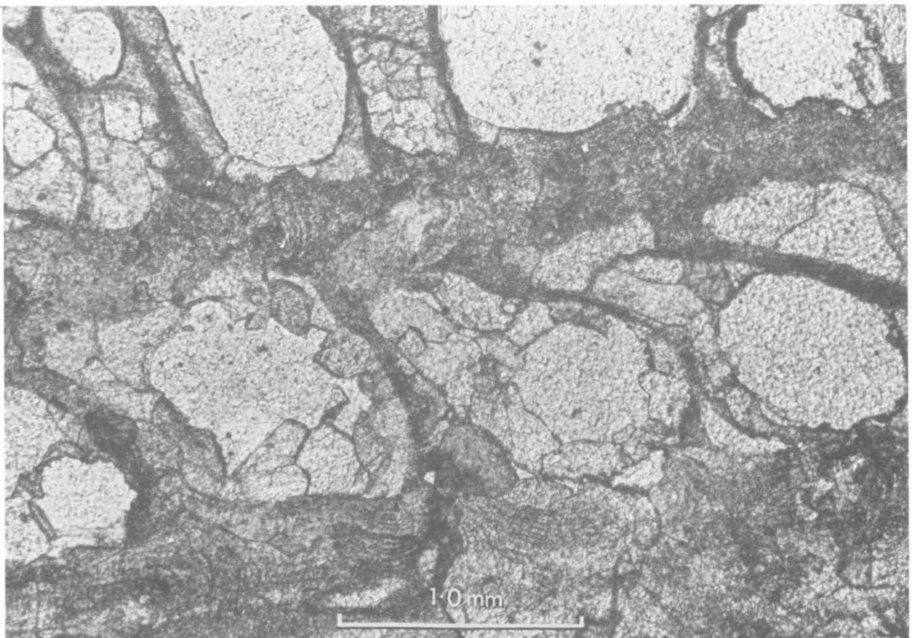


Plate 47, fig. 2. Thin section (ordinary light) of the coral shown in Plate 47, fig. 1, showing coarse recrystallized calcite. (M/1482)

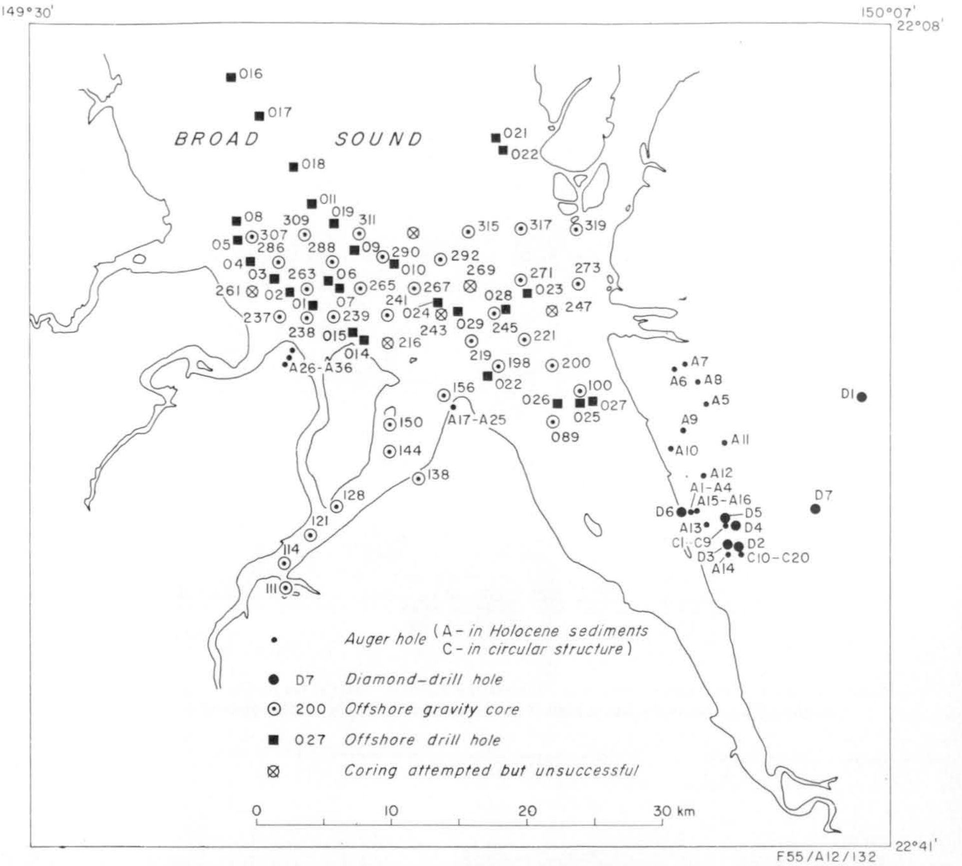


Figure 100. Location of offshore vibracore and gravity cores, and onshore diamond and auger holes.

sequence (Fig. 102) reveals that the onshore Holocene sequence is in general significantly thinner than the offshore sequence which is up to 10 m thick.

Between 16 000 and 6000 years B.P., sea level was substantially below the present-day level (see later); consequently the onshore Holocene marine sequence is entirely late Holocene i.e. 6000 years B.P. or less. This sequence was examined in three areas, Torilla Plains, Charon Point, and the area between The Hoogly and Waverley Creek. The Holocene stratigraphy of the Torilla Plains area has been dealt with by Burgis (1975). The stratigraphy of the other two areas is given in a series of vertical logs, and the information is summarized in Figure 103 as a series of cross-sections. The sequence consists almost everywhere of 1 to 3 m of grey sand and muddy sand, at the base, overlain by up to 2 m of dark grey to black mud with abundant mangrove fragments, which is in turn overlain by 1 to 2 m of olive-grey mud almost devoid of wood fragments. In places the olive-grey mud is overlain by a gravel primarily of shell debris where ridges overlie the sequence, and it is evident from the sections in Figure 103 that the ridges are not all beach ridges extending to some depth, but that some are perched ridges or cheniers (see later). In places the olive-grey mud is overlain by a thin soil. Burgis (1975) noted that in places on the landward side of Torilla Plains, fluvial gravel overlies this soil.

Using the characteristics of the sediments being laid down in the present-day depositional environments and comparing them with the lithology of the sediments intercepted during the drilling, it is possible to recognize the prevailing depositional conditions with a high degree of confidence. The sequence consists of open intertidal muds and sands at the base, overlain by mangrove swamp deposits; in places it is possible to distinguish between mangrove of the intertidal and supratidal zones (Burgis, 1975), which is in turn overlain by supratidal flat deposits.

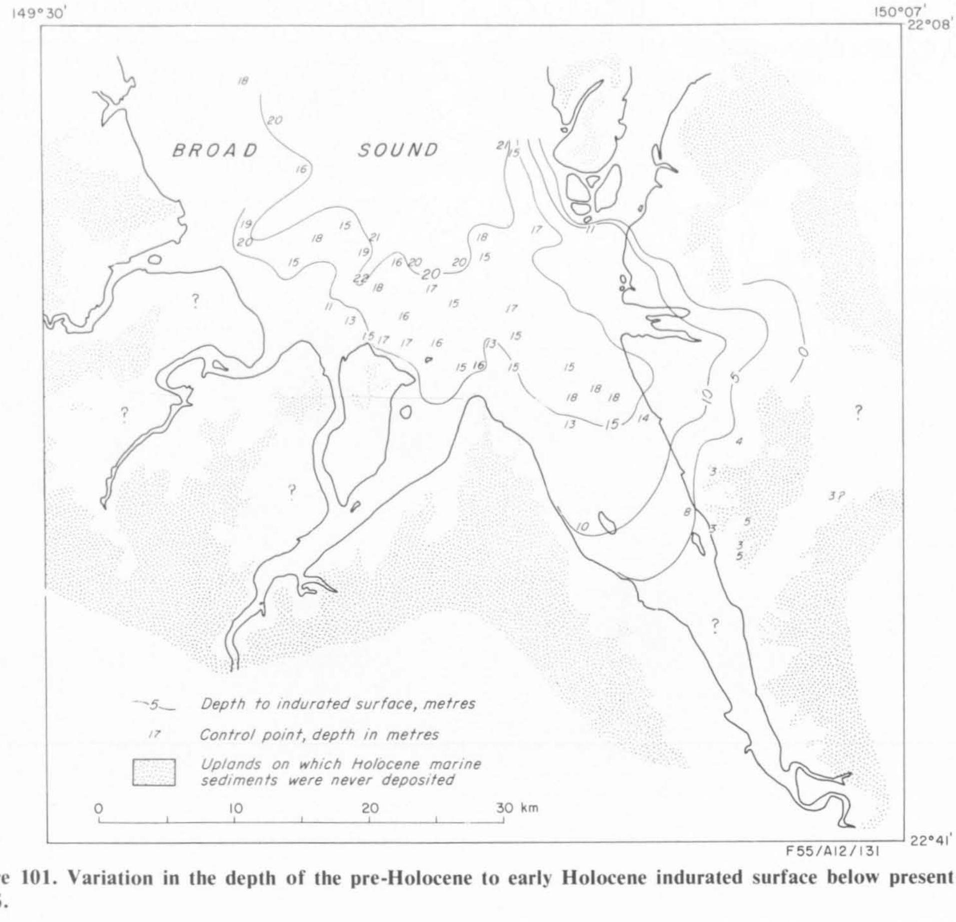


Figure 101. Variation in the depth of the pre-Holocene to early Holocene indurated surface below present-day HWS.

The upward sequence is the modern intertidal-supratidal sequence, and is an excellent illustration of Walthers Law that the vertical sequence recapitulates the lateral sequence. Structures and textures are very similar in both the modern and the late Holocene sediments. Consequently the upward succession represents a shallowing event and is obviously regressive. No transgressive sediments were recognized in the sequence, possibly because the Holocene transgression associated with rising sea level between 16 000 and 6000 years B.P. was so rapid that there was little associated sedimentation. The regressive nature of the sequence is confirmed by the cheniers (see later) which show that the sequence becomes younger to seaward. It is noted that the stages of soil formation and influx of fluvial sediments are also integral parts of the regressive sequence. The idealized regressive sequence shown in Figure 104 is useful not only for serving as a model for other regressive sequences in the geological record but also for clarifying some of the sedimentary and diagenetic processes. The mangrove swamp deposits in particular change somewhat at depth. At the surface they are predominantly brown and quite strongly oxidized but at a depth of a metre or more become black and strongly reducing; this has a marked effect on the geochemistry of the sediments (Cook & Mayo, in prep.).

Before the drilling program it was assumed that the sediments of the muddy facies of the open intertial environment were ephemeral sediments unlikely to be preserved in the sedimentary record. In fact, such sediments were found to be common in the Holocene sediments at Broad Sound. Drilling also clarified that supratidal flats are everywhere underlain by mangrove swamp deposits. The supratidal flat deposits commonly extend to below the top of the adjacent mangrove swamp deposits as exemplified by the Torilla Plains sequence (Fig. 104). Thus the model for high intertidal-supratidal environments is one of progressive lateral and upward growth of the

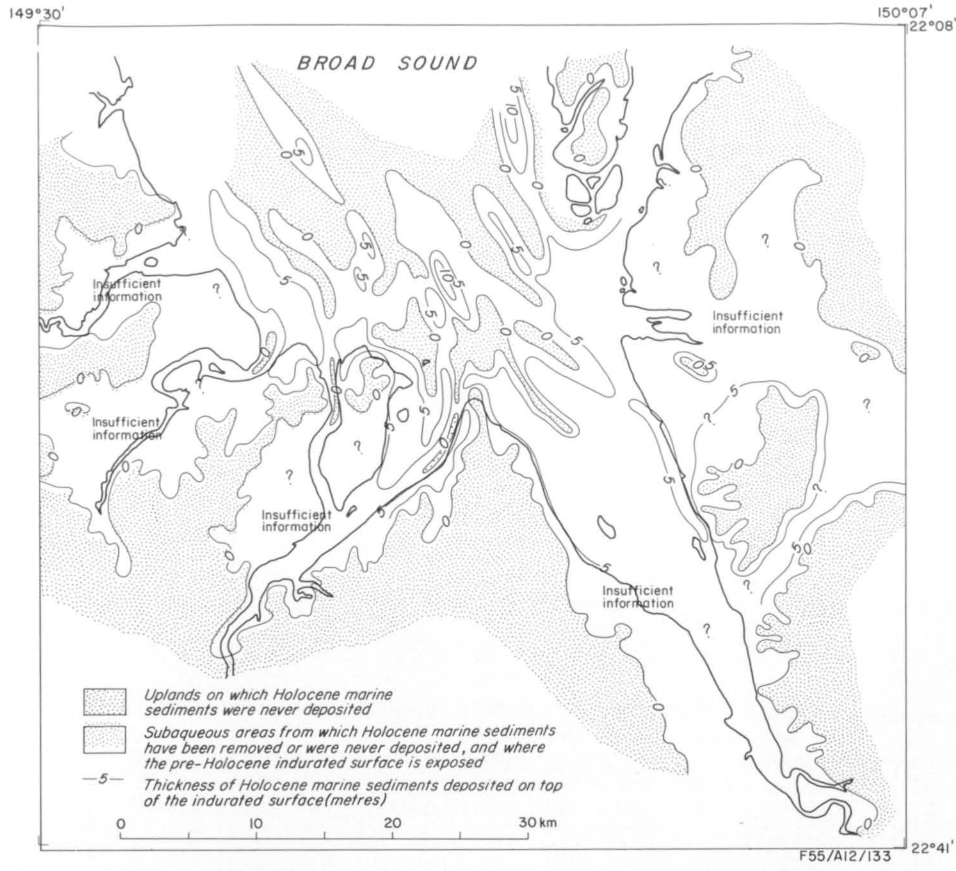


Figure 102. Thickness of Holocene marine sediments in the Broad Sound area.

mangrove swamp deposits until these deposits become sufficiently elevated that hypersaline conditions prevail. Unable to withstand high salinity the mangrove trees die. The sediment is now no longer bound by the roots and trees and consequently on each spring tide the old mangrove swamp sediment is subject to minor erosion and redistribution, so that there is some 'in situ development' of supratidal flats from the now-inactive mangrove swamp. The relative importance of lateral progradation and vertical accretion for the exclusion of seawaters and the associated formation of supratidal flats is uncertain. Insufficient data are available to indicate vertical rates of sedimentation for all the depositional environments. If a linear rate of accumulation is assumed, radiocarbon ages on mangrove material in auger-holes A7 and A19 (Fig. 101) indicate rates of sedimentation for mangrove swamp deposits of 0.6 m/1000 years and 2.4 m/1000 years. However, mangrove material separated vertically by 1.0 m, in auger hole A28, had the same age to within one standard deviation. Therefore the present data are insufficent to indicate anything other than that the rate of sedimentation in mangrove swamp environments is variable and is probably not linear. As the elevation increases, the rate may decrease exponentially. Undoubtedly sedimentation can be rapid at times. It would seem that, for the onshore Holocene sequence as a whole, the vertical rate of accretion averages 0.5 to 1.5 m per 1000 years. Offshore, sedimentation may be much more rapid. In offshore drill-hole 024 shell material with a radiocarbon age of 2430 years B.P. (sample SUA-128) was intercepted at a depth of about 8 m below the sediment-water interface, indicating a sedimentation rate of about 3 m/1000 years. However, the rate of sedimentation in intertidal-subtidal areas is variable; as elsewhere, residual deposits with an age of 16 000 years B.P. are exposed on the sea bottom, indicating a marked local sedimentary hiatus.

The lateral rate of accretion resulting from depositional progradation is better documented by radiocarbon dating of chenier and mangrove

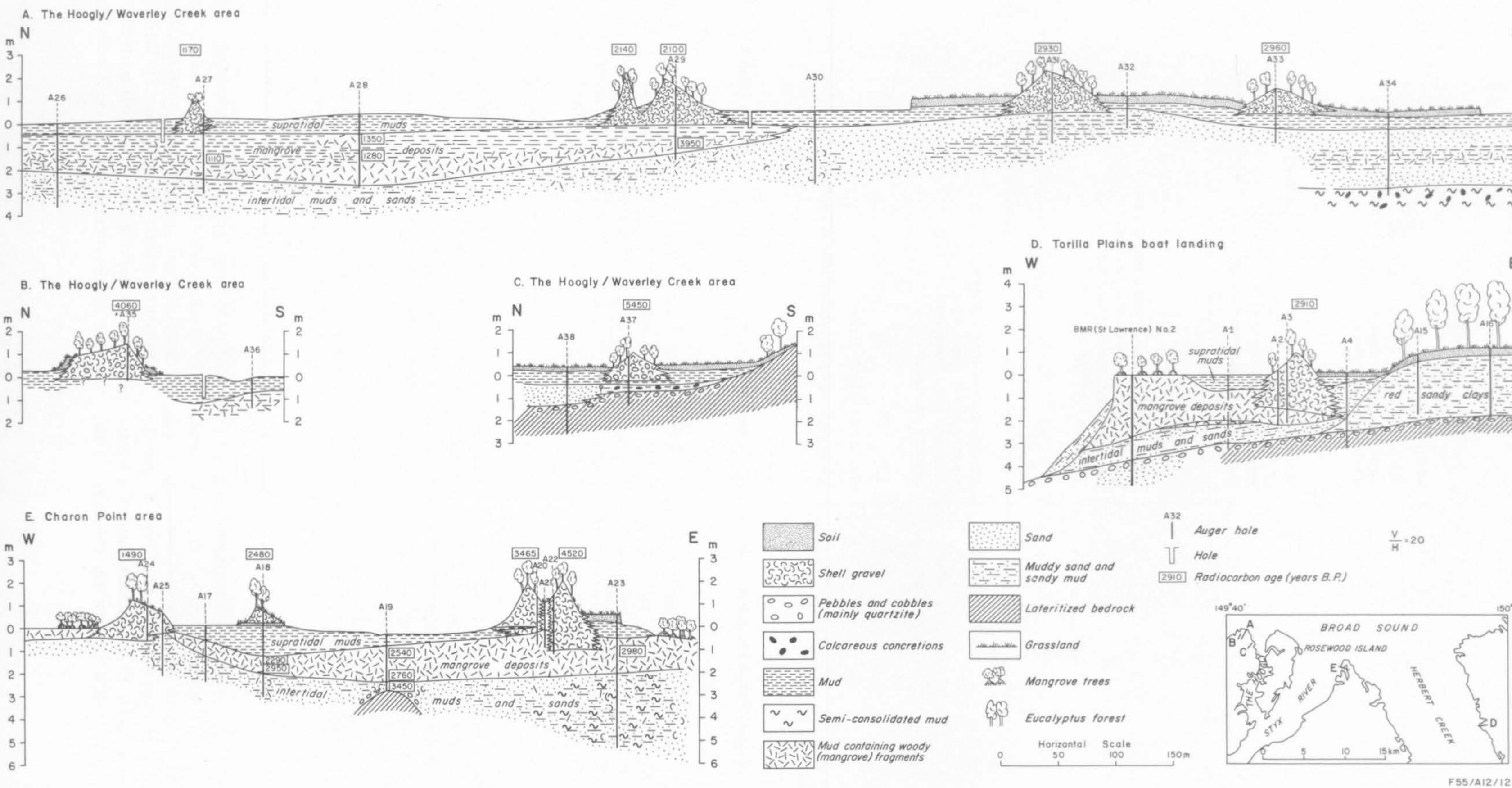


Figure 103. Cross-sections through the Holocene marine sequence in The Hoogly/Waverley Creek area (Sections A-C), the Torilla Plains boat landing (D), and Charon Point (E).

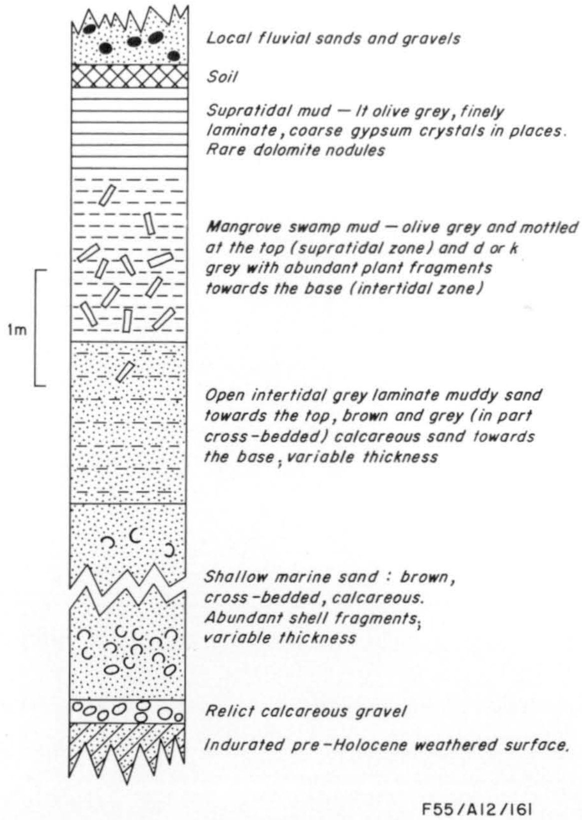


Figure 104. Generalized section for the regressive late Holocene sequence at Broad Sound.

swamp material. It is variable, with old chenier material occurring close to the present-day shoreline in places, indicating little or no progradation. It is, however, possible to determine a maximum rate. Cook & Polach (1973a) determined the maximum rate of progradation in the Charon Point and Waverley Creek areas as 1.2 km per 1000 years and 1.1 km per 1000 years, respectively. In the Torilla Plains area progradation appears to have been about 1.7 km per 1000 years; the more rapid regression in this area is probably a result of some tectonic uplift (see later). This uplift may also account for the thinner Holocene sequence in the Torilla Plains area compared to the sequence of the west side of Broad Sound.

Chenier Sequences

In a number of places around Broad Sound, low elongate ridges rise 1 to 2 m above the general level of the surrounding coastal plain. Similar features have been described from southwest Louisiana by Howe, Russell, McGuirt, Craft, & Stephenson (1935), Price (1955), and Coleman (1966) and are there known as cheniers. This name has been applied elsewhere to shallow-based sandy ridges resting on clay, in contrast to beach ridges which may be flanked by mudflats but generally extend to greater depths and rest on a sandy base. Cook & Polach (1973a) have described the Broad Sound cheniers; consequently they will not be considered in detail here.

Cheniers are found at a number of localities around Broad Sound (Fig. 6). Scattered cheniers are present on Torilla Plains, the most prominent being at Fort Cope (Pl. 6, fig. 2). The best developed sequences occur on the west side of Broad Sound at the mouths of the Styx, The Hoogly, and Waverley estuaries (Pl. 48, figs. 1 and 2). Here, individual cheniers up to 5 km long, 50 m wide, and 2 m high, are composed mainly of coarse shell debris, and have poorly defined bedding in place (Pl. 49, fig. 2). Despite their comparatively low relief, they support a prolific vegetation cover (in contrast to the surrounding treeless coastal plains) and consequently form prominent features (Pl. 50, fig. 1). Radiocarbon ages have been obtained on shell material from a number of cheniers (Table 11). These ages may

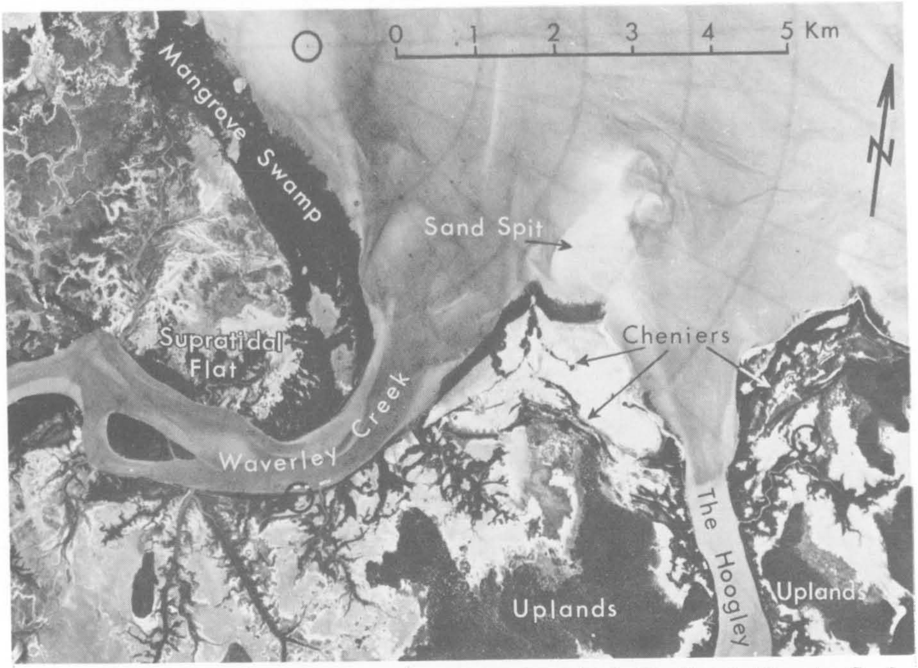


Plate 48, fig. 1. Vertical aerial photograph of the chenier plains in The Hoogly/Waverley Creek area. (GA/7826)

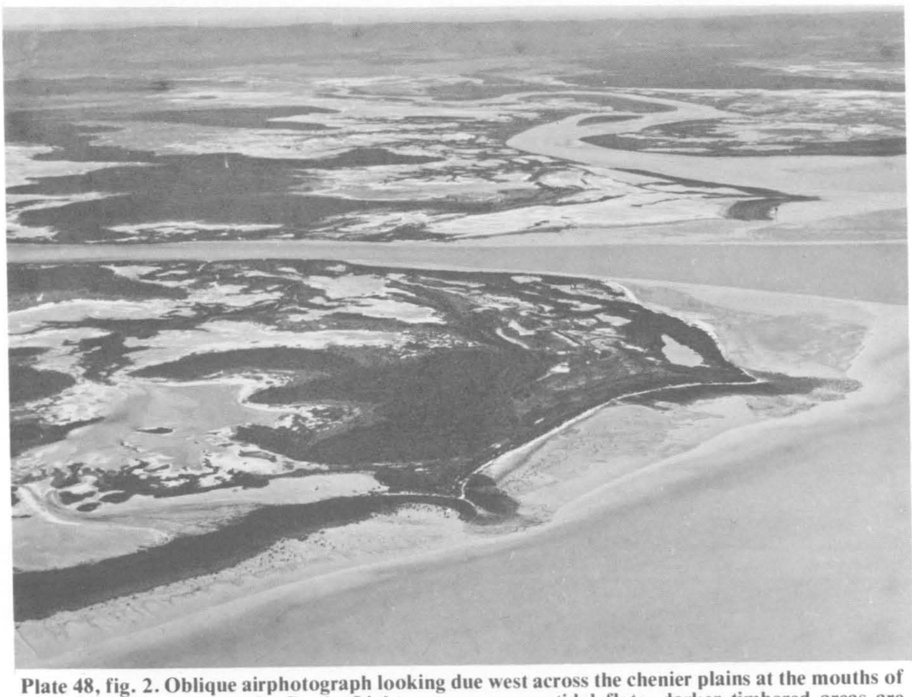


Plate 48, fig. 2. Oblique airphotograph looking due west across the chenier plains at the mouths of The Hoogly and Waverely Creek. Light areas are supratidal flats, darker timbered areas are uplands. Dark pattern along the coast is mangrove swamp. (GA/3645)

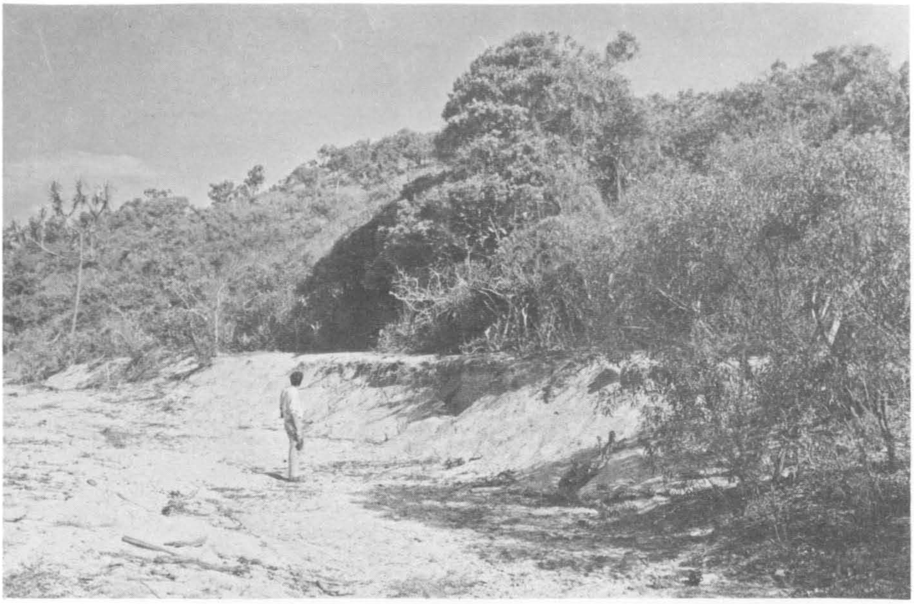


Plate 49, fig. 1. Heavily timbered ridge of shell debris, at Charon Point. (GA/4084)

Plate 49, fig. 2. Bedded shell debris in the ridge (shown in Plate 49, fig. 1.) at Charon Point. (GA/7869)

Plate 50, fig. 1. Timbered chenier surrounded by bare supratidal flats, near Charon Point. (M/1100)

Plate 50, fig. 2. Low chenier which is undergoing some erosion at the present time, at Charon Point. (M/1100/9).

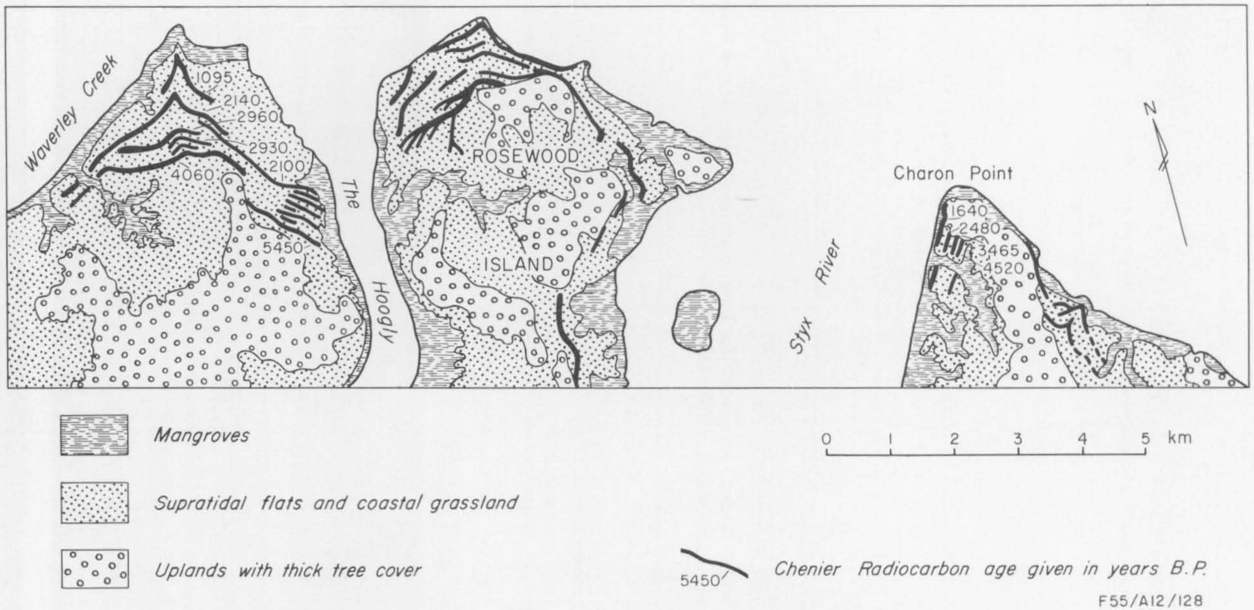


Figure 105. Positions and radiocarbon ages of cheniers in the southwest part of Broad Sound.

perhaps be regarded as giving the age of formation of the chenier, but some reworking of shelly material may have occurred. This is happening at a number of localities at the present day where erosion of an old chenier is taking place (Pl. 50, fig. 2). Despite this, the ages obtained show a well defined sequence of becoming younger seawards (Fig. 105), suggesting either that little or no reworking of older material has taken place or, alternatively, that any contribution of 'old' shell material was minor compared to the contribution of 'young' shell material.

If dates obtained on shells and wood are compared, some minor inconsistencies are apparent. The chenier at Charon Point (Fig. 103) with an age of 2480 ± 100 years B.P. (ANU-793) is underlain by wood (free of humic acid) with a radiocarbon age of 2290 ± 80 years B.P. (ANU-912B) and 2760 ± 190 years B.P. (ANU-966A). This would seem to confirm that in this case, at least, the date obtained on shells from the chenier gives only its approximate date of formation. From the evidence of the dates obtained on wood from the underlying units it could be considered that the age obtained is a maximum age for the formation of the chenier.

The most seaward chenier in The Hoogly/-Waverley sequence has a radiocarbon age of 1170 ± 70 years B.P. (ANU-904A) and 1020 ± 70 years B.P. (ANU-904B). At the same locality wood from mangrove deposits at a depth of about 2 m has the same radiocarbon age (to within two standard deviations) of 1110 ± 100 years B.P., whereas the mangrove deposits would be expected to be older than the cheniers. The reason for the similarity in age may be that the shells result from erosion of the underlying mangrove unit, and hence the carbonate material in both units has much the same radiocarbon age. At some other localities, however, the underlying mangrove deposits are significantly older than the overlying chenier. The chenier material in auger-hole A29, which has a radiocarbon age of 2100 ± 70 years B.P. (ANU-900) is underlain by mangrove deposits containing wood with a radiocarbon age of 3950 ± 125 (ANU-910).

The Broad Sound cheniers are believed to have formed mainly in response to purely local depositional conditions, possibly in response to a fluctuating sediment supply. It is noticeable that the greatest concentration of cheniers occurs on the southwest side of the Sound where the wave fetch is greatest and the shore most subject to erosion. Consequently, any decrease in sediment supply would be followed by coastal erosion, leading to death of mangrove, and cheniers forming (from winnowed-out shelly material) to shoreward of the old mangrove swamps. This process is discussed by Cook & Polach (1973a). The radiocarbon ages on the cheniers indicate a seaward progradation of the shoreline over the past 5500 years.

Holocene Tectonics and Sea-Level Changes

As a result of the waning of the Pleistocene ice sheets, major changes in sea level have occurred over the past 15 000-17 000 years. These changes have been documented by many authors including Bloom (1967, 1970, 1971), Coleman & Smith (1964), Fairbridge (1958, 1961), Morner (1969, 1971a, b), Schofield (1960), Schofield & Thompson (1964), and Shepard & Seuss (1956). Of particular relevance to sea-level changes in the Australian region are publications by Bird (1971), Cook & Polach (1973a), Gill (1971), Glenie, Schofield, & Ward (1968), Hopley (1968, 1971), Thom, Hails, & Martin (1969), Thom, Wright, & Coleman (1972), and Ward (1971).

Most workers agree that from about 16 000 to 6000 years B.P. there was a rapid worldwide rise in sea level, but there is little specific agreement on the period between 6000 years B.P. and the present. Some suggested curves given in Figure 106 show the wide variety of interpretations for the late Holocene period.

The fundamental reason for these differences in interpretation is the difficulty in separating relative changes of sea level resulting from glacial eustacy from those resulting from hydro-isostasy and tectonism. Bloom (1971) pointed to the problem of isostatic adjustment due to water loading. In many areas, including Broad Sound, it is difficult to separate the various parameters to produce a sea-level curve. The difficulties are exemplified by the fact that whereas Thom et al. (1969) considered from evidence on the south Queensland/New South Wales coast that sea level stabilized at the present-day level about 6000 years ago, others such as Hopley (1971) have considered that during this same period, sea level has been as much as 3.5 m above the present-day level.

The Broad Sound region lies between north Queensland, from where data can be taken to indicate a high sea level, and the southern Queensland/northern New South Wales coast where sea level is taken to have stabilized about 6000 years ago. It is difficult, however, to determine whether Broad Sound has been tectonically stable during the Holocene. There is the additional problem in deciding where to place mean sea level in an area such as Broad Sound with a tidal range as high as 10 m. The only level that can be established with any degree of confidence is the High-Water Springs (HWS) level on the basis of the elevation of the supratidal mud flats, but even this level may vary by as much as ± 1 m throughout the

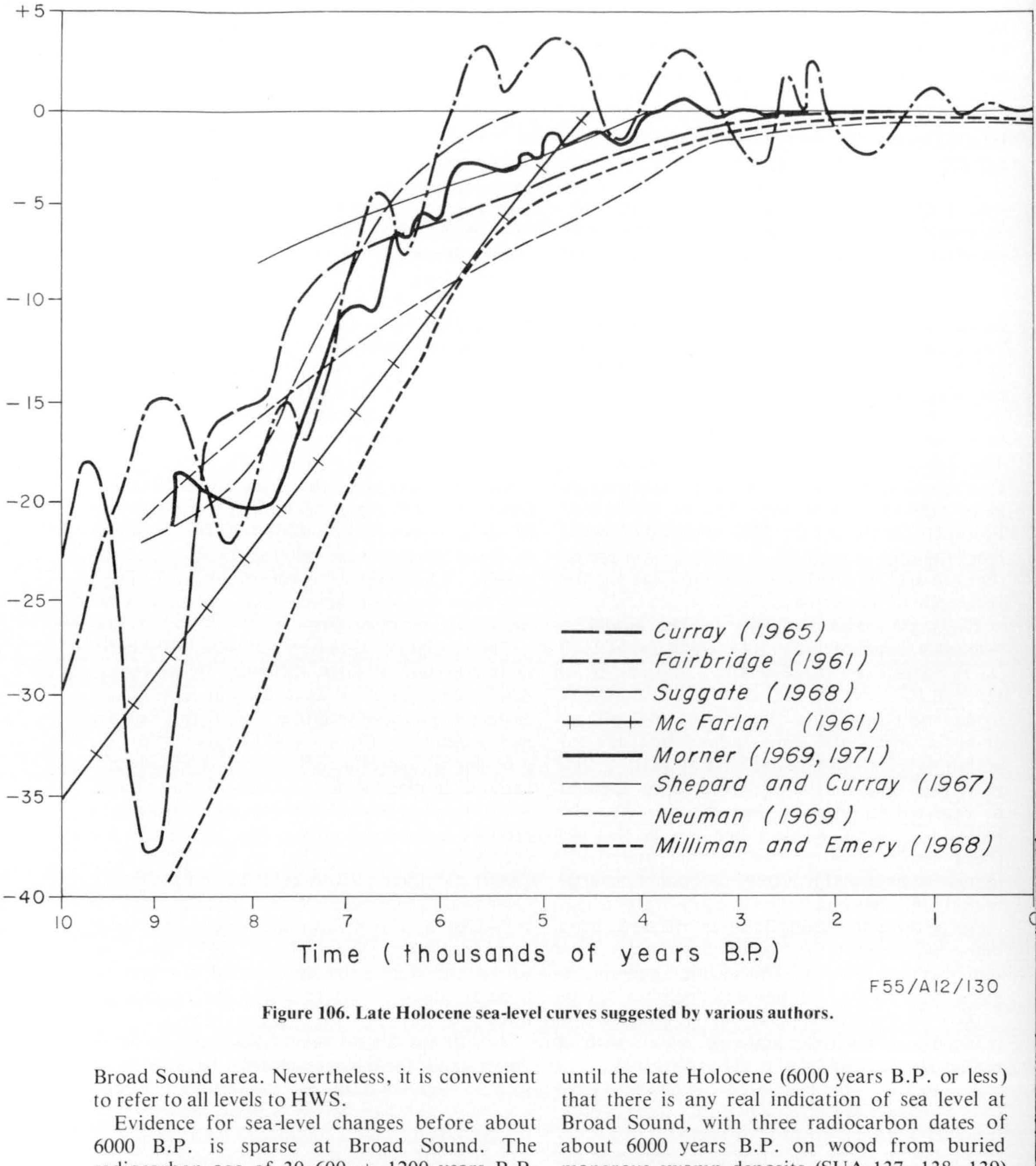


Figure 106. Late Holocene sea-level curves suggested by various authors.

Broad Sound area. Nevertheless, it is convenient to refer to all levels to HWS.

Evidence for sea-level changes before about 6000 B.P. is sparse at Broad Sound. The radiocarbon age of 30 600 ± 1200 years B.P. (SUA-110) for dead coral at low-water mark merely indicates that at some time before 30 000 years B.P., sea level was at or above the present-day level. The age of about 16 000 years B.P. (SUA-129, SUA-130) on carbonate nodules thought to be pedogenic in origin suggests that 16 000 years ago, sea level was 20 m or more below present-day HWS. Consequently, it is not until the late Holocene (6000 years B.P. or less) that there is any real indication of sea level at Broad Sound, with three radiocarbon dates of about 6000 years B.P. on wood from buried mangrove swamp deposits (SUA-137, 138, 139) in the Torilla Plains area.

In Figure 107 the elevation of radiocarbon samples is related not to the present-day HWS but to that prevailing at the time of deposition. This is approximated by regarding the top of the supratidal flat deposits overlying the mangrove swamp deposition as indicating HWS at the time of mangrove swamp deposition. Because of the

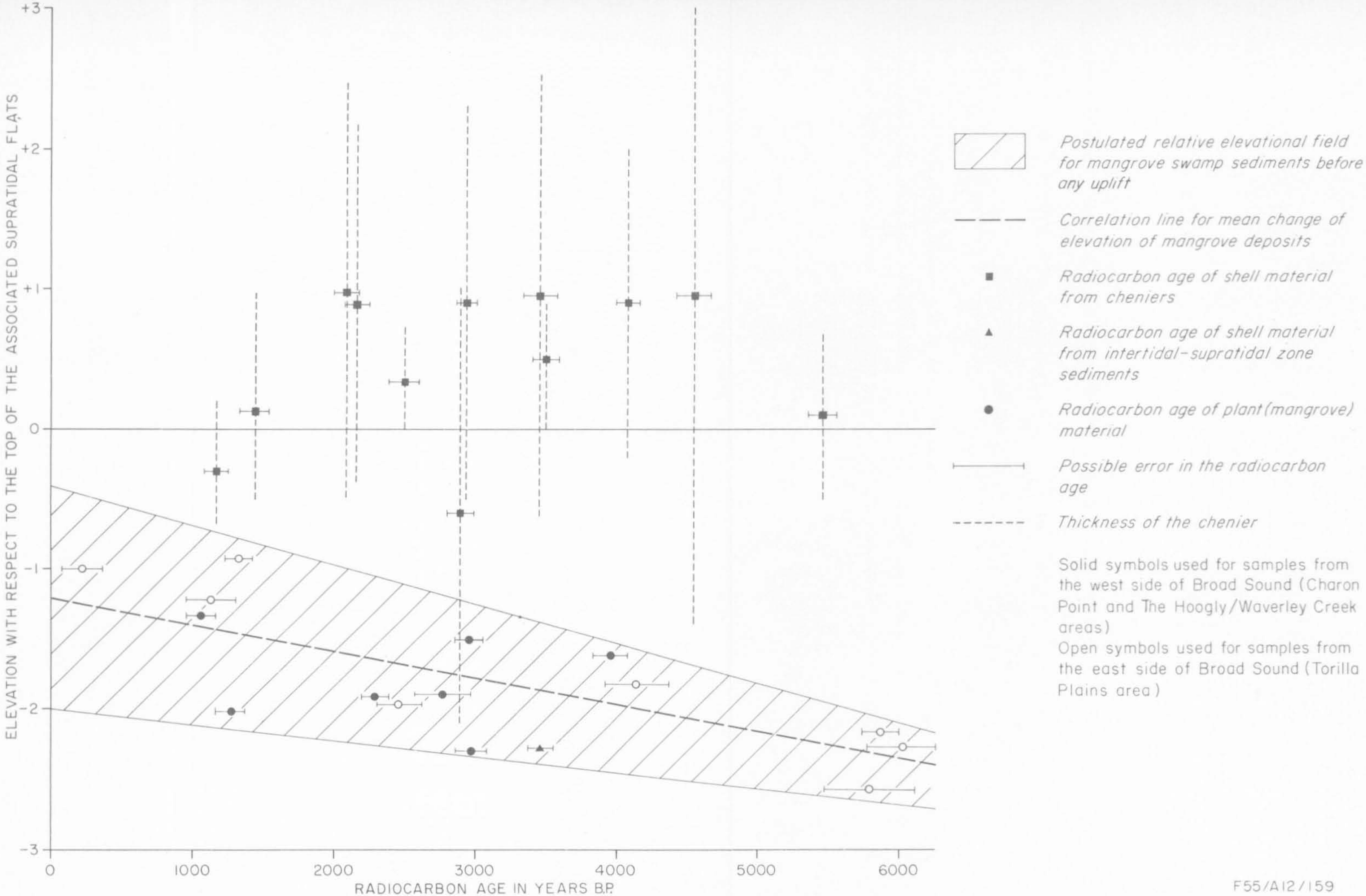


Figure 107. Elevation of radiocarbon samples with respect to their elevation above or below the surface of associated mangrove swamp deposits.

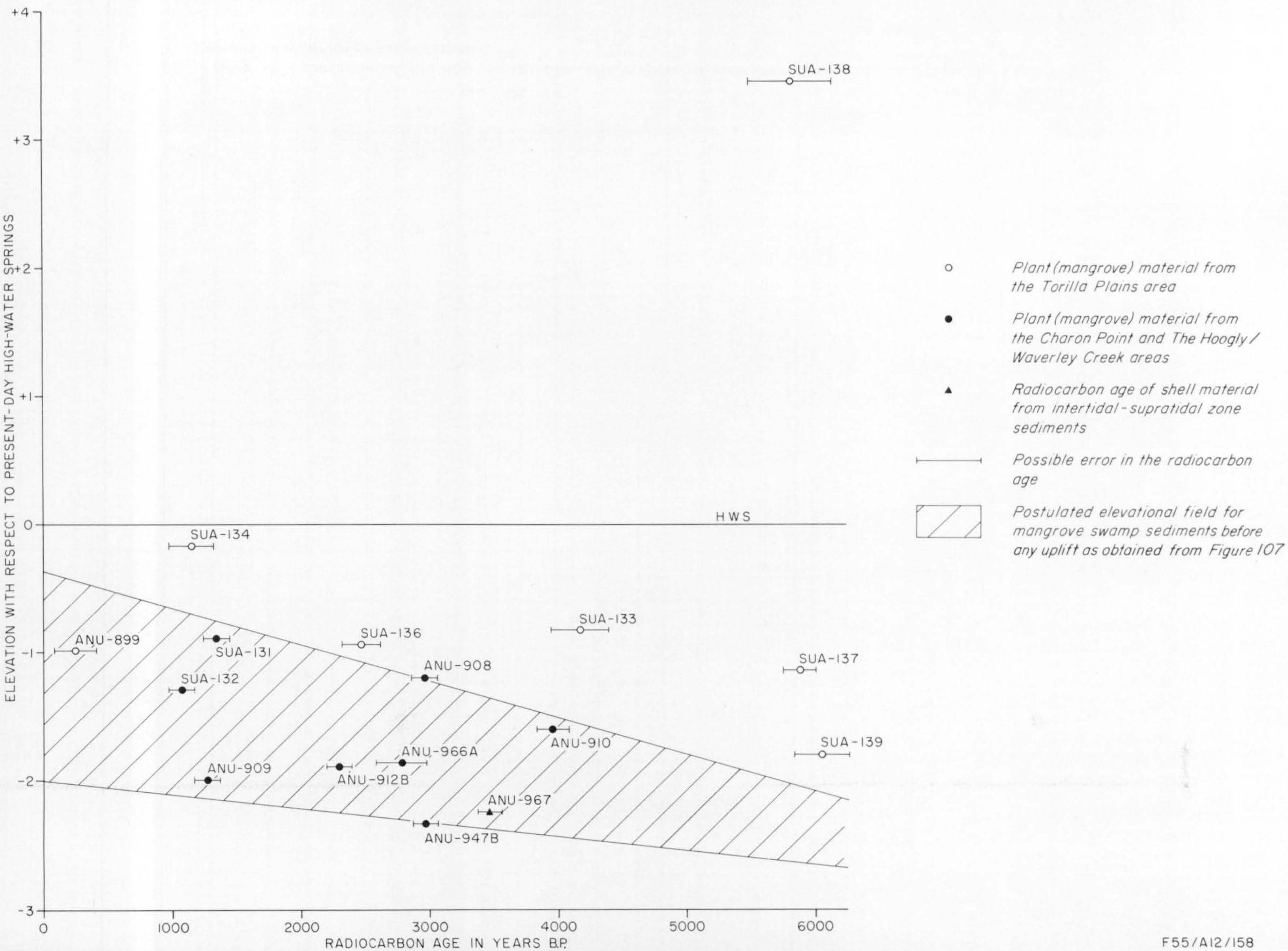


Figure 108. Elevation of radiocarbon (wood) samples with respect to present-day HWS.

time lag involved in the deposition of the supratidal flat sediments, this level is only an approximation. Nevertheless, a linear trend is apparent with relative elevation of the mangrove swamp deposits increasing with decreasing age, a change of about 12 m occurring over a period of 6000 years. Thus, the change is relatively minor. This trend obviously does not reflect an overall sea-level change which would have resulted in the elevation of the surface of all deposits and consequently there would have been no relative change. Therefore the trend in Figure 107 is considered more likely to be the result of a gradual increase in the tidal range over the past 6000 years. Such a change might reasonably be expected as the Broad Sound estuaries have become increasingly V-shaped over the past 6000 years.

No clear trend is evident from the elevation of the cheniers relative to the surface of the supratidal flat deposits (also shown in Fig. 107). There is the suggestion of an increase in elevation relative to the HWS prevailing at the time of deposition in the period 4000 to 2500 years B.P., which might correspond to, for instance, a period of increased storm activity. However, at present the trend is too poorly defined to be considered significant. Perhaps the most important single feature in Figure 107 is the lack of chenier or mangrove swamp material older than about 6000 years B.P. This indicates that before 6000 years B.P., sea level was rising too rapidly for extensive chenier and mangrove swamp deposits to form, but since that time any sea-level changes were probably minor.

Jardine (1928) has suggested from evidence in the Torilla Plains area that about 4500 years ago sea level stood 4.5 to 6 m higher than at the present day. Accurate levelling across Torilla Plains was not undertaken during the present investigations. The coastal grasslands which represent ancient inactive supratidal flats are up to an estimated 4 to 6 m above the present-day HWS. If the elevation of samples and their radiocarbon ages are now re-plotted with respect to present-day HWS (Fig. 108) a different picture emerges to that in Figure 107. The field of mangrove swamp material is now much more scattered, with Torilla Plains samples from the remainder of Broad Sound. Thus opposite sides of Broad Sound suggest different sea levels for the same time, and the question is which, if either, is the tectonically stable side of Broad Sound. Sample SUA-138 which is from about 15 km inland in particular might be taken as evidence that 6000 years ago sea level stood 4 to 6 m above the present-day level. However, the elevation of sample SUA-139 which is also from the east side of Broad Sound and which has a radiocarbon age of about 6000 years B.P. suggests that at that time, sea level stood close to the present-day level when an allowance is made for the change in the tidal range. Cook & Polach (1973a) also considered from the evidence of the cheniers that sea level stabilized about 5000 years ago (or 5500 years ago, using the revised ages) and since that time has not varied by more than about ± 1 m from the present-day level.

Most radiocarbon samples in Figure 108 fall into the mangrove field previously established in Figure 107, and the implication of this field is that sea level has not changed greatly over the past 6000 years. If the few samples falling outside this field are regarded as atypical and are assumed to have been elevated by tectonic uplift, the relative rate may be determined. If, however, a change in the tidal range has also occurred, as inferred by the trend of the mangrove swamp in Figure 107, then a correction, though small, should be applied to the elevation. This may be done by obtaining the equation of the correlation line in Figure 107. The formula for this straight line may be expressed as

$e = tm + c$

where

e = elevation of the sample in metres with respect to the HWS at the time of deposition

t = radiocarbon age of the sample in years B.P.

m = the gradient of the correlation line

c = the intercept on the y axis, which is equivalent to the mean elevation of the mangrove swamp deposits with respect to present-day HWS.

This is determined as

$e = -.000183\,t - 1.22$ . . . Equation 1

The relative rate of uplift (R), in metres a year, may be determined from the present-day elevation of the sample (h) by the formula.

$$R = \frac{h - e}{t}$$

Substituting for e, using the value given in Equation 1,

$$R = \frac{h + 1.22}{t} + .000183 \text{ . . . Equation 2.}$$

This formula (Equation 2) has been applied to all those samples falling outside the general field of occurrence of mangrove swamp samples (Fig. 108) to give rates of uplift (Table 13). The value obtained for SUA-139 indicated that there has been no significant uplift in the region of that sample. However, elsewhere in the Torilla Plains region values range from 0.20 to 1.10 m/1000 years. The implication is that the area is comparatively unstable with a high rate of uplift. The data are sparse, but the fact that the rate varies suggests differential vertical movement, implying warping. Uplift in the Torilla Plains region is

N

TABLE 13. INFERRED RATE OF UPLIFT AT LOCALITIES IN THE TORILLA PLAINS AREA.

Drilling site	*Radiocarbon sample*	*Radiocarbon age (years)*	*Rate of uplift (metres per 1000 years)*
A 11	SUA-133	4140	.30
A 7	SUA-134	1130	1.10
A 7	SUA-136	2470	0.30
A 11	SUA-137	5870	0.20
D 1	SUA-138	5790	0.98
D 4	SUA-139	6010	0.01

suggested by the elevation of the pre-Holocene indurated surface (Fig. 101), and by the thinner Holocene sequence on the east side of Broad Sound (Table 14). Just how much of the Broad Sound Peninsula is affected by this uplift is uncertain, although Holocene uplift of beach rock may have also occurred at the northern end of the Peninsula. The extensive pre-Holocene gravels and alluvial fans on the east side of Broad Sound Peninsula suggest that uplift has been continuing for some time. In addition, the ranges and the cliffed coast on the east side of the peninsula, compared to the low swampy west coast, suggests that the degree of relative uplift is greater on the east side. Some of this movement may have occurred along the Broad Sound Fault of Kirkegaard et al. (1970), who considered that there had been recent movement in the Shoalwater Bay area. However, further work will be necessary to document the neotectonics of this region.

In conclusion, radiocarbon ages in the Broad Sound area suggest that sea level stabilized at about the present-day level 6000 years ago. Since that time there has been a minor increase (about 1 m) in the tidal range in the Sound. There may have been a period of increased storm activity between 4500 and 2500 years B.P., but this is poorly documented. In general, sea level appears to have varied by no more than about ± 1 m from the present-day HWS. There has, however, been some tectonic uplift in places during the late Holocene, with an inferred uplift of up to 1 m per 1000 years in parts of the Torilla Plains area.

Holocene History

In the period immediately preceding the postglacial transgression, the whole Broad Sound area was subaerially exposed. The region sloped gently to the north; soils developed on the surface, and there was extensive weathering of Pleistocene and older sediments producing a pre-Holocene indurated surface. Offshore seismic data indicate a fairly extensive drainage pattern in the western half of the area, associated with the Styx, Waverley, and St Lawrence drainage system (Fig. 109a). There does not appear to have been a major Pleistocene Fitzroy River system passing through Broad Sound. The only deep channel was that associated with pre-Pleistocene faulting and sedimentation, as exemplified by Figures 89 and 90. This may have corresponded to a major river channel but is undoubtedly a comparatively old feature.

In the period 16 000 to 6000 years B.P. there was a rapid rise in sea level. Winnowing of fine material from the weathered pre-Holocene land surface during this transgression resulted in gravel deposits overlying the indurated surface. Shelf material was probably swept into Broad Sound, but in general there was little sedimentation in the Sound during this time. At about 6000 years B.P. sea level stabilized; Broad Sound was at that time a much more extensive body of water, with numerous islands on the east side (Fig. 109b). Nearshore intertidal sand bodies initially formed from terrigenous materials as at that time there was little calcareous material on the shelf apart from that near the Barrier Reef.

TABLE 14. AVERAGE THICKNESS OF THE HOLOCENE SEQUENCE IN THE BROAD SOUND AREA

	Sediment Thickness (metres)			
Depositional environment	*Torilla Plains*	*Charon Point*	*The Hoogly-Waverley*	*Broad Sound Average*
Supratidal flat	0.6	0.8	0.6	0.7
mangrove swamp	1.3	1.2	2.0	1.5
open intertidal	1.2	2.3	2.1	1.6
Total	3.1	4.3	4.7	3.8

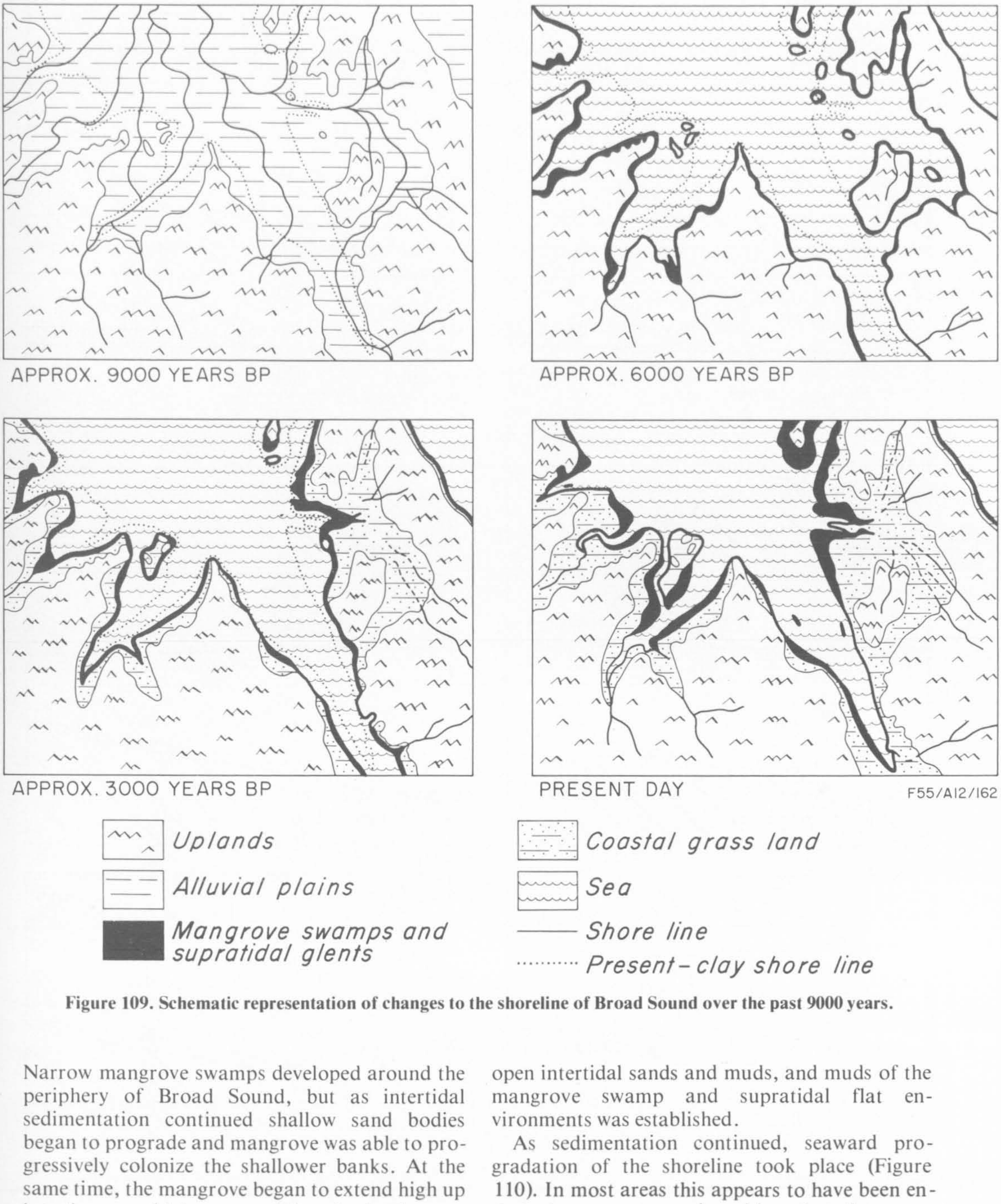


Figure 109. Schematic representation of changes to the shoreline of Broad Sound over the past 9000 years.

Narrow mangrove swamps developed around the periphery of Broad Sound, but as intertidal sedimentation continued shallow sand bodies began to prograde and mangrove was able to progressively colonize the shallower banks. At the same time, the mangrove began to extend high up into the supratidal zone, until its colonization was limited by hypersaline water. The more landward mangrove then died and hypersaline supratidal flats were established, on which mud was deposited during spring tides. Therefore, by shortly after 6000 years B.P., the basic facies distribution pattern of shallow-marine gravels, open intertidal sands and muds, and muds of the mangrove swamp and supratidal flat environments was established.

As sedimentation continued, seaward progradation of the shoreline took place (Figure 110). In most areas this appears to have been entirely in response to deposition, but there was some uplift on the east side of Broad Sound, particularly in the Torilla Plains area. As a result, regression was more rapid on the east side of the Sound. As progradation continued, there was progressive exclusion of sea water, and grass was able to establish itself on the old supratidal flats,

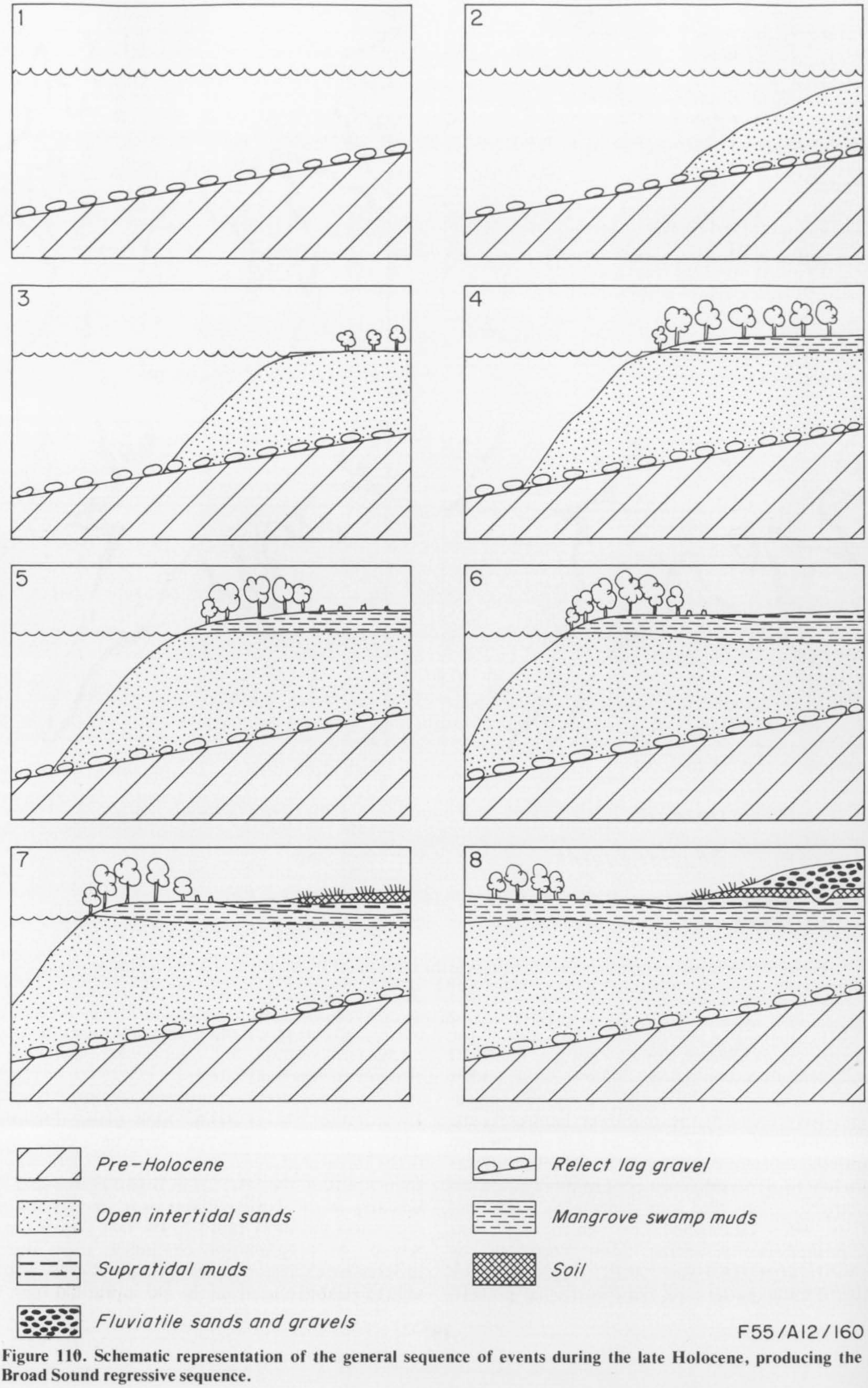


Figure 110. Schematic representation of the general sequence of events during the late Holocene, producing the Broad Sound regressive sequence.

producing extensive coastal grasslands. In these areas, continental conditions began to predominate and fluvial fans started to cover the grasslands in places. This sequence is illustrated schematically in Figure 110. During the past 6000 years cheniers formed, possibly in response to a localized decrease of sediment supply into Broad Sound and perhaps also in times of increased storm activity. However, for the most part sedimentation continued uninterrupted during the past 6000 years. During this time the calcareous component of the sediments may have become more abundant as a more prolific carbonate-secreting fauna established itself in the shelf waters to the north, and was swept into the Sound by tidal currents.

The outline of the various estuaries converging on Broad Sound became progressively more V-shaped as sedimentation proceeded (Fig. 109). This led to a slight increase in the tidal range, possibly also resulting in increases in the tidal current velocity, leading ultimately to the present-day situation where erosion almost balances deposition, and sediment redistribution is the primary mechanism.

DISCUSSION AND CONCLUSIONS

A wide range of processes and phenomena has been documented from the Broad Sound region. A review of all the various features is given in the summary. This discussion deals with some of the more important conclusions reached as a result of this study. These are of two types: those concerned with present-day processes, including the question of the source of the sediment, and those which are likely to help in understanding the depositional environments of ancient rocks. Any potential economic significance must also be considered. Finally the importance of the Broad Sound investigations as an environmental study requires evaluation.

HOLOCENE PROCESSES

In this Bulletin most of the processes considered are of only local consequence, although Holocene sea-level changes are potentially of global significance. The Broad Sound investigations have shown that using a wide variety of parameters including biogenic, grainsize, and mineralogical variations it is possible to delineate patterns of sediment dispersal within the Sound and to determine the probable source areas. In the northern half of Broad Sound much of the sediment is relict calcareous pre-Holocene material. Any modern sediment there is predominantly biogenic and must be regarded as being of marine origin. Much of it forms in situ; some is possibly swept across the shelf by tidal currents and into Broad Sound. In the southern half of Broad Sound, particularly in the upper reaches of the estuaries, the sediment is primarily terrigenous and mainly of fluvial origin. Between the two extremes is a large amount of modern sediments (and a considerable volume of Holocene sediment deposited over the past 6000 years) of mixed provenance.

It is likely that during the Holocene sea-level rise and for a short time after sea level stabilized, a large quantity of sediment was carried across the continental shelf, much of it finding its way into coastal embayments such as Broad Sound. Therefore, initially the rate of sedimentation may have been high, but soon stabilized to the present-day conditions. This is supported by the relative stability in the rate of shoreline progradation over the past 5000 to 6000 years, as indicated by the chenier sequences (Cook & Polach, 1973a). During that time, sediment of both continental and marine origin has been trapped in Broad Sound. All the Holocene calcium carbonate may be ascribed to a marine origin. Thus a significant proportion of the open intertidal sediments (about 40 percent) is of marine origin compared with only 4 percent in the supratidal flat environment. The immediate source of the terrigenous component is less certain and was considered in the 'grainsize' and 'mineralogy' sections. The conclusion reached there was that most of the terrigenous sediment is of nearby fluvial origin. This contrasts with the view of many workers in other areas that the terrigenous estuarine sediments are derived primarily from the continental shelf.

The sediment distribution pattern in Broad Sound is complicated not only by the strong tidal currents but also by the role of mangrove swamp as both receiver and supplier of sediments. Thus, although the Broad Sound estuaries are regarded as being approximately in equilibrium with erosion and deposition balanced, a great deal of sediment is constantly being moved within the estuarine system. Analysis of grainsize indicates that a four-fold division into the sorted sand, sorted mud, unsorted gravel, and unsorted muddy sand units is possible. A puzzling aspect of this system is the grouping together (in the unsorted muddy sand unit) of sediments in the upper reaches of estuaries with mangrove channel

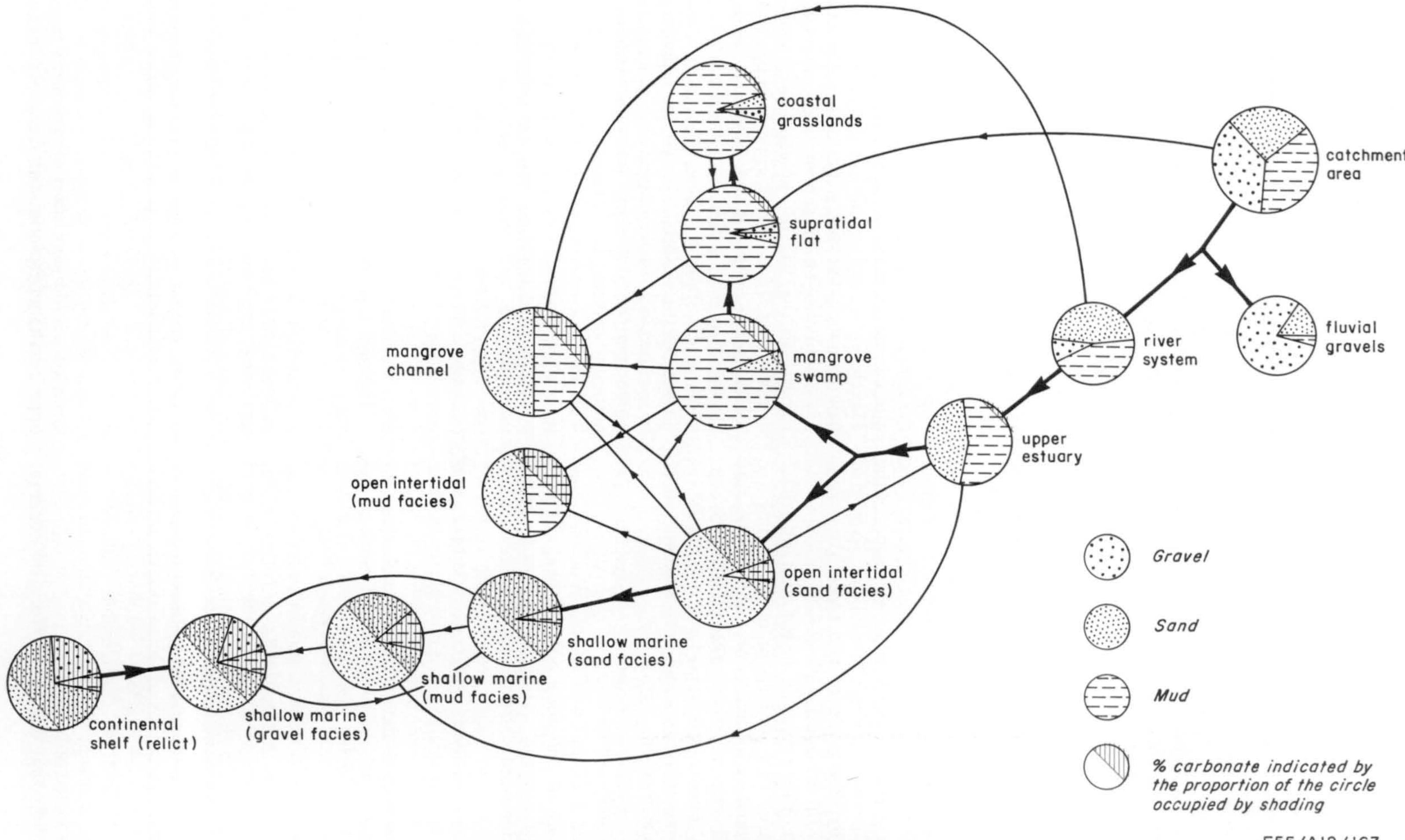


Figure 111. Schematic representation of sediment dispersal in Broad Sound.

sediments. A few mangrove channels are also fluvial systems and are net suppliers of terrigenous material, but most are not. The reason for the primary source material in the upper reaches of estuaries and mangrove channel sediments being so similar is that the mangrove channel and also the muddy facies of the open intertidal environment represent zones of mixing. In these zones there is mixing of sediment from the sorted sand unit (mainly open intertidal sands) and sorted mud unit (mainly mangrove swamp and supratidal muds) resulting in a sediment closely resembling the original source sediment. Thus most terrigenous sediment now being deposited in the estuaries is primarily of fluvial (mainly flood) origin, via the upper reaches of the estuary. A small proportion enters via mangrove channels and there is some direct input of terrigenous material onto the supratidal flats, mainly during the wet summer season. A minor amount of terrigenous material still comes from the relict Holocene sediments in the northern half of Broad Sound. This sedimentary pattern is shown schematically in Figure 111.

The Holocene stratigraphy of Broad Sound is important in showing that at 16 000 years B.P., sea level was considerably below that of the present day. There is strong evidence to suggest that about 6000 years ago it stabilized at about the present-day level. This supports the conclusion reached by Thom et al. (1969), but is in conflict with evidence from elsewhere, particularly the east coast of the United States, that sea level stabilized about 3500 years ago and later. Such a global disparity in absolute sea level cannot exist and requires further investigation. Relative vertical movement of continental proportions or the mechanism of plate tectonics may account for these differences (Thom & Chappell, 1975).

Another important facet of the Holocene stratigraphy is the evidence of local though marked vertical movement on the east side of Broad Sound, possibly involving uplift of up to 1 m/1000 years. Should such movement continue it will lead to marked physiographic changes within a comparatively short time. It is also important in highlighting the fact that neotectonic activity is locally important, and that in places Australia is not nearly as tectonically stable as is generally considered. However further work is required in the Torilla Peninsula area to determine more precisely the magnitude of the uplift.

Broad Sound and Palaeoenvironments.

A primary aim of the Estuary Study Project was to investigate possible modern analogs of ancient phosphogenic environments, particularly that of the Middle Cambrian of the Georgina Basin. There are some superficial similarities in the regional facies picture, with terrigenous sediment predominating on the periphery of the embayment and calcareous sediments in the centre. However, the two types of carbonate are totally different. There are some parallels between the terrigenous and phosphatic Georgina Basin sediments and the intertidal Broad Sound sediments, particularly in the range of sedimentary structures such as scour-and-fill structures, cross-beds, and intraformational breccias. From these it seems reasonable to postulate an intertidal and in places a supratidal origin for the phosphatic Beetle Creek Formation of the Georgina Basin. Perhaps the most relevent information on phosphogenesis is that on the geochemistry of Broad Sound pore waters. This will be discussed in Cook & Mayo (in prep.), but it is important to note here that post-depositional phosphatization is a significant mechanism, and that pore waters which in places have high phosphate content are probably responsible for the phosphatization. Thus, some findings of the Broad Sound investigation are important to an understanding of Beetle Creek sediments of the Georgina Basin, but the overall Broad Sound environment — an ephemeral tropical estuarine complex — does not appear to be a modern counterpart of the Cambrian phosphogenic environment. The Broad Sound investigation supports the suggestion of a very nearshore environment for the Beetle Creek Formation, but an estuarine origin for the phosphate is not supported by the investigation.

Although Broad Sound probably is not a modern analog for the Georgina Basin, it provides a model likely to be of wide application in the understanding of ancient depositional environments. A feature of the Broad Sound sediments is that they become progressively coarser seawards. This is reflected in the vertical Holocene marine sequence (Fig. 104) which shows a downward coarsening. The other important feature of the Holocene sequence is that it is regressive. This emphasizes that despite the importance placed on transgressive sequences in geological literature, regressive sequences are likely to be of equal importance, yet are perhaps less commonly recognized. Thus the Broad Sound sequence serves as a model for a regressive 'fining upwards' sequence as illustated in Figure 104. The Stairway Sandstone model of Cook (1967, 1972) is an example of a phosphatic regressive 'fining upwards' sequence which is probably an Ordovician analog of the Broad Sound model. Part of the Devonian sequence of the Canning Basin, reported by Read (1973), also appears to be comparable. Now that the Broad

Sound model has been documented it is likely that many more ancient analogs will be found.

ECONOMIC SIGNIFICANCE

The main economic significance of the Broad Sound study lies not in finding Holocene phosphate deposits but in providing a better understanding of the environmental conditions under which phosphate and other economic deposits may have formed in the past. This is done by examining the sedimentological and geochemical factors which influence the relative concentration of phosphorus in sediments and which will be considered in Cook & Mayo (in prep.). Environmental reconstruction is important in the search for hydrocarbons and many mineral deposits. It enables the search to be directed in the most prospective area once the palaeoenvironmental position is known with respect to the shoreline. Cheniers have been compared to shoestring sands. They are highly porous elongate bodies, surrounded by impermeable fine-grained organic-rich sediments. They therefore consititute ideal traps for hydrocarbons. Therefore a knowledge of the morphology and mode of origin of Holocene cheniers may assist in locating ancient hydrocarbon-bearing counterparts.

The only facet of the Broad Sound study which might have some immediate application is in the location of heavy-mineral deposits. Results so far indicate that the heavy-mineral content of Broad Sound sediments is sparse. A knowledge of the changes of eustatic sea level is also potentially important in finding heavy-mineral accumulations. During the Holocene, sea level rose rapidly between 16 000 and 6000 years B.P. There would have been little or no opportunity for economic heavy-mineral accumulation during this time. Sea level stabilized 6000 years ago, and consequently there has been more opportunity for heavy-mineral deposits to form during the past 6000 years. Therefore, the search for heavy-minerals deposits in Holocene deposits should be concentrated in the late Holocene portion of the sequence.

ENVIRONMENTAL SIGNIFICANCE

Estuaries are of vital importance to man; many major cities are located on them. Schubel (1971, p. 5) pointed out that 'it is in the estuary man has his most intimate contact with the marine environment. He makes many uses of estuaries; for shipping and transportation, for their biological and mineralogical resources, and for the many and varied recreational opportunities which they afford the inhabitants of the surrounding areas. The demands made on the estuary by these varied uses are often in sharp conflict. Many of our estuaries have been deleteriously affected by our rapidly growing society'.

Studies such as Broad Sound prove that the estuarine system should not be extensively modified without an awareness of possible consequences. Modification of the characteristic V-shape of an estuary by infilling or dredging is likely to lead to erosion or siltation elsewhere as the estuary strives to regain a stable configuration. The Broad Sound study (Cook & Mayo, in prep.) has also shown that mangrove swamps are a prolific source of dissolved nutrients. Mangrove channels carry large quantities of nutrients from the mangrove swamps into the estuarine system. Therefore, destruction of mangrove swamps should not be undertaken lightly as it may affect the entire nutrient cycle in the estuary. The study also served to emphasize that even in comparatively stable areas the possibility of vertical movement must not be ignored as this, together with sedimentation, may result in major displacements of the shoreline in a comparatively short time.

Both Mallacoota Inlet and Broad Sound were selected for the Estuary Study Project because of their lack of pollution. Such estuaries are likely to become rarer in the future. In order to restore estuaries to a reasonable ecological condition it is important to have as a reference an estuary relatively unmodified by man. It is necessary that reference estuaries are studied in detail in order that changes taking place in other estuaries may be better understood. The concept of a reference standard by which to measure environmental changes is commonly regarded as a new concept resulting from a recent growth in environmental awareness. However, it is an old concept in geology, first propounded by Playfair (1802, p. 140) who stated that 'The accurate geographical maps and surveys which are now making; the soundings; the observation of currents; the barometric measurements, may all combine to ascertain the reality, and to fix the quantity of those changes which terrestrial bodies continually undergo'.

Many changes regarded as being the result of estuarine modification by man may in fact be natural processes. Estuarine systems such as Broad Sound are commonly in a state of dynamic equilibrium, with erosion taking place in one area and simultaneous deposition in another place; mangrove trees die off in one area and simultaneously colonize elsewhere. All these changes in unmodified estuaries need to be documented and understood.

The Broad Sound study is important not only as a key to the past but as a reference for the future.

REFERENCES

ALLEN, G. P., 1971 — Relationship between grain size parameter distribution and current patterns in the Gironde Estuary (France). *J. sediment. Petrol.*, 41, 74-88.

AMERICAN GEOLOGICAL INSTITUTE, 1962 — DICTIONARY OF GEOLOGICAL TERMS. *New York, Doubleday.*

ARMSTRONG, K. A., 1973 — Methods of sample preparation and analysis used in the Broad Sound estuary study project. *Bur. Miner. Resour. Aust. Rec.* 1973/73 (unpubl.).

BATHURST, R. C. G., 1958 — Diagenetic fabrics in some British Dinantian limestones. *Liverpool Manchester Geol., 2, 11-36.*

BIRD, E. F. C., 1967 — COASTAL LANDFORMS. *Canberra, ANU Press.*

BIRD, E. F. C., 1971 — Holocene shore features at Trinity Bay, north Queensland. *Search,* 2(1), 27-8.

BISCAYE, P. E., 1964 — Distribution between kaolinite and chlorite in recent sediments by X-ray diffraction.*Am. Miner.*, 49, 1281-9.

BISCAYE, P. E. 1965 — Mineralogy and sedimentation of Recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. *Geol. Soc. Am. Bull.*, 72, 803-831.

BLOOM, A. L. 1967 — Pleistocene shorelines: A new test of isostasy. *Geol. Soc. Am. Bull.*, 78, 1477.

BLOOM, A. L. 1970 — Paludal stratigraphy of Truk, Ponape, and Kusaie, Eastern Caroline Islands. *Geol. Soc. Am. Bull.*, 81, 1895.

BLOOM, A. L., 1971 — Glacial — eustatic and isostatic controls of sea level since the late glaciation. *In* TUREKIAN, K. K. (ed.) — LATE CENOZOIC ICE AGES. *New Haven, Yale Univ. Press,* 357-79.

BURGIS, W. A., 1975 — Cainozoic history of the Torilla Peninsula, Broad Sound, Queensland. *Bur. Miner. Resour. Aust. Rep 172.*

CARROLL, DOROTHY, 1970 — Clay minerals, a guide to their X-ray identification. *Geol. Soc. Am., spec. Pap.* 126.

CHAPPELL, J., & POLACH, H. A., 1972 — Some effects of partial recrystallisation on C^{14} dating late Pleistocene corals and molluscs. *Quatern. Res.*, 2, 1-25.

CHAVE, K. E., 1962 — Factors influencing the mineralogy of carbonate sediments. *Limnol. Oceanogr.*, 7, 218-23.

COLEMAN, J. M., 1966 — Recent coastal sedimentation, central Louisiana coast. *Louisiana State Univ., Coast Studies Inst. tech. Rep.* 29.

COLEMAN, J. M. GAGLIANO, S. M. & SMITH, W. G., 1966 — Chemical and physical weathering on saline high tidal flats, northern Queensland. *Geol. Soc. Am. Bull.*, 77, 205-6.

COLEMAN, J. M., & SMITH, W. G., 1964 — Late recent rise of sea level. *Geol. Soc. Am. Bull.*, 75, 833-40.

CONAGHAN, P. J. 1966 — Sediments and sedimentary processes in Gladstone Harbour. *Qld. Univ., Geol. Dept Pap.*, 6(1), 1-52.

COOK, P. J., 1967, Reconstruction of an ancient shallow marine environment. *Am. Assoc. Petrol. Geol.*, 51, 459-460.

COOK, P. J., 1972 — Sedimentological studies on the Stairway Sandstone of central Australia. *Bur. Miner. Resour. Aust. Bull.* 95.

COOK, P. J., 1973 — Supratidal environment and geochemistry of some recent dolomite concretions, Broad Sound, Queensland, Australia. *J. sediment. Petrol,* 43(4), 998-1011.

COOK, P. J., & MAYO, in prep. — Geochemistry of a tropical estuary (Broad Sound, Queensland). *Bur. Miner. Resour. Aust. Bull.*182.

COOK, P. J. & POLACH, H. A., 1973a — A chenier sequence at Broad Sound, Queensland, and evidence against a Holocene high sea level. *Marine Geol.*, 14, 253-68.

COOK, P. J., & POLACH, H. A., 1973b — Discovery of recent supratidal dolomite at Broad Sound, Queensland. *Search,* 4(3), 78-9.

CROOK, K. A. W., 1960 — Classification of arenites. *Am. J. Sci.*, 258, 419-28.

DEFFEYES, K. S., LUCIA, F. J., & WEYL, P. K. 1965 — Dolomitization of recent Plio-Pleistocene sediments by marine evaporite waters on Bonaire, Netherland Antilles. *In* PRAY, L. C., & MURRAU, R. C. (eds.) — Dolomites and limestone diagenesis. *Soc. Econ. Paleont. Mineral. spec. Publ.* 13, 71-88.

DE KEYSER, F., & COOK, P. J. 1972 — Geology of the Middle Cambrian phosphorites and associated sediments of northwest Queensland. *Bur. Miner, Resour. Aust. Bull.* 138.

DEPARTMENT OF NATIONAL DEVELOPMENT 1965 — Fitzroy Region. Queensland. *Canberra, Dept Nat. Devel., Resour. Ser.*

DIETZ, R. S., 1941 — Clay minerals in Recent marine sediments. *Ph. D. thesis, Univ. Illinois.*

DORN, W. S., & MCCRACKEN, D. D., 1972 — NUMERICAL METHODS WITH FORTRAN IV CASE STUDIES. *N.Y., Wiley.*

EASTON, A. K., 1970 — The tides of the continent of Australia. *Flinders Univ. Res. Pap.* 37.

EMERY, K. O. 1968 — Relict sediments on continental shelves of the world. *Am. Ass. petrol. Geol.*, 52, 445-64.

ENDEAN, R., KENNY, R., & STEPHENSON, W., 1956 — The ecology and distribution of intertidal organisms on the rocky shores of the Queensland mainland. *Aust. J. Marine Freshwater Res.*, 7(1), 88-146.

FAIRBRIDGE, R. W., 1958 — Dating the latest movements of the Quaternary sea level. *Trans N.Y. Acad. Sci. Ser. 2,* 20, 471-82.

FAIRBRIDGE, R. W., 1961 — Eustatic changes in sea level. *In* AHRENS, L. H., PRESS, F., RUNCORN, S. K., & UREY, M. C. (eds.) — PHYSICS AND CHEMISTRY OF THE EARTH 4., *London, Pergamon, 99-185.*

FOLK, R. L., 1954 — The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *J. Geol.*, 62(4), 344-59.

FOLK, R. L., 1965 — PETROLOGY OF SEDIMENTARY ROCKS. *Austin. Univ. Texas, Hemphills.*

FOLK, R. L., 1966 — A review of grainsize parameters. *Sedimentology,* 6, 73-93.

FOLK, R. L., & WARD, W. C., 1957 — Brazos River Bar: A study in the significance of grain size parameters. *J. sediment. Petrol.*, 27, 3-26.

GALLOWAY, R. W., 1972 — Geology and geomorphology of the Shoalwater Bay area. *CSIRO, Div. Land. Res. tech. Mem.* 72/10, 57-69 (unpubl.).

GARRETT, R. G., 1967 — A program for the rapid screening of multivariate data from the earth sciences and remote sensing. *Northwestern Univ. Rep.* 11, 66pp.

O

GIBSON, D. L., 1972 — Clay mineralogy of recent sediments of the Broad Sound area, Queensland. *Bur. Miner. Resour. Aust. Rec.* 1972/65 (unpubl.).

GILL, E. D., 1971 — Applications of radiocarbon dating in Victoria, Australia. *Proc. Roy. Soc. Vic.,* 84(1), 71-86.

GLENIE, R. C., SCHOFIELD, J. C., & WARD, W. T., 1968 — Tertiary sea levels in Australia and New Zealand. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 5, 151-63.

GOLDICH, S. S., 1938 — A study in rock weathering. *J. Geol.,* 46, 17-58.

GOLDSMITH, J. R., & GRAF, D. L., 1958 — Relation between lattice constants and composition of the Ca-Mg carbonates. *Am. Mineral.,* 43, 84-101.

GRESSLEY, A., 1838 — Observation geologique sur le Jura Soleuroise. *N. Denkschr. Allg. Schweiz. ges. Naturw.,* 2, 1-112.

GRIFFITHS, J. C. 1963 — Statistical approach to the study of potential oil reservoir sandstones. *Computers in Min. Ind.,* 9, 637-668.

GRIM, R. E., 1968 — CLAY MINERALOGY, *N.Y., McGraw Hill.*

GRIM, R. E., DIETZ, R. S., & BRADLEY, W. F., 1949 — Clay composition of some sediments from the Pacific Ocean off the California coast and the Gulf of California. *Geol. Soc. Am. Bull.,* 60, 1785-803.

GRIM, R. E., & VERNET, J. P., 1961 — Etude par diffraction des minerauz argilleux de vases Mediterraneenes. *Suisse Mineral, Petrog. Bull.,* 41, 65-70.

HJULSTROM, FILIP, 1939 — Transportation of detritus by moving water. *In* Trask, P.D. (ed.) — Recent marine sediments. *Am. Ass. petrol. Geol.* 3 — 31.

HOEL, P. G., 1962 — INTRODUCTION TO MATHEMATICAL STATISTICS. *N.Y., Wiley.*

HOPLEY, D., 1968 — Morphology of the Curacao Island spit, North Queensland. *Aust. J. Sci.,* 31(3), 122-3.

HOPLEY, D., 1971 — The origin and significance of North Queensland island spits. *Geomorphology.* 15(4), 371-89.

HOWE, H. V., RUSSELL, R. J., MCGUIRT, J. H., CRAFT, B. C., & STEPHENSON, M. B., 1935 — Reports on the geology of Cameron and Vermillion Parishes. *Louisiana geol. Surv. Bull.* 6.

HSU, K. J., 1960 — Texture and mineralogy of the Recent sands of the Gulf Coast. *J. sediment. Petrol.,* 30 (3), 380-403.

HYDROGRAPHIC DEPARTMENT 1962 — Australia Pilot Vol. 4, 5th edn. *London, Admiralty.*

ILLINGS, L. V., WELLS, S. J., & TAYLOR, J. C. M., 1965 — Penecontemporaneous dolomite in the Persian Gulf. *In* PRAY, L. C., & MURRAY, R. C. (eds.) — Dolomitization and limestone diagenesis. *Soc. Econ. Paleont. Mineral, spec. Publ.,* 13, 89-111.

ISBELL, R. F., & HUBBLE, G. D., 1967 — Fitzroy region, Queensland: Soils, *Dept. Nat. Devel., resour. Ser.*

JARDINE, F., 1928 — The Broad Sound drainage in relation to the Fitzroy River, *Rep. Great Barrier Reef Cttee.,* 2, 88-92.

JOHNS, D. W., GRIM, R. E., & BRADLEY, W. F., 1954 — Quantitative estimations of clay minerals by diffraction methods. *J. sediment. Petrol.,* 24, 242-51.

KINSMAN, D. J. J., 1969 — Modes of formation of sedimentary associations and diagenetic features of shallow water and supratidal evaporites. *Am. Ass. petrol. Geol. Bull., 53, 830-40.*

KINTER, E. B., & DIAMOND, A. S., 1955 — A new method for preparation and treatment of orientated-aggregate specimens of soil clays for X-ray diffraction analyses. *Proc. 5th Conf. Clays Clay Miner.,* 318-44.

KIRKEGAARD, A. G., SHAW, R. D., & MURRAY, C. G., 1970 — Geology of the Rockhampton and Port Clinton 1:250 000 Sheet areas. *Geol. Surv. Qld. Rep.* 38, 155 pp.

KRUMBEIN, W. C., & PETTIJOHN, F. J., 1938 — MANUAL OF SEDIMENTARY PETROGRAPHY. *N.Y., Appleton-Century Crofts.*

KRUMBEIN, W. C., & SLOSS, L. L. 1963 — STRATIGRAPHY AND SEDIMENTATION. *San Francisco, Freeman.*

LOGAN, B. W., 1971 — Cryptozoon and associated stromatolites from the Recent, Shark Bay, Western Australia. *J. Geol.,* 69, 517-33.

LUCIA, F. J., 1972 — Recognition of evaporite-carbonate shoreline sedimentation. *Soc. Econ. Paleont. Mineral, spec. Publ.,* 16, 169-91.

MCALPINE, J. R., 1972 — Climate of the Shoalwater Bay area. *CSIRO, Div. Land Res., tech. Mem.* 72/10, 44-56.

MCCAVE, I. N., 1971 — Sand waves in the North Sea off the coast of Holland. *Marine Geol.,* 10, 199-225.

MCFARLAN, J. E., 1961 — Radiocarbon dating of late Quaternary deposits, South Louisiana. *Geol. Soc. Am. Bull.,* 72(1), 129-58.

MALONE, E. J., OLGERS, P., & KIRKEGAARD, A. G., 1969 — The geology of the Duaringa and St Lawrence 1:250 000 Sheet areas. *Bur. Miner. Resour. Aust. Rep.* 121.

MAXWELL, W. G. H., 1968 — ATLAS OF THE GREAT BARRIER REEF. *Amsterdam, Elsevier.*

MAYO, W., 1972 — A computer program for calculating statistical parameters of grainsize distributions derived from various analytical methods, *Bur. Miner. Resour. Aust. Rec.* 1972/140 (unpubl.).

MAYO, W., 1974 — Determining the distribution and classification of the Broad Sound surficial sediments using numerical techniques. *Bur. Miner. Resour. Aust. Rec.* 1974/85 (unpubl.).

MEADE, R. H., 1969 — Landward transport of bottom sediments in estuaries of the Atlantic Coastal Plain. *J. sediment. Petrol.,* 39, 222-34.

MILLIMAN, J. D., & EMERY, K. O., 1968 — Sea levels during the past 35 000 years. *Science,* 162, 1121-3.

MILNE, I. H., & EARLY, J. W., 1958 — Effect of source and environment on clay minerals. *Am. Ass. petrol. Geol.,* 24, 328-38.

MORNER, N. A., 1969 — Eustatic and climatic changes during the last 15,000 years. *Geol. en Mijnbouw.,* 48(4), 389-99.

MORNER, N. A., 1971a — Late Quaternary isostatic, eustatic and climatic changes. *Quaternaria,* XIV, 65-83.

MORNER, N. A., 1971b — The holocene eustatic sea level problem. *Geol. En Mijnbouw.,* 699-70.

NELSON, B. W., & BRAY, 1970 — Stratigraphy and history of the Holocene sediments in the Sabine-High Island area, Gulf of Mexico. *Soc. Econ. Paleont. Mineral. spec. Publ.,* 15, 48-77. OFF, THEODORE, 1963 — Rythmic linear sand bodies caused by tidal currents. *Am. Ass. petrol. Geol. Bull.,* 47, 324-41.

OINUMA, K., KOBAYASHI, K., & SUDO, T., 1959 — Clay mineral composition of some Recent marine sediments. *J. sediment. Petrol.,* 29, 56-63.

OTTO, G. H., 1938 — The sedimentation unit and its use in field sampling. *J. Geol.,* 46, 569-82.

PETTIJOHN, F. J., 1957 — SEDIMENTARY ROCKS. *N.Y., Harper.*

PILKEY, O. H., 1964 — The size distribution and mineralogy of the carbonate fraction of United States south Atlantic shelf and upper slope sediments. *Marine. Geol.,* 2, 121-136.

PLAYFAIR, JOHN, 1802 — ILLUSTRATIONS OF THE HUT-

TONIAN THEORY OF THE EARTH, *London, Calder & Davies.*

PRICE, W. A., 1955 — Environment and formation of the chenier plain. *Quaternaria.*, 2, 75-86.

PRIOR, W. A., & GLASS, H. D., 1961 — Cretaceous-Tertiary clay mineralogy of the upper Mississippi Embayment. *J. Sediment. Petrol.*, 31, 38-51.

PRITCHARD, D. W., 1967 — What is an estuary: physical viewpoint. *In* LAUFF, G. H. (ed.) — Estuaries. *Am. Ass. Adv. Sci. Publ.*, 83, 3-5.

RAFTER, T. A., 1973 — Radiometric dating — achievements and prospects in the Quaternary. *Inst. Nuclear. Sci. N.Z. Publ.* 650.

RATEEV, M. A., GORBUNOVA, Z. N., LISITZYN, A. P., & NOXOV, G. L., 1969 — The distribution of clay minerals in the ocean. *Sedimentology,* 13, 21-44.

READ, J. F., 1973 — Carbonate cycles, Pillara Formation (Devonian), Canning Basin, Western Australia. *Bull. Canad. petrol. Geol.*, 21(1), 38-51.

REINSON, G. E., in press — Hydrology and sediments of a temperate estuary (Genoa River — Mallacoota Inlet), Victoria. *Bur. Miner. Resour. Aust. Bull.* 178.

ROOSJEN, B., 1966 — Final report of the sparker survey Broad Sound area. *United Geophysical Co. Rep. for Ampol Exploration Ltd.* (unpubl.).

RUSSELL, R. D., 1937 — Mineral composition of Mississippi River sands. *Geol. Soc. Am. Bull.*, 48, 1307-48.

SCHOFIELD, J. C., 1960 — Sea level fluctuations during the last 4,000 years as recorded by a chenier plain, Firth of Thames, New Zealand. *N.Z. Geol. Geophys.*, 3(3), 467-85.

SCHOFIELD, J. C. & THOMPSON, H. R., 1964 — Postglacial sea levels and isostatic uplift. *N.Z. J. Geol. Geophys.*, 7(2), 360-70.

SCHROEDER, J. H., DWORNIK, E. J., & PAPIKE, J. J., 1969 — Primary protodolomite in echinoderm skeletons. *Geol. Soc. Am. Bull.*, 80, 1613-16.

SCHUBEL, J. R., 1971 — Man, pollution and the estuary. *In* SCHUBEL, J. R. (convenor) — The estuarine environment, A.G.I. short course lecture notes. *Washington, Am. geol. Inst.*, XV5 — XV8.

SCHUBEL, J. R., & PRITCHARD, D. W., 1971 — What is an estuary. *In* SCHUBEL, J. R. (convenor) — The estuarine environment, A.G.I. short course notes. *Washington, Am. geol. Inst.*, II-III.

SCHULTZ, L. G., 1960 — Quantitative X-ray determinations of some aluminous clay minerals in rock. *Proc. 7th Conf. Clays Clay Miner.*, 216-44.

SHEPARD, F. P., 1954 — Nomenclature based on sand-silt-clay ratios. *J. sediment. Petrol.*, 24(3), 151-8.

SHEPARD, F. P. & CURRAY, J. R., 1967 — Carbon-14 determination of sea-level changes in stable areas. *In* PROGRESS IN OCEANOGRAPHY, Vol. 4. *Oxford, Pergamon,* 283-91.

SHEPARD, F. P. & SEUSS, H. E., 1956 — Rate of postglacial rise of sea level. *Science,* 123, 1082-3.

SHINN, E. A., GINSBURG, R. N., & LLOYD, R. M., 1965 — Recent supratidal dolomite from Andros Island, Bahamas. *Soc. Econ. Paleont. Mineral. spec. Publ.*, 13, 112-23.

SIESSER, W. G., 1971 — Mineralogy and diagenesis of some South African coastal and marine carbonates. *Marine Geol.*, 10, 15-38.

SPENCER, DEREK W., 1963 — The interpretation of grain size distribution curves of clastic sediments. *J. sediment. Petrol.*, 33, 180-90.

SUNDBORG, A., 1956 — The River Klaralven, a study in fluvial processes. *Geografiska Annal.*, 38, 127-316.

THOM, 1967 — Mangrove ecology and deltaic geomorphology, Tabasco, Mexico. *J. Ecol.*, 55, 301-43.

THOM, B. G., & CHAPPELL, J. A., 1975 — Holocene sealevels relative to Australia. *Search,* 6(3), 90-3.

THOM, B. G., HAILS, J. R., & MARTIN, A. R. H., 1969 — Radiocarbon evidence against higher post-glacial sea levels in eastern Australia. *Marine Geol.*, 7, 161-8.

THOM, B. G., WRIGHT, L. V., & COLEMAN, J. M., 1974 — Mangrove ecology and deltaic-estuarine geomorphology; Cambridge Gulf-Ord River, Western Australia. *J. Ecol.*, 63 (1), 203-32.

THOMAS, R. L., KEMP, A. L. W. & LEWIS, C. F. M., 1972 — Distribution, composition and characteristics of the surficial sediments of Lake Ontario. *J. sediment. Petrol.*, 42, 66-85.

VAN ANDEL, Tj. H., CURRAY, J. R., & VEEVERS, J. J., 1961 — Recent carbonate sediments of the Sahul Shelf — northwestern Australia. *1st Nat. Coastal Shallow Water Res. Conf. Proc.*, 564-7.

VAN ANDEL, Tj. H., & VEEVERS, J. J. 1967 — Morphology and sediments of the Timor Sea. *Bur. Miner. Resour. Aust. Bull.* 83.

VANN, J. H., 1963 — Developmental processes in laterite terrain in Amapa. *Geogr. Rev.*, 406-17.

WALKER, T. R., 1967 — In situ formation of red-beds in modern and ancient deserts. *Geol. Soc. Am. Bull.*, 73, 237-42.

WARD W. T., 1971 — Postglacial changes in level of land and sea. *Geol. En Mijnbouw,* 50(5), 703-18.

WEST, R. C., PSUTY, N.P. & THOM, B. G., 1969 — The Tabasco Lowlands of southeastern Mexico, Coastal Studies Series 27. *Lousiana State Univ. Press.*

WHITEHOUSE, U. G., 1952 — Chemistry of marine sedimentation. *In* Study of nearshore Recent sediments and their environs in the northern Gulf of Mexico. *API Project 51, progr. Rep. 7.*

WHITEHOUSE, U. G., & JEFFREY, L. M., 1955 — Peptization resistance of selected samples of kaolinite montmorillonite and illitic clay materials. *Clays & clay minerals, Nat. Acad. Sci., Nat. Res. Council Publ.*, 395, 260-81.

WHITEHOUSE, U. G., JEFFREY, L. M. & DEBRECHT, J. D., 1960 — Differential settling tendencies of clay miners in saline waters. *Proc. 6th Conf. Clays Clay Miner.*, 1-79.

WRIGHT, L. V., COLEMAN, J. M. & THOM, B. G., 1972 — Emerged tidal flats in the Ord River estuary, Western Australia. *Search,* 3, 339-41.

WRIGHT, L. D., COLEMAN, J. M., & THOM, B. G., 1973 — Processes of channel development in a high-tide range environment: Cambridge Gulf-Ord River delta, Western Australia. *J. Geol.*, 81, 15-41.

APPENDIX 1

ILL-CONDITIONING OF GRAINSIZE PARAMETER DETERMINATIONS

To estimate the effect of any ill-conditioning in the calculation of the grainsize distribution parameters, the gravel results from a number of samples (Group B in Fig. 50(b), and the clay readings (9 phi to 14 phi) with some other samples (Group C in Fig. 50(b)) were omitted and the values of the four grainsize distribution parameters were re-determined. The percentage change in the value of each of the four parameters was calculated using:

$$\% \text{ change} = \frac{(\text{original value} - \text{new value}) \times 100}{\text{original value}}$$

It was necessary to divide by the original value and not the new value as the skewness and kurtosis values of the samples with the minor modes removed were often very close to zero which resulted in percentage changes up to 11 000 percent. This percent change was divided by the percentage removed from the original sample to give an estimate of the percent change in the parameter caused by removal of one percent of either the coarse or fine minor mode. The results of these calculations are given in Table A.

Table A shows that the percent changes in the mean grainsize measure are of the same order as the one percent change in the data. That is, the determination of this parameter is quite well-conditioned. The standard deviation shows large percentage changes, mostly between about 10 and 30 percent, resulting from a one percent change in the data. The importance of the size of the changes is apparent when the precision of the grainsize techniques is remembered, for five percent change in the data would result in about 100 percent change in the standard deviation value. Of course, the examples shown are extreme cases with grainsize data being completely removed from one end of the grainsize range, but often this is precisely the case when a percent mud cut-off is used to decide whether or not to pipette the mud fraction. Ideally, a change in any measured parameter should reflect a change of the same order of magnitude in the input data. The mean grainsize measure seems to satisfy this, even in the above extreme case, but the standard deviation over-reacts to changes in the input data. It is interesting to speculate on the usefulness of the median as a grainsize measure on these results presented for the mean grainsize values. The median, by definition, is less affected by changes in the extremes of a grainsize distribution than the mean, but if the determination of the mean is well-conditioned, even in the above extreme case perhaps the median as a grainsize measure will not satisfactorily reflect changes in the input data. This view is supported by Folk (1965).

Most of the changes in skewness values range between 10 and 70 percent, the largest being a 78 percent change. Therefore, a 5 percent change in the data from the distribution extremities can produce a change in the skewness value by up to about 400 percent.

The percentage changes in the kurtosis values can be as high as the skewness changes, but to complicate the problem the kurtosis value can actually increase in some cases when data are removed from the extremities of the grainsize distribution. This is shown in the group C results in Table A by the negative percentage change in the kurtosis in some samples. These samples also only had less that 10 percent changes in the skewness value and had higher clay content in the 9 to 14 phi range than the other samples in this group. This phenomenon is difficult to explain but it is obviously related to the amount of clay removed for the calculation and the consequent increase in the frequency percent of the remaining grainsize classes, especially those at the opposite extreme of the distribution. Therefore, not only is the determination of kurtosis values poorly conditioned but the resulting changes in the parameters for similar data changes vary in direction.

The changes in the skewness and kurtosis values in these samples are considered too high to enable reliable interpretations from these parameters, when the precision of the grainsize techniques is taken into account. At first it might seem reasonable to simply remove groups B and C from any future analysis of the results, but of course the problem is not merely limited to samples in those groups, as illustrated in Figure 54C. Therefore, it is concluded that with the Broad Sound samples the skewness and kurtosis determinations are far too sensitive to enable worthwhile interpretation to be made.

Even though the standard deviation determinations are also very sensitive to changes in the input data they are not as ill-conditioned as the skewness and kurtosis determinations, and the size and direction of these changes can be predicted with some confidence. The problems resulting from this ill-conditioning are illustrated by the following two examples.

Figure 57b shows a typical example in this group but the distribution appears negatively skewed (similar to Group B (Fig. 50b) and there is only a minor amount (2.8% of the total) of fine particles making up the right 'tail'. This was due to extrapolation of the clay weight remaining after the pipette analysis was completed down to 9 phi. The sum of the percent frequencies of the 5 extrapolated intervals does not appear to add to 2.8 percent in Figure 48, but these frequencies have been scaled for true diagrammatic representation of the distribution (Mayo, 1972). In fact this 2.8 percent of the sample changes the skewness from 0.29 to 3.86.

Figure 54c shows a typical negatively skewed frequency distribution of group B, the minor coarse modes being due to shells and nodules. Because of minor amounts of clay (0.96%) far removed from the mean size, the resulting skewness value is 0.51, placing the sample in Group A (Fig. 50b).

TABLE A. PERCENTAGE CHANGES IN THE GRAINSIZE DISTRIBUTION PARAMETER VALUES CAUSED BY THE REMOVAL OF 1% OF THE COARSE (GROUP B) OR FINE (GROUP C) EXTREMITY OF THE DISTRIBUTION

GROUP C

Sample	*% of last 5 class intervals*	*Mean (% increase)*	*Standard deviation (% decrease)*	*Skewness (% decrease)*	*Kurtosis (% decrease)*
4	5.6	1.6	10.9	10.2	10.1
10	3.6	1.8	17.2	16.1	20.7
15	7.6	1.5	7.5	9.9	3.3
20	2.9	2.0	18.9	32.7	27.8
21	4.4	1.0	12.2	22.1	16.9
26	1.0	2.2	37.6	77.7	79.1
31	1.4	2.1	41.4	35.6	55.6
40	1.8	1.9	31.2	36.6	48.0
48	1.5	4.5	29.9	71.0	50.3
81	11.0	2.1	23.3	11.6	-5.6
83	9.7	2.1	22.8	-2.8	-7.2
109	10.0	1.4	6.3	4.5	-1.8
111	4.9	1.6	11.9	7.1	7.1
252	11.9	1.4	17.4	0.1	-10.5
260	2.6	1.9	16.1	27.6	15.4
283	1.5	2.5	30.3	68.4	57.9
347	3.0	1.9	19.8	30.2	15.0
348	7.1	1.6	8.9	11.9	5.1
349	3.4	2.0	13.1	32.9	21.5
350	2.8	2.0	17.9	33.1	23.0

GROUP B

61	2.7	1.9	14.8	37.4	34.0
73	1.7	1.7	11.9	22.8	32.6
87	1.6	1.8	28.2	62.8	61.1
88	8.0	2.9	7.5	8.5	4.3
91	2.4	1.9	12.7	31.8	35.2
96	2.0	1.9	17.0	43.7	45.8
99	4.2	1.2	13.3	13.9	19.8
145	3.2	2.2	15.9	34.0	29.9
167	4.1	2.2	12.7	27.0	23.8
188	1.6	1.9	26.3	59.7	49.4
190	7.0	2.2	7.3	21.4	3.1
201	9.2	2.2	7.9	11.9	12.9
305	3.9	2.2	5.8	22.0	21.7
320	7.7	3.3	6.4	14.1	12.7

APPENDIX 2

TOTAL ERROR WITH THE MEAN AND STANDARD DEVIATION GRAINSIZE VALUES

Before a final decision can be made as to whether the mean and standard deviation of grainsize distributions may be used in numerical analyses, it is necessary to test the significance of the combined analytical and sampling error of both variables. This was done using one-way analysis of variance on three sets of samples from the mangrove swamp, the supratidal flats, and a combination of open intertidal and mangrove channel samples (each set represents one of the genetically classified sedimentary units). Triplicate samples were taken at seven randomly selected localities in both the mangrove and mudflats environments and eight in the pre-sorting unit. The results are shown in Table B.

One-way analysis of variance tests for differences between the means of each set of triplicate samples in the above units. If there is no significant difference between the sets for a particular variable, then the combination of errors may mask any variation. The F distribution is used to test for significant differences and therefore a calculated F value greater than the 95 percent critical value for the F distribution (given in Table 4) indicates whether differences between localities are significant despite the analytical and sampling errors. Differences are significant (at the 95 percent level) with both the mean and standard deviation values except for the standard deviation values in the low-energy sorting unit. However, these tests show that the use of these two variables in future numerical analyses is warranted.

TABLE B. TESTS FOR SIGNIFICANCE OF COMBINED ANALYTICAL AND SAMPLING ERROR

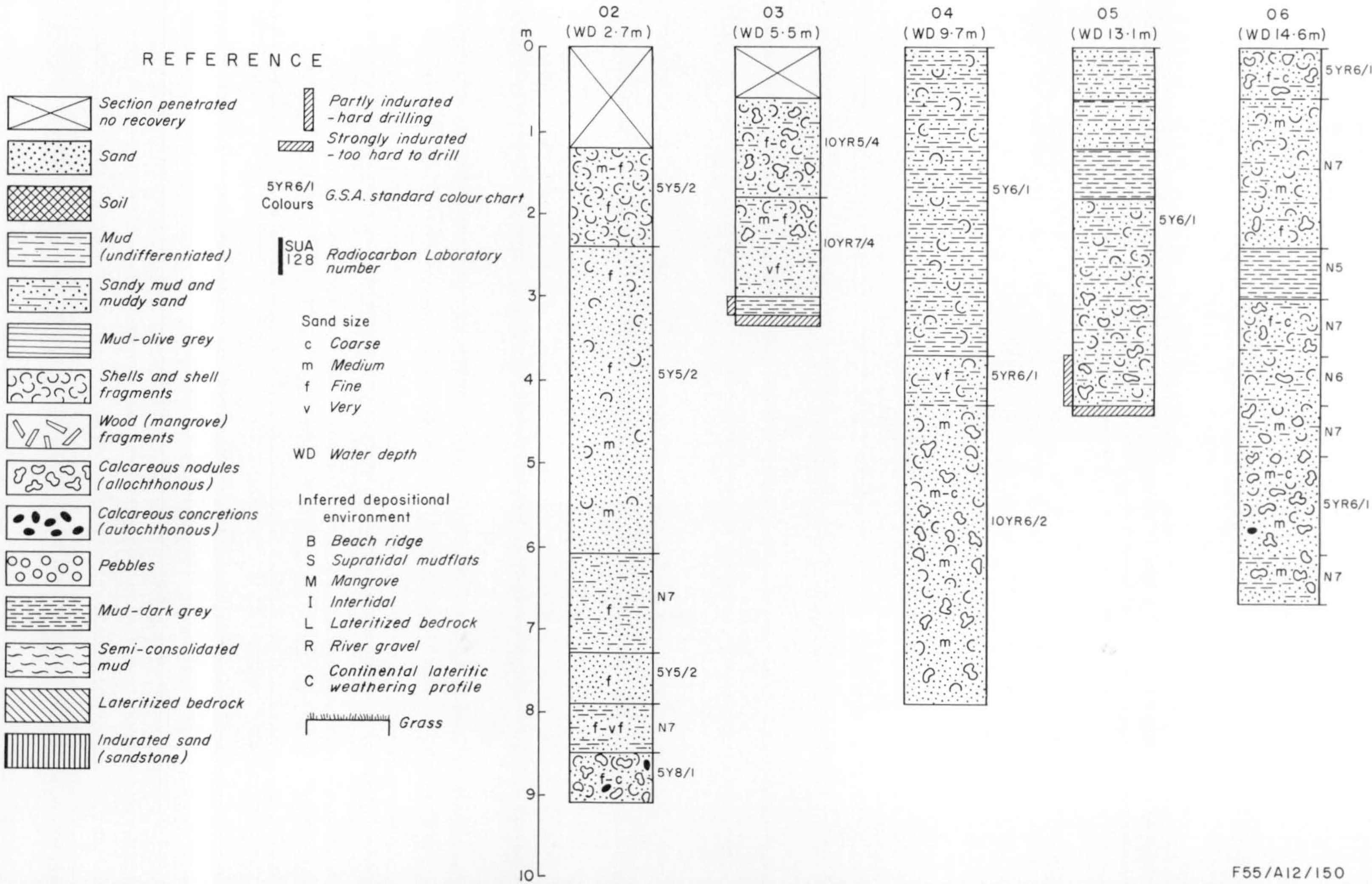
Unit	*Variable*	*Source*	*Degree of freedom*	*Mean source*	*F. value*
SUPRATIDAL FLATS (low-energy sorted)	MEAN	Between groups	6	2.739	4.534*
		Within groups	14	0.605	
	STANDARD DEVIATION	Between groups	6	0.192	0.722
		Within groups	14	0.266	
MANGROVE SWAMP (low-energy sorted)	MEAN	Between groups	6	1.060	3.019*
		Within groups	14	0.351	
	STANDARD DEVIATION	Between groups	6	0.015	0.262
		Within groups	14	0.058	
OPEN INTERTIDAL PLUS MANGROVE CHANNEL (pre-sorting)	MEAN	Between groups	7	5.304	47.188*
		Within groups	16	.112	
	STANDARD DEVIATION	Between groups	7	1.001	21.531*
		Within groups	16	.047	

* Significant differences in the means (F(6,14) at 95% = 2.85, F(7,16) at 95% = 2.66)

APPENDIX 3

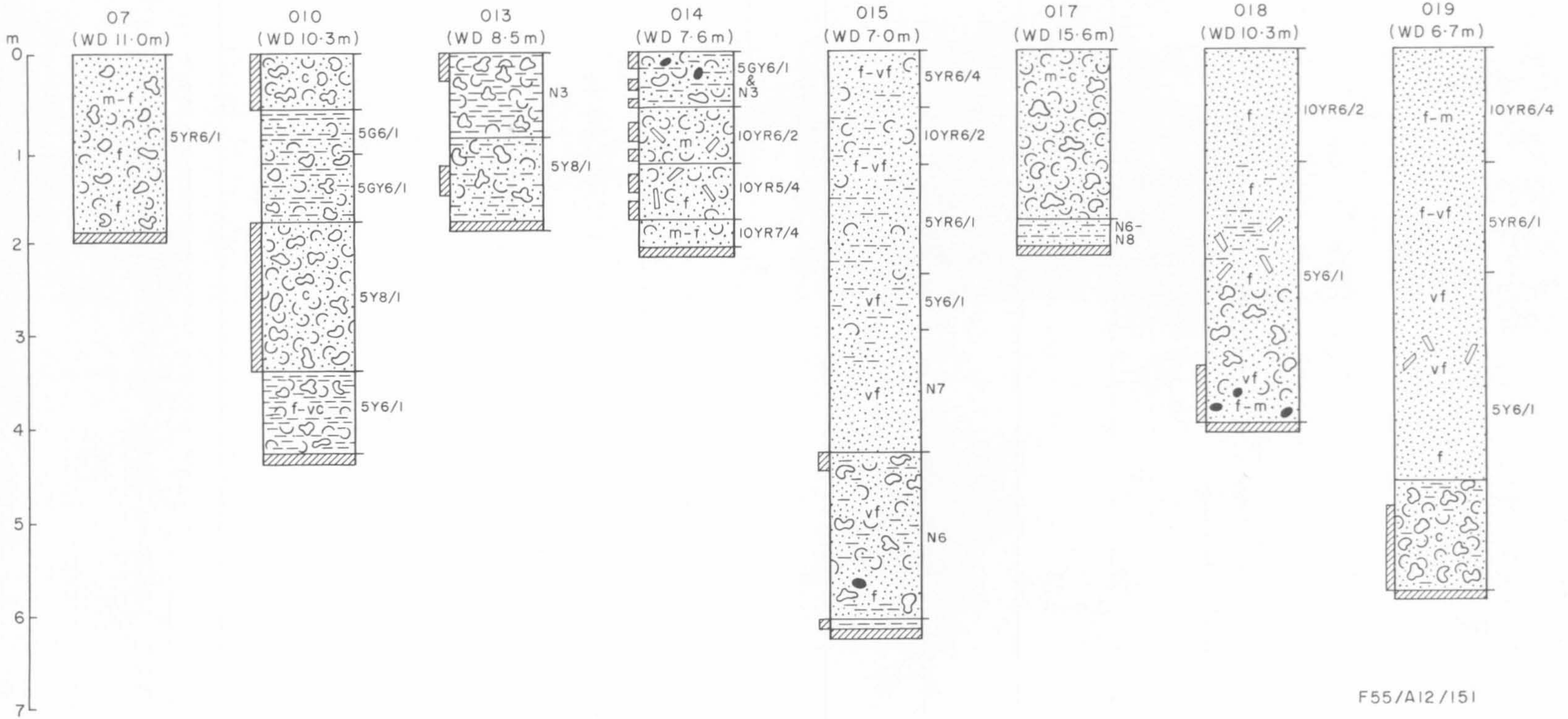
STRATIGRAPHY OF ONSHORE AND OFFSHORE DRILL HOLES

Appendix 3 summarizes stratigraphic information obtained both onshore and offshore. Drilling sites are indicated in Figure 100. Offshore sites, which have the prefix 0, were drilled with a vibratory drill. Onshore sites, which have the prefix A, were drilled by hand auger. Information obtained onshore by diamond drilling is given by Burgis (1975). The locations of radiocarbon samples are shown on the vertical sections. Samples prefixed by SUA were dated at the Radiocarbon Laboratory of Sydney University. Those prefixed by ANU were dated at the Radiocarbon Laboratory of the Australian National University.



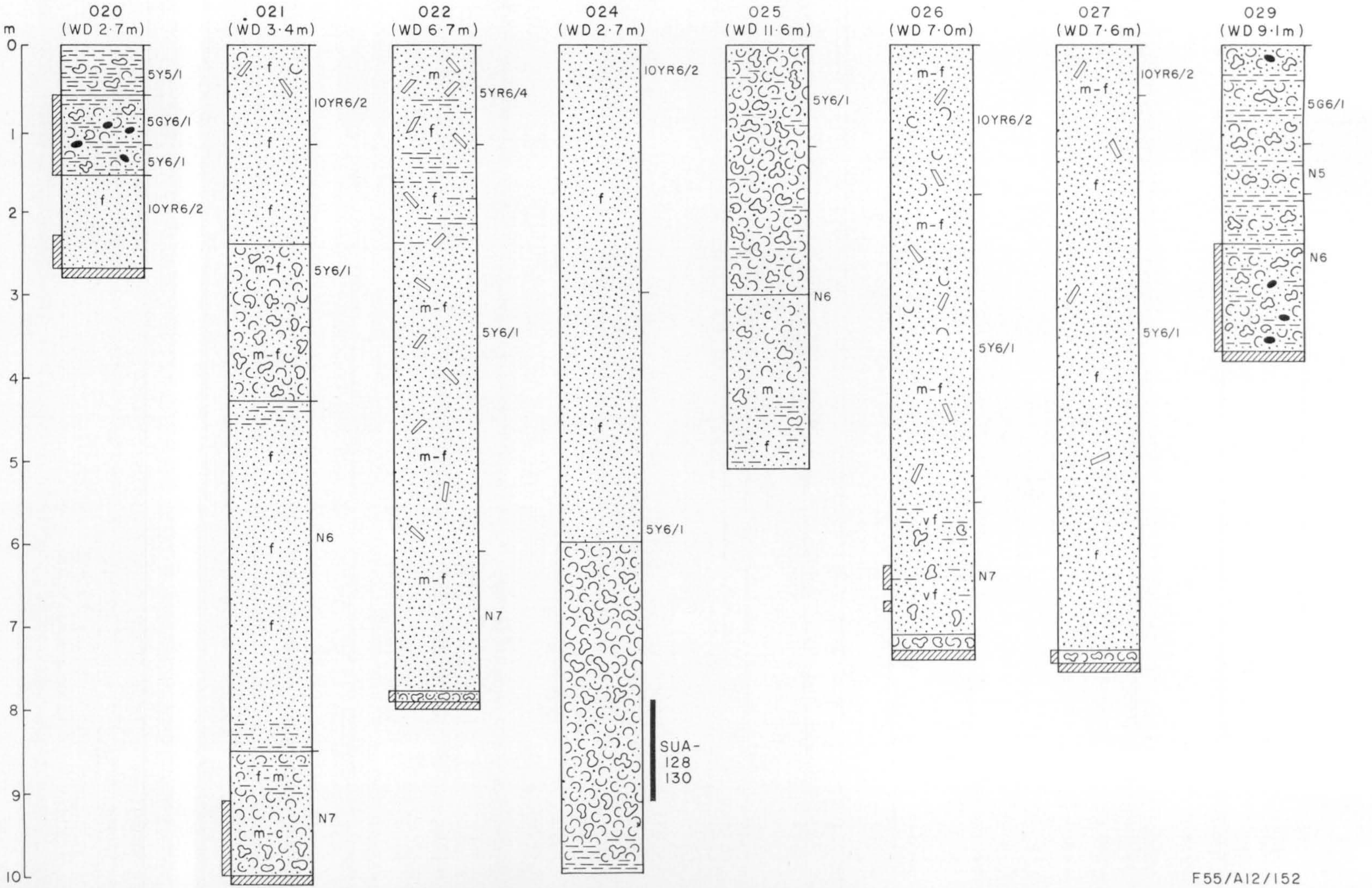
REFERENCE
Section penetrated no recovery
Sand
Soil
Mud (undifferentiated)
Sandy mud and muddy sand
Mud - olive grey
Shells and shell fragments
Wood (mangrove) fragments
Calcareous nodules (allochthonous)
Calcareous concretions (autochthonous)
Pebbles
Mud - dark grey
Semi-consolidated mud
Lateritized bedrock
Indurated sand (sandstone)
Partly indurated - hard drilling
Strongly indurated - too hard to drill
5YR6/1 Colours G.S.A. standard colour chart
SUA 128 Radiocarbon Laboratory number
Sand size
c Coarse
m Medium
f Fine
v Very
WD Water depth
Inferred depositional environment
B Beach ridge
S Supratidal mudflats
M Mangrove
I Intertidal
L Lateritized bedrock
R River gravel
C Continental lateritic weathering profile
Grass
m
0
1
2
3
4
5
6
7
8
9
10
02 (WD 2·7m)
m-f
f
5Y5/2
f
5Y5/2
m
m
f
N7
f
5Y5/2
f-vf
N7
f-c
5Y8/1
03 (WD 5·5m)
f-c
10YR5/4
m-f
10YR7/4
vf
04 (WD 9·7m)
5Y6/1
vf
5YR6/1
m
m-c
10YR6/2
m
m
05 (WD 13·1m)
5Y6/1
06 (WD 14·6m)
f-c
5YR6/1
m
N7
m
f
N5
f-c
N7
N6
m
N7
m-c
5YR6/1
m
m
N7

F55/A12/150

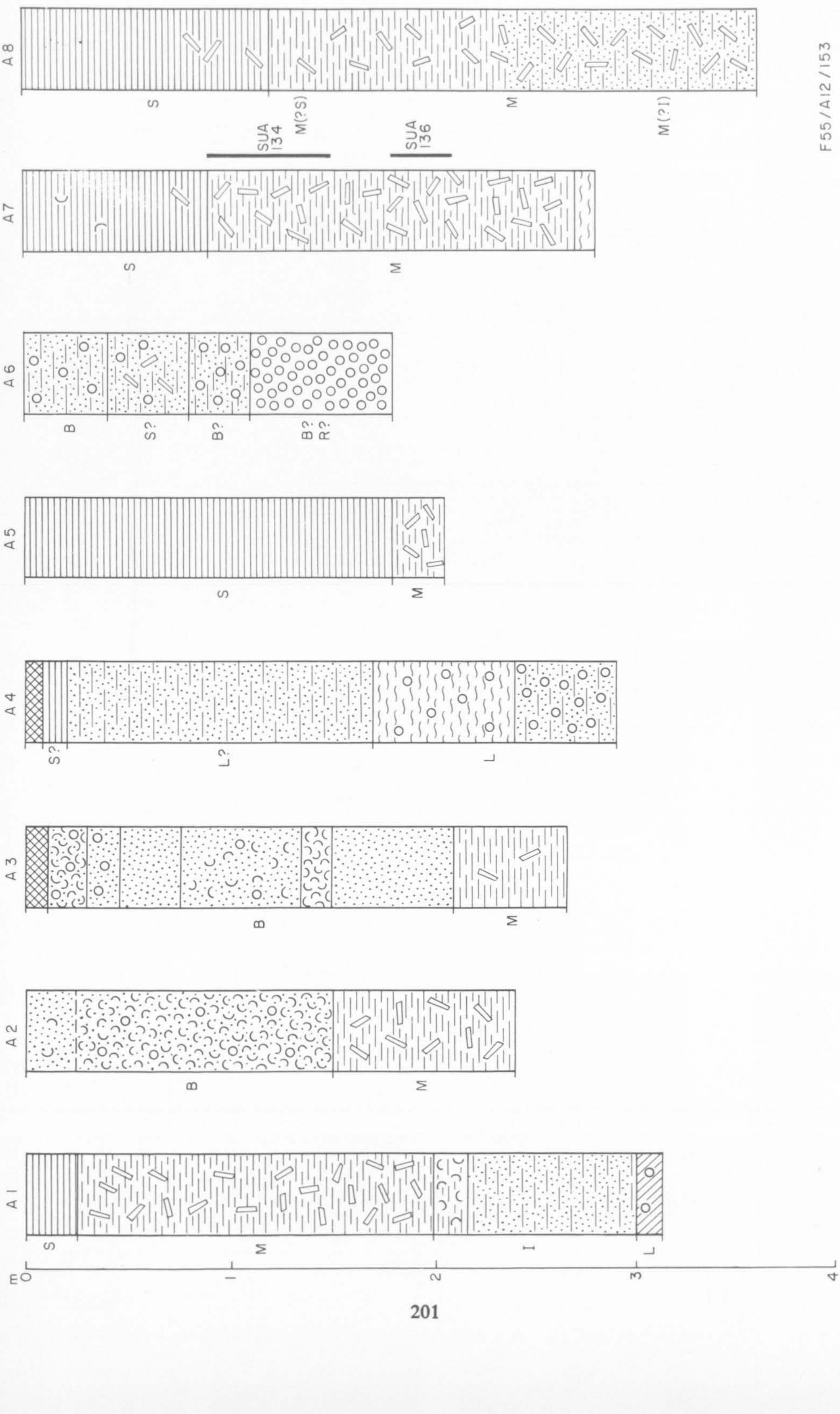


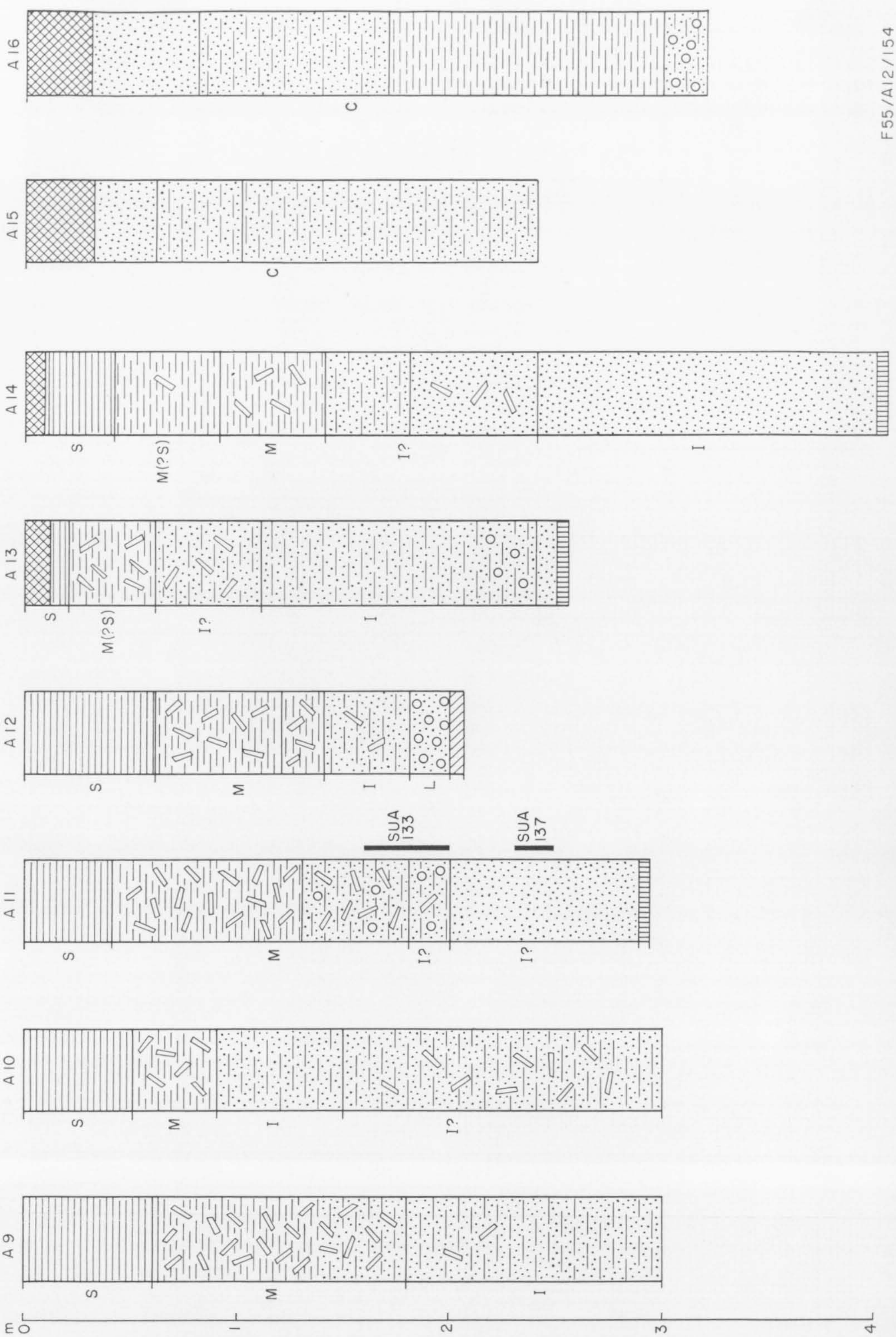
m
0
1
2
3
4
5
6
7
07
(WD 11·0m)
m-f
f
f
5YR6/I
010
(WD 10·3m)
c
5G6/I
5GY6/I
5Y8/I
f-vc
5Y6/I
013
(WD 8·5m)
N3
5Y8/I
014
(WD 7·6m)
5GY6/I
&
N3
m
10YR6/2
f
10YR5/4
m-f
10YR7/4
015
(WD 7·0m)
f-vf
5YR6/4
f-vf
10YR6/2
5YR6/I
vf
5Y6/I
vf
N7
vf
f
N6
017
(WD 15·6m)
m-c
N6-
N8
018
(WD 10·3m)
f
10YR6/2
f
f
5Y6/I
vf
f-m
019
(WD 6·7m)
f-m
10YR6/4
f-vf
5YR6/I
vf
vf
f
5Y6/I
c

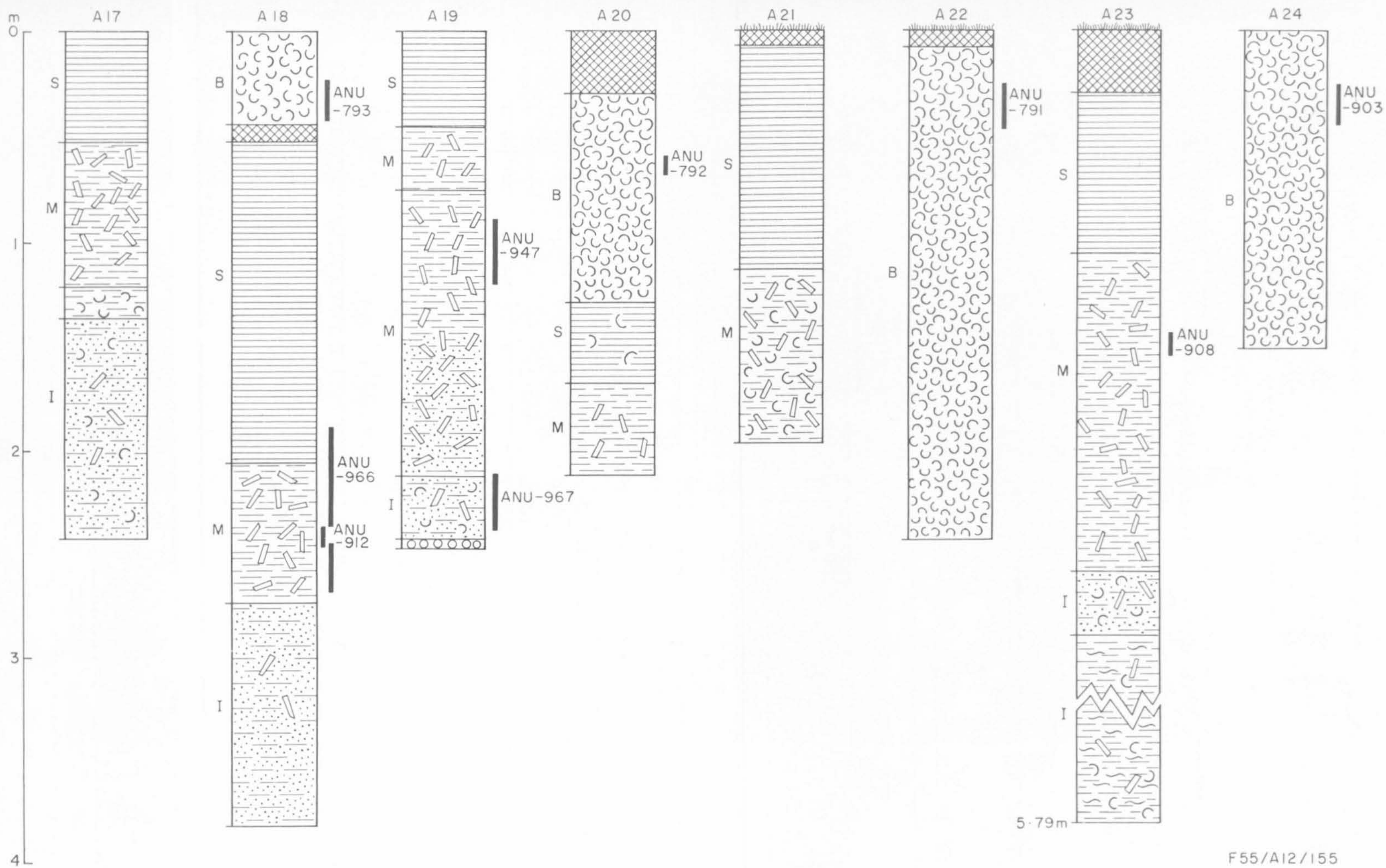
F55/A12/151

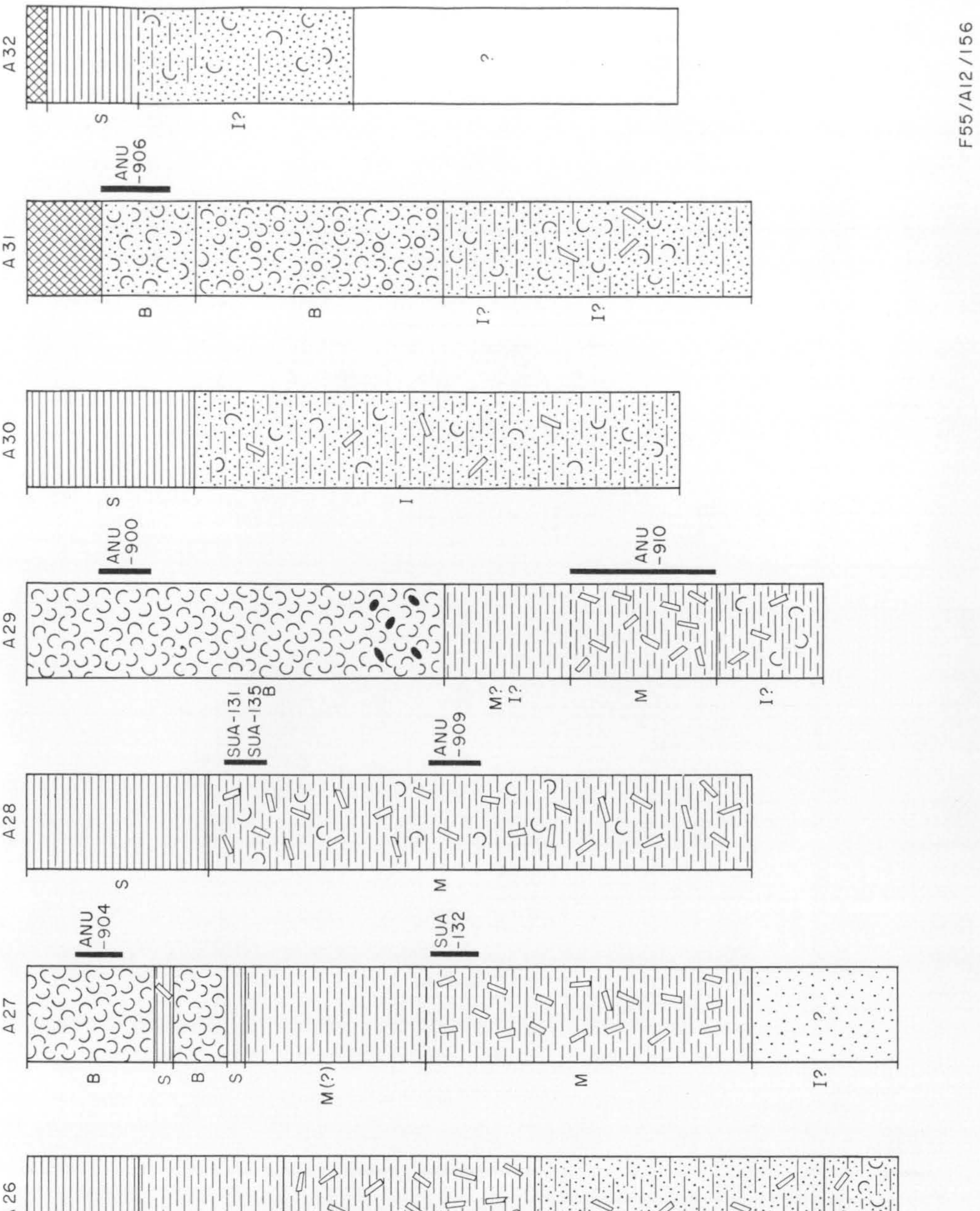

020
(WD 2·7m)
021
(WD 3·4m)
022
(WD 6·7m)
024
(WD 2·7m)
025
(WD 11·6m)
026
(WD 7·0m)
027
(WD 7·6m)
029
(WD 9·1m)
m
0
1
2
3
4
5
6
7
8
9
10
5Y5/1
5GY6/1
5Y6/1
10YR6/2
5Y6/1
N6
N7
5YR6/4
5Y6/1
N7
10YR6/2
5Y6/1
SUA-
128
130
5Y6/1
N6
10YR6/2
5Y6/1
N7
10YR6/2
5Y6/1
5G6/1
N5
N6
f
m-f
m-c
f-m
m
c
vf

F55/A12/152

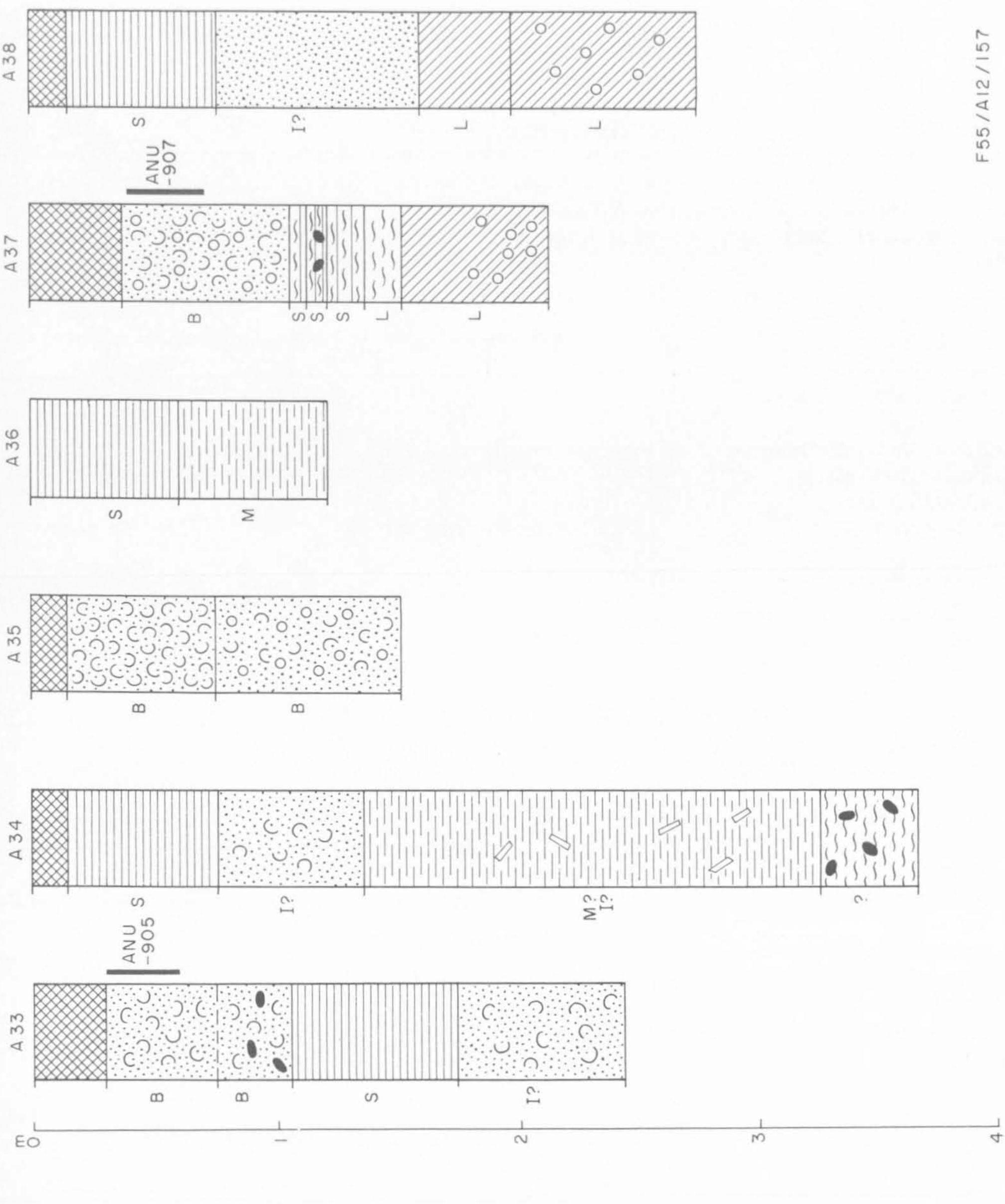

A1
A2
A3
A4
A5
A6
A7
A8
S
M
I
L
B
S?
L?
B?
R?
M(?S)
M(?I)
SUA 134
SUA 136
F55/A12/153
m
0
1
2
3
4


A 9
A 10
A 11
A 12
A 13
A 14
A 15
A 16
S
M
I
I?
L
M(?S)
C
SUA 133
SUA 137
m
0
1
2
3
4
F55/A12/154


m
0
1
2
3
4
A17
A18
A19
A20
A21
A22
A23
A24
S
M
I
B
ANU -793
ANU -966
ANU -912
ANU -947
ANU-967
ANU -792
ANU -791
ANU -908
ANU -903
5·79m
F55/A12/155



A25
A26
A27
A28
A29
A30
A31
A32
ANU -904
SUA -132
SUA-131
SUA-135
ANU -909
ANU -900
ANU -910
ANU -906
B
I
S
M(?)
M
I?
M? I?
?
m 0
1
2
3
4
F55/A12/156



A 33
A 34
A 35
A 36
A 37
A 38
ANU
-905
ANU
-907
B
S
I?
M?
I?
?
M
L
m
0
1
2
3
4
F55/A12/157

APPENDIX 4

AVAILABILITY OF BROAD SOUND DATA

A computer listing of the textural and mineralogical raw data of the individual Broad Sound samples used in this investigation may be obtained by writing to

The Director, Bureau of Mineral Resources, P.O. Box 378, Canberra City, A.C.T. 2601.

Samples with any missing data have been removed. The following information is supplied for the remaining 289 samples (out of an original 305):

Sample number		
Grid reference		
Sedimentary unit		
Sedimentary environment		
Mean grainsize	)	
Grainsize standard deviation	)	
Grainsize skewness	)	
Grainsize kurtosis	)	
Percent gravel	)	Carbonate not removed
Percent sand	)	
Percent mud	)	
Percent silt	)	
Percent clay	)	
Percent gravel	)	
Percent sand	)	Carbonate removed
Percent mud	)	
Percentage calcium carbonate		
Dolomite	)	
Mg-calcite	)	
Calcite	)	Percentages from XRD peak areas (as in text)
Plagioclase	)	
Orthoclase	)	
Aragonite	)	
Percent total heavy minerals (of the non-carbonate fraction)		
Percent opaque heavy minerals		
Percent non-opaque heavy minerals		
Zircon	)	
Epidote	)	
Tourmaline	)	
Rutile	)	Percentage in point count (of the non-opaque
	)	heavy mineral fraction)
Hornblende	)	
Garnet	)	
Zoisite	)	

Percentages of kaolinite, illite, and montmorillonite plus mixed-layer clays for selected Broad Sound samples are given by Gibson (1972).

The listing also includes geochemical data which are the subject of a second publication in this series by Cook & Mayo (in prep.).