Continental Shelf Sediments: Southern Queensland and Northern New South Wales

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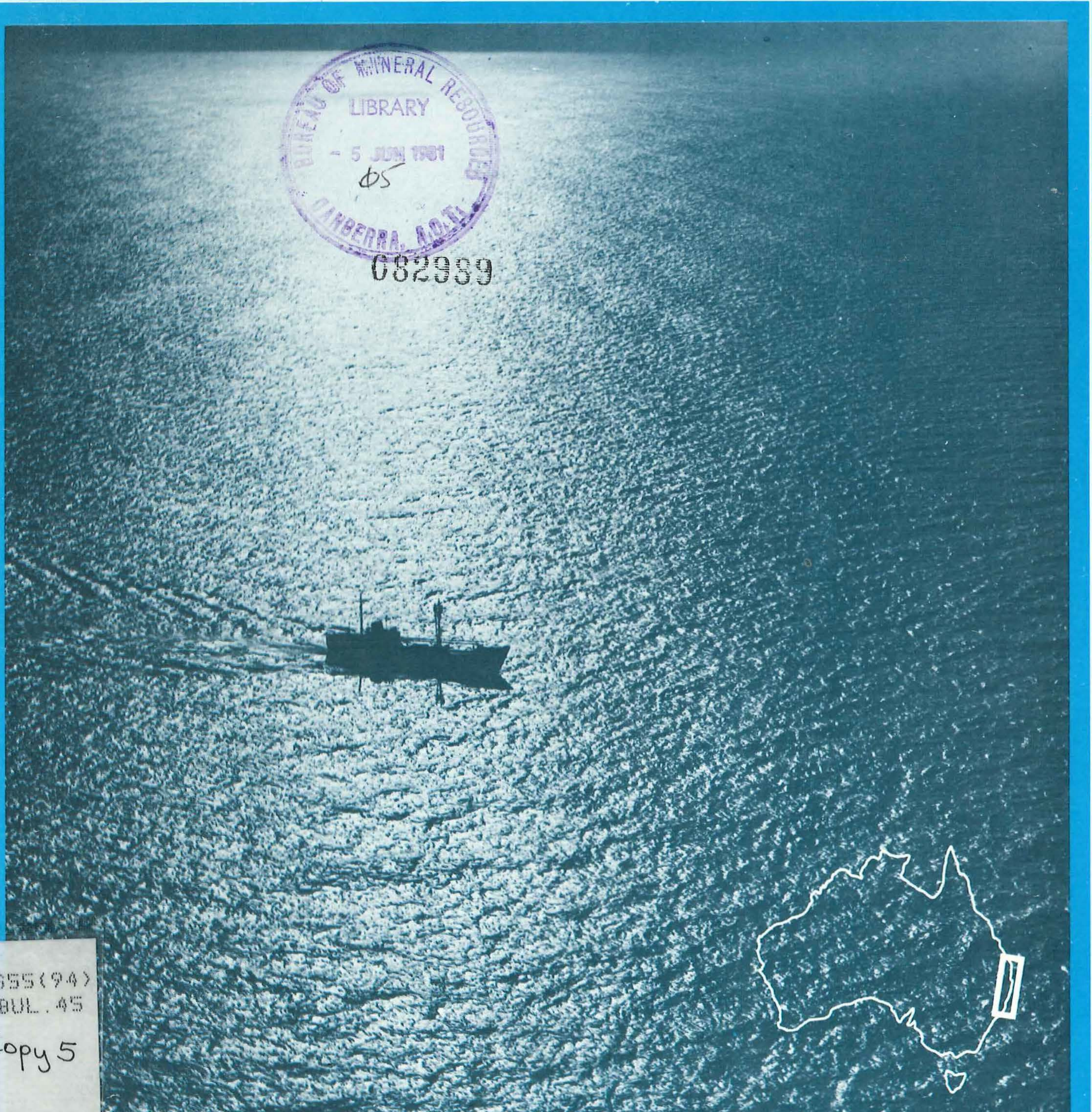
J. F. Marshall



DEPARTMENT OF NATIONAL DEVELOPMENT & ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY
AND GEOPHYSICS

BULLETIN 207

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J. F. MARSHALL

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CONTENTS

ABSTRACT . . . v

INTRODUCTION . . . 1

Acknowledgements . . . 2

Regional geology . . . 2

Coastal geology . . . 2

Coastal geomorphology . . . 4

Previous work . . . 4

Climate and oceanography . . . 4

Climate . . . 4

Surface water circulation . . . 5

Sampling techniques and laboratory procedures . . . 5

TEXTURES OF THE SEDIMENTS . . . 5

Statistical grainsize parameters . . . 9

Carbonate distribution . . . 9

Synthesis of textural and carbonate data . . . 9

MINERALOGY OF THE SEDIMENTS . . . 9

Terrigenous components . . . 9

Quartz . . . 9

Quartz types . . . 9

Group A . . . 10

Group B . . . 10

Group C . . . 11

Group D . . . 11

Feldspar . . . 11

Terrigenous rock fragments . . . 11

Carbonate components . . . 11

Foraminifera . . . 11

Molluscs . . . 11

Bryozoa . . . 11

Echinoderms . . . 11

Calcareous red algae . . . 12

Halimeda . . . 12

Intraclasts . . . 12

Carbonate cements . . . 16

Other authigenic components . . . 16

Glauconite . . . 16

Iron oxides . . . 20

Phosphorite . . . 20

Heavy minerals . . . 21

Economic aspects . . . 24

Present-day sedimentation patterns . . . 24

GEOCHEMISTRY OF THE SEDIMENTS . . . 26

General distribution . . . 26

Iron . . . 26

Arsenic . . . 26

Phosphate . . . 26

Titanium . . . 26

Geochemistry of the high-Fe sediments . . . 26

Origin of the high-Fe sediments . . . 31

Origin of the phosphorites . . . 31

REFERENCES . . . 32

APPENDIX 1. Station locations, water depth, and sediment colour . . . 34

APPENDIX 2. Grainsize data . . . 36

APPENDIX 3. Geochemical data, 1970 samples . . . 38

APPENDIX 4. Geochemical data, 1972 samples . . . 39

TABLES

1. Average monthly temperatures and rainfall: Brisbane and Port Macquarie . . . 4
2. Phosphate analyses of nodules and cemented nodules from the outer shelf of northern New South Wales 28
3. R-mode factor analysis of outer shelf sediments with high and low iron contents . . 30
4. Chemical analyses of selected high-Fe sediments 30

FIGURES

1. Locality map 1
2. M.V. *San Pedro Strait* 2
3. Regional geology of the onshore area 3
4. Location of sample stations 6
5. Variations in grainsize (mean diameter) 7
6. Grainsize standard deviation 8
7. Carbonate distribution 10
8. Relation between mean grainsize, standard deviation, and carbonate content . . . 12
9. Photomicrographs of sediment types 14
10. Photomicrographs of intraclasts 15
11. Photomicrographs of carbonate cements 17
12. Photomicrographs of carbonate cements 18
13. Photomicrographs of high-Fe sediments 19
14. Photomicrographs of phosphatic nodules and cemented nodules 20
15. Photomicrographs of phosphatic sediments 22
16. Distribution of heavy minerals 23
17. Distribution of iron 25
18. Distribution of arsenic 27
19. Distribution of phosphate 28
20. Distribution of titanium 29

PLATE

1. Southern Queensland and northern New South Wales continental shelf sediments .

ABSTRACT

Sands are predominant over the entire continental shelf, and mud is absent or only a minor component of the sediments. The amount of gravel, largely biogenic, is high in some places, but it has a scattered distribution. The amount of carbonate on the outer shelf is relatively low as a result of the formation of authigenic minerals. The amount and type of carbonate material have a substantial bearing on the grainsize and sorting of the sediments. The terrigenous component of the sediments is dominated by quartz, and there are usually only minor amounts of feldspar and rock fragments. Four types of quartz grains have been identified on the basis of roundness, sorting, and grainsize. These quartz types are believed to be related to various sources including beach and fluvial deposits. Skeletal carbonate components include mainly foraminifera, molluscs, Bryozoa, echinoderms, and calcareous red algae. Intraclasts with either micrite or sparite cement are common and various types of carbonate cements have developed, predominantly within the chambers of organisms. Authigenic components of the shelf sediments consist of glauconite, goethite, and apatite. These are most abundant on the outer shelf, especially between 29° and 32°S. Goethite and glauconite most commonly fill the chambers of organisms, especially foraminifera, and apatite is present within the matrix of nodules and boulders of cemented nodules. Most of the sediments on the shelf are considered to be relict.

Sediments were analysed for iron, arsenic, phosphorus, and titanium. High iron values, up to 25 percent Fe_2O_3, are present on the outer shelf between 29° and 32°S. These high values are related to sediments which have high concentrations of goethite and glauconite. High arsenic values (up to 390 ppm As) are associated with these sediments, and also with the phosporites. Phosphorus values of about 6-10 percent P_2O_5 characterise nodules from the same area. Most titanium values are less than 0.5 percent TiO_2. Factor analysis indicates a good correlation between Fe, As, and P_2O_5. The iron-rich sediments on the outer shelf are considered to have formed by the oxidation of glauconite, resulting in the formation of hydrated iron oxides. Arsenic and to some extent phosphorus have been adsorbed onto the hydrated iron oxides. The phosporites are considered to have formed in two stages: (1) direct precipitation of carbonate-apatite between mineral grains, and (2) subsequent replacement of micritic carbonate.

INTRODUCTION

A marine geological survey of the continental shelf off southern Queensland and northern New South Wales (Fig. 1) was carried out in 1970 by the Bureau of Mineral Resources (BMR). During the 1970 cruise the continental shelf between the southern part of the Great Barrier Reef and latitude 32°S was surveyed (Jongsma & Marshall, 1971). The marine geology of the northern part of this area, between the Swain Reefs and Fraser Island, has been described by Marshall (1977). The survey consisted primarily of sea-bed sampling and shallow seismic reflection profiling. Sampling stations were positioned in a grid of 10 nautical miles (18.5 km).

Because of the narrowness of the shelf off northern New South Wales it was considered that the 10 n. mile sampling grid employed during the 1970 survey was inadequate. Therefore, additional, more closely spaced sampling stations were occupied on the northern New South Wales shelf during a BMR cruise in 1972 (Davies & Marshall, 1972). Additional seismic reflection profiling was also undertaken.

For both the 1970 and 1972 surveys BMR chartered the M.V. *San Pedro Strait*, an oil rig supply vessel of 330 tons gross, operated at that time by San Pedro (Offshore) Pty Ltd (Fig. 2). The vessel had an overall length of 36.6 m, and was powered by two 456-horsepower diesel engines giving a cruising speed of 10 knots. Two winches capable of 5 tonnes draw were located on the main deck aft of the superstructure. Ample room on the main deck gave the party plenty of working space. Two portable laboratories owned by BMR were welded to the deck, and a large A-frame with a raised platform was positioned on the stern of the vessel to facilitate dredging operations. The *San Pedro Strait* was equipped with a Simrad 'Skipper' 38.5 kHz echo-sounder, a Decca 202 radar unit, and an Arkas automatic pilot. The echo-sounder display was a straight-line dry-paper continuous record with a 2-range scale to a

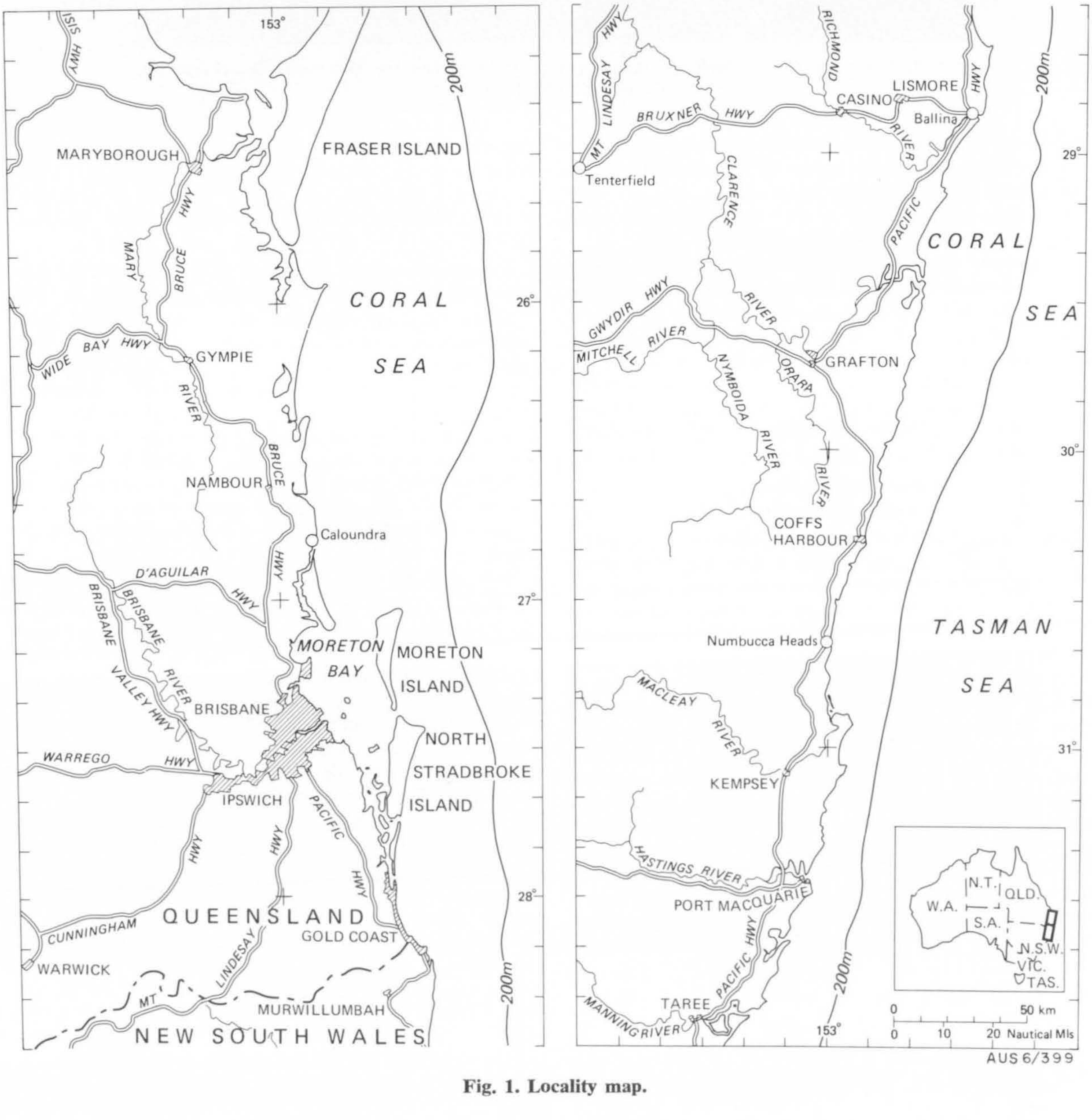

Fig. 1. Locality map.

Fig. 2. M.V. San Pedro Strait showing A-frame on stern and the two portable laboratories on deck (M/1334).

maximum depth of 1100 m. Position fixing of sampling stations and seismic traverses relied on radar when near the coast; the maximum radar range was 45 km. Celestial navigation and dead reckoning were used when the ship was out of radar range of land.

The vessel was well suited for the purposes of the survey, although she tended to pound heavily in head seas. During the 1970 survey rough seas hampered operations during late October to early December, and eight days were lost as a result of adverse weather. Failure of the vessel's steering gear resulted in a loss of one week when the vessel returned to Brisbane for repairs. During the early part of the 1972 survey, during late February and March, two days were lost as a result of bad weather.

Acknowledgements

The work at sea was accomplished successfully through the co-operation of the officers and crew of the M.V. *San Pedro Strait*. During the 1970 cruise the scientific staff on board consisted of H. A. Jones, D. Jongsma, and J. F. Marshall, and the technical staff and R. Dulski, M. Tratt, and D. M. Foulstone. During the 1972 cruise the scientific staff was H. A. Jones, P. J. Davies, and J. F. Marshall, and the technical staff M. Tratt, P. Mooney, and D. M. Foulstone. Laboratory work onshore was done by D. Warren and J. Reid. W. Mayo provided the computer program for the grainsize analysis while R. Macduff assisted with the factor analysis. The section on heavy minerals is based on a report prepared by J. Smart. Various aspects of the work were discussed with H. A. Jones, P. J. Davies, and P. J. Cook, and I am grateful for their comments and assistance. H. A. Jones and G. E. Wilford critically reviewed the manuscript and suggested various improvements.

REGIONAL GEOLOGY

Coastal geology

The main structural elements of the coast and immediate hinterland consist of the New England Fold Belt, the Clarence Moreton Basin, and the Maryborough Basin (Fig. 3). Aspects of the geology of these provinces are presented in detail in Hill & Denmead (1960), McElroy (1962), Ellis (1966), and Packham (1969).

The New England Fold Belt is bounded on the west and south by thrusts of the Hunter-Mooki system. East of the thrust system two major serpentinite belts, approximately 240 km apart, have been emplaced along major fractures. Between the two serpentinite belts there are steeply dipping early Palaeozoic strata and granites and porphyries of the New England Batholith. The New England Batholith has a meridional trend and intrudes the surrounding Palaeozoic rocks. Adamellite is the predominant rock type, followed by granodiorite and granite. Near the coast there are a series of east-west transcurrent faults, which have largely determined the positions of the major rivers.

The Mesozoic strata of the coastal basins rest unconformably on rocks of the fold belt. The Clarence-Moreton Basin contains up to 3000 m of sediments consisting mainly of coal measures, such as the Nymboida (Triassic) and Walloon (Jurassic) Coal Measures, and sequences of predominantly arenaceous sediments. These rocks have been gently folded. A residual rim of basement (Palaeozoic) rocks is present along parts of the coast. This suggests that the basin is not extensively developed offshore.

The Mesozoic rocks of the Maryborough Basin contain Triassic and Jurassic non-marine sediments, mainly conglomerate, sandstone, and coal measures. Granitic intrusions were emplaced during the early Triassic while volcanism became active at the end of the Jurassic and continued into the early Cretaceous. During the Cretaceous, marine sediments were deposited followed by coal measures. These sediments were folded during the Late Cretaceous. During the Tertiary a relatively thin sequence of non-marine sediments was deposited. The northeast section of the Maryborough Basin is present offshore, beneath Hervey Bay. To the south the Mary-

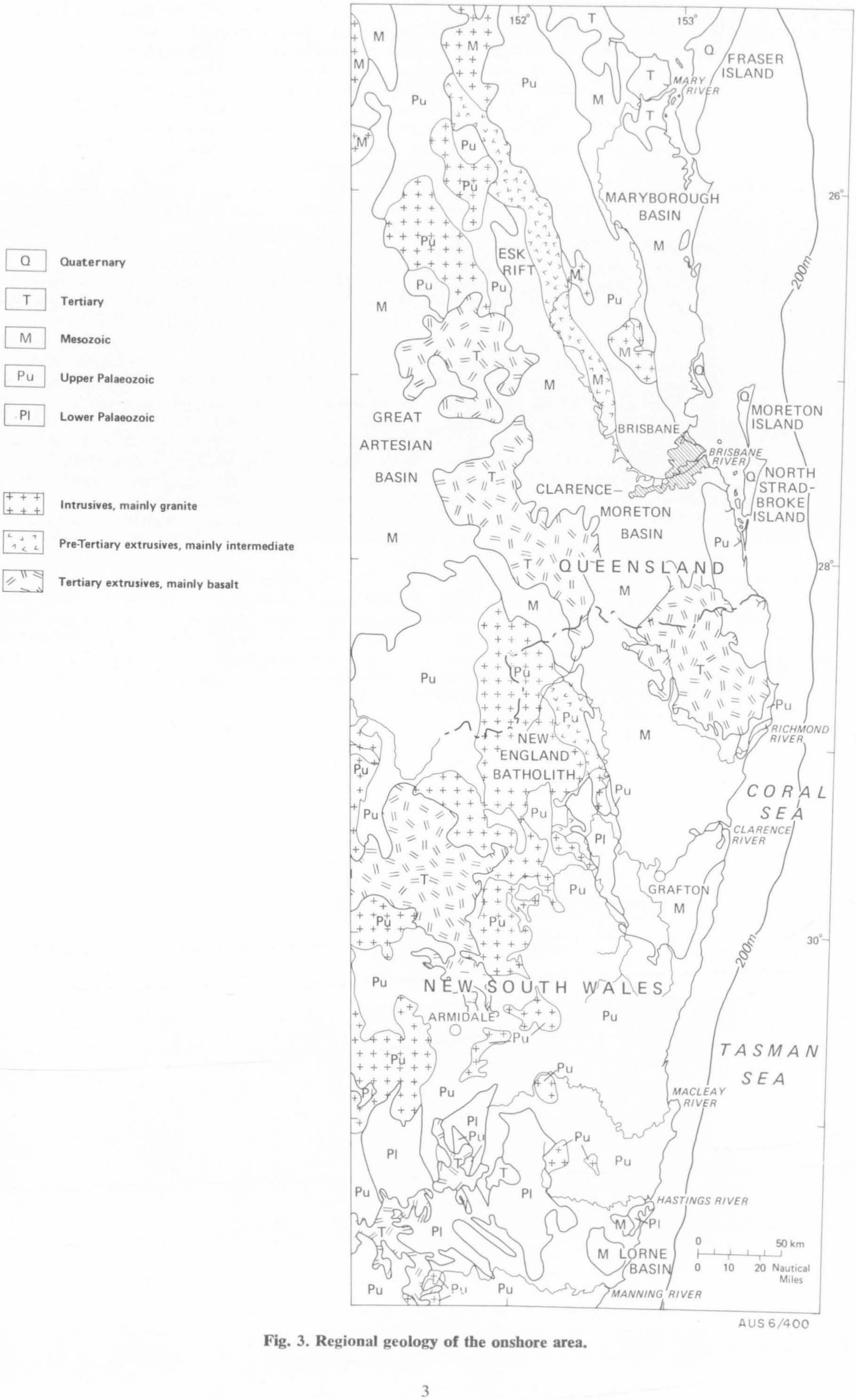

Fig. 3. Regional geology of the onshore area.

borough Basin probably extends offshore beneath the southern Queensland shelf.

In the coastal region between the Manning and Macleay Rivers the Lorne Basin forms a small circular structure approximately 30 km in diameter. The basal beds of the basin rest with a marked unconformity on early Permian sediments. The basin contains Triassic conglomerate, sandstone, and shale. The characteristic red colour of these sediments suggests a correlation with the Narrabeen Group of the Sydney Basin. Abundant post-Triassic lavas and minor intrusions are also present.

Basalts ranging from alkaline to tholeiitic are widespread throughout the area. Dating of the basalts by Wellman & McDougall (1974) has shown that most have ages within the range 55 to 11 m.y. ago (Late Paleocene to Middle Miocene).

Offshore several large sandy islands have developed during the Cainozoic. The larger ones, in particular Fraser, Moreton, and North Stradbroke Islands, have elevations of 200-240 m, and consist of predominantly unconsolidated quartz sands forming high fixed dunes.

Coastal geomorphology

Aspects of the coastal morphology of southern Queensland and northern New South Wales are discussed by Coaldrake (1960), Whitehouse (1968), and Langford-Smith & Thom (1969). The coast is roughly parallel to the meridional trend of the New England Fold Belt. Near the Queensland border the coast begins to turn slightly to the northwest, but the northerly trend is continued by Stradbroke and Moreton Islands. At the southern end of the New England Fold Belt the coast truncates those Palaeozoic rocks which have been subjected to transcurrent faulting. This has resulted in strike promontories and offshore rocky islands being developed in this area (Langford-Smith & Thom, 1969).

Most of the coast is a drowned embayed coast. Where the immediate hinterland is mountainous the coastline is dominated by high rocky cliffs. Where the hinterland is more subdued the coast is typified by long, gently curved sandy bays with few and relatively inconspicuous headlands (Langford-Smith & Thom, op. cit.).

Multiple bay barriers are a common geomorphic feature along the northern New South Wales and, to some extent, the southern Queensland coasts. Two distinct barrier systems, the Inner Barrier and the Outer Barrier, have been recognised (Thom, 1965). The Inner Barrier extends intermittently for almost 1000 km along the coast north of Newcastle. The Outer Barrier is a Holocene feature that has developed since sea level reached its present position approximately 6000 years ago (Thom & Chappell, 1975). ^{230}Th/^{234}U dating has confirmed that the Inner Barrier was formed during the last interglacial between 118 000 and 142 000 years BP (Marshall & Thom, 1976). Barrier lagoons and swamps have developed behind the Inner Barrier and between the Inner and Outer Barriers.

Previous work

Aspects of the marine geology of the continental shelf off southern Queensland and northern New South Wales have been discussed by Conolly (1969). The shelf to the north and south of the present study area has been covered by marine geological surveys by BMR (Marshall, 1977; Davies, 1979). The continental margin in the area has been covered by a multi-sensor geophysical survey by BMR (Symonds, 1973). Phosphorite nodules on the outer shelf of northern New South Wales have been described by von der Borch (1970) and Marshall (1971). Results obtained from a detailed bathymetric survey of the continental shelf for the Division of National Mapping have provided an important source of data on the detailed morphology of the shelf (Jones, 1973a, b; 1974). An exploratory oil well (Matjara No. 1) drilled offshore from Moreton Island by Amalgamated Petroleum NL (1968) has provided some data on the sub-surface stratigraphy. Offshore exploration by mining companies has covered parts of the inner shelf off northern New South Wales. Details of this work are presented by Jones & Davies (1979).

CLIMATE AND OCEANOGRAPHY

Climate

The east coast of Australia is affected by three main pressure systems: the tropical low-pressure zone, the subtropical high-pressure zone, and the subpolar low-pressure zone. The subtropical high-pressure zone dominates along the southern Queensland and northern New South Wales coast. During winter its axis is at about 25°S, and in summer at about 35°S. As the high-pres-

TABLE 1. AVERAGE TEMPERATURE AND RAINFALL: BRISBANE AND PORT MACQUARIE*

Month	*Brisbane*			*Port Macquarie*		
	Average daily maximum °C	*Average daily minimum °C*	*Average rainfall mm*	*Average daily maximum °C*	*Average daily minimum °C*	*Average rainfall mm*
January	29.1	20.8	193	25.3	18.1	160
February	29.2	20.8	196	25.6	18.6	180
March	28.2	19.3	151	24.9	16.9	173
April	26.7	16.9	66	23.2	14.3	168
May	23.7	13.4	73	20.4	10.5	145
June	21.7	11.2	86	18.4	8.7	132
July	20.7	9.4	75	17.8	7.1	103
August	22.0	10.4	48	18.6	7.9	92
September	24.0	12.8	33	20.1	10.0	89
October	25.9	15.8	111	21.7	12.9	97
November	27.5	18.1	90	23.0	15.0	95
December	28.5	19.6	131	24.3	16.9	129

* Temperature figures are based on 15-17 years' observation; rainfall figures are based on up to 70 years' observation (Bureau of Meteorology, 1975).

sure zone moves north during the winter it is replaced in the south by the subpolar low-pressure zone. This forms a series of depressions which move across the southern part of the continent in an easterly direction.

Temperatures of the region are moderate, average maximum temperatures being some 4°C cooler at Port Macquarie than at Brisbane (Table 1). The moderate temperatures along this part of the coast during summer are attributed to the sea-breeze which blows from directions between northeast and southeast. Rainfall is extremely variable, although Brisbane does show a marked decrease between April and September (Table 1). Along the northern New South Wales coast the rainfall can be quite high throughout the year, and the annual precipitation is higher than that of southern Queensland.

Surface water circulation

The water circulation along the east coast of Australia is dominated by a strong, narrow southerly flow that forms the western boundary current of the subtropical gyre in the South Pacific. This current, the East Australian Current, is formed between 20° and 25°S where from January to March it is supplied by equatorial water masses from the north and northeast, and from April to September by subtropical water masses from the east (Wyrtki, 1966).

Between 27° and 32°S a relatively strong, southerly flowing current is established on the outer continental shelf with surface velocities up to 4 knots (2 m/s). From 32°S the current breaks up into a number of anticyclonic eddies, about 250 km in diameter, which move to the south. The postulated circulation patterns of these eddies vary considerably from year to year.

Tidal currents are relatively insignificant on this part of the shelf compared to the shelf north of Fraser Island.

SAMPLING TECHNIQUES AND LABORATORY PROCEDURES

Most of the sediment samples were recovered with a small pipe dredge which was worked on 4 mm wire from a fast-running 3-horsepower diesel winch mounted on the stern of the ship. Where hard sea bottom was suspected, conventional rock dredges 130 cm long with mouth openings of 80 cm by 20 cm were used. These were lowered on 9 mm steel wire using the ship's 5-tonne winch and the large A-frame on the stern of the vessel. The location of bottom sample stations is shown in Figure 4.

When a sample was recovered it was described briefly in the log book, and the colour of the wet sediment was determined, using the Rock Color Chart published by the Geological Society of America. About 50 g of sample was treated with Rose Bengal solution (0.025% w/v in alcohol) in order to stain and preserve any living material, and then sealed and kept for micropalaeontological use. Another small split was sealed and stored as a reference sample. The rest of the sediment was stored in glass jars for laboratory work onshore.

In the laboratory the untreated samples were digested in 15 percent hydrogen peroxide solution to remove organic material. The samples were then washed with distilled water and air dried at 50°C. The dried sample was split into three unequal fractions. The two smaller splits were set aside, one for thin sectioning, and the other for chemical analysis. The largest split was retained for grainsize analysis.

For grainsize analysis the sample was sieved into gravel (>2.0 mm), sand (2.0-0.062 mm), and mud (<0.062 mm) fractions, and the percentages of each were determined. The silt and clay percentages in the mud fraction were determined by pipette analysis.

Grainsize analysis of the gravel fraction was determined by sieving, using opening sizes of −5.25, −4.25, −3.25, −2.25, −2.0, −1.75, −1.50, −1.25 and −1.0 phi units. Size distribution of the sand fraction was determined by settling tube. The BMR settling tube has been described by Mayo (1972); it is basically similar to other automatic recording settling tubes (Felix, 1969), and consists of a glass tube with an internal diameter of 7.5 cm and a length of fall of 161 cm. The collecting pan is a thin plastic disc which is connected to a transducing cell at the mouth of the tube by a prestretched monofilament nylon line. Signals from the transducing cell are amplified, and the output is presented in the form of a cumulative curve on an X-Y recorder. The height of the curve was measured at quarter-phi intervals, and the readings were entered directly onto data sheets. The mud fraction was analysed by the pipette method, using withdrawals for the fractions finer than 4.0, 4.5, 5.0, 5.5, 6.0, 7.0, 8.0, and 9.0 phi.

Grainsize distributions were calculated on a CDC 3600 computer using a program devised by Mayo (1972). The output consisted of the standard parameters (mean, standard deviation, skewness, and kurtosis); the percentages of gravel, sand, silt, and clay; and a graphical output consisting of the cumulative and frequency curves.

Although the pipette analysis was only carried out to 9 phi, the total weight of clay finer than 9 phi was extrapolated by the computer to 14 phi to achieve a better approximation of the mean, etc.

TEXTURES OF THE SEDIMENTS

Almost all the shelf sediments fall into the sand category of Shepard's (1954) classification scheme (Plate 1). Only one sample (1434), on the outer shelf at 26°20′S, had an appreciable mud content, of about 40 percent. Other sample stations immediately around it had zero mud contents. Elsewhere the amount of mud is negligible, and the only region of slightly muddy sediments (4.14% mud) is on the middle to outer shelf between latitudes 30° and 31°S.

Although mud is an uncommon feature of the sediments, gravel has a fairly wide distribution across the shelf. In a few places the amount of gravel exceeds 60 percent of the total sediment (Plate 1), and at one station (1411) the sediment was entirely gravel. The distribution of the gravel is usually patchy, and often it cannot be correlated from one sample station to the next. In a few places, such as on the outer shelf between 31° and 32°S, gravel does have a wide distribution. The areas of gravel accumulation are not restricted to a particular part of the shelf; they may be present on either the inner or outer shelf. In most places the gravel consists of bioclastic detritus, but on the outer shelf between 30° and 32°S phosphatic nodules and boulders of cemented nodules are an important component.


▲ 1537 Sediment sample station

Fig. 4. Location of sediment sample stations.

The predominantly sandy sediments of the southern Queensland and northern New South Wales continental shelf differ texturally from shelf areas immediately to the north and to the south. In the Capricorn Channel there is a considerable proportion of fine-grained sediments (Marshall, 1977), although sediments in waters shallower than 100 m are predominantly sand. Davies (1979) has shown that a belt of muddy sediments is present on the mid shelf off central and southern New South Wales. Considering that a number of substantial rivers (by Australian standards) debouch their sediment load onto the inner shelf in the area under consideration, it is surprising that there is a paucity of muds on the inner and mid shelf areas. Aerial photographs of the entrance of the Richmond River reproduced by Herbert (1969) show a plume of fine-grained sediment extending for about 2 km from the river mouth, but sediment samples in this area have no appreciable mud component. It can only be assumed that the continental shelf in this area is one of relatively high energy, and that fine-grained material has been continuously winnowed into deeper water.

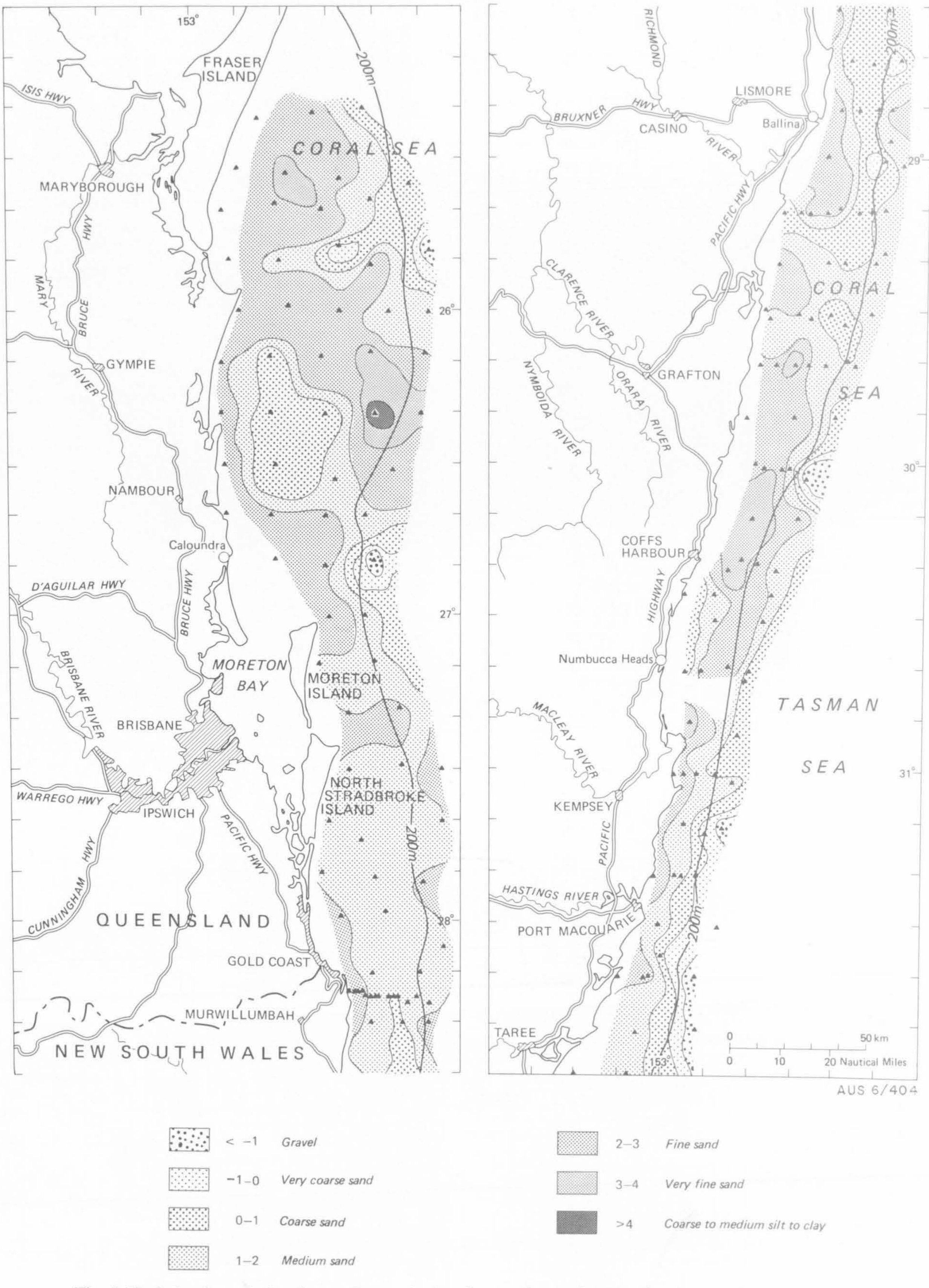

Fig. 5. Variation in grainsize (mean diameter) of surface sediments in phi units. Contour interval 1 phi unit.

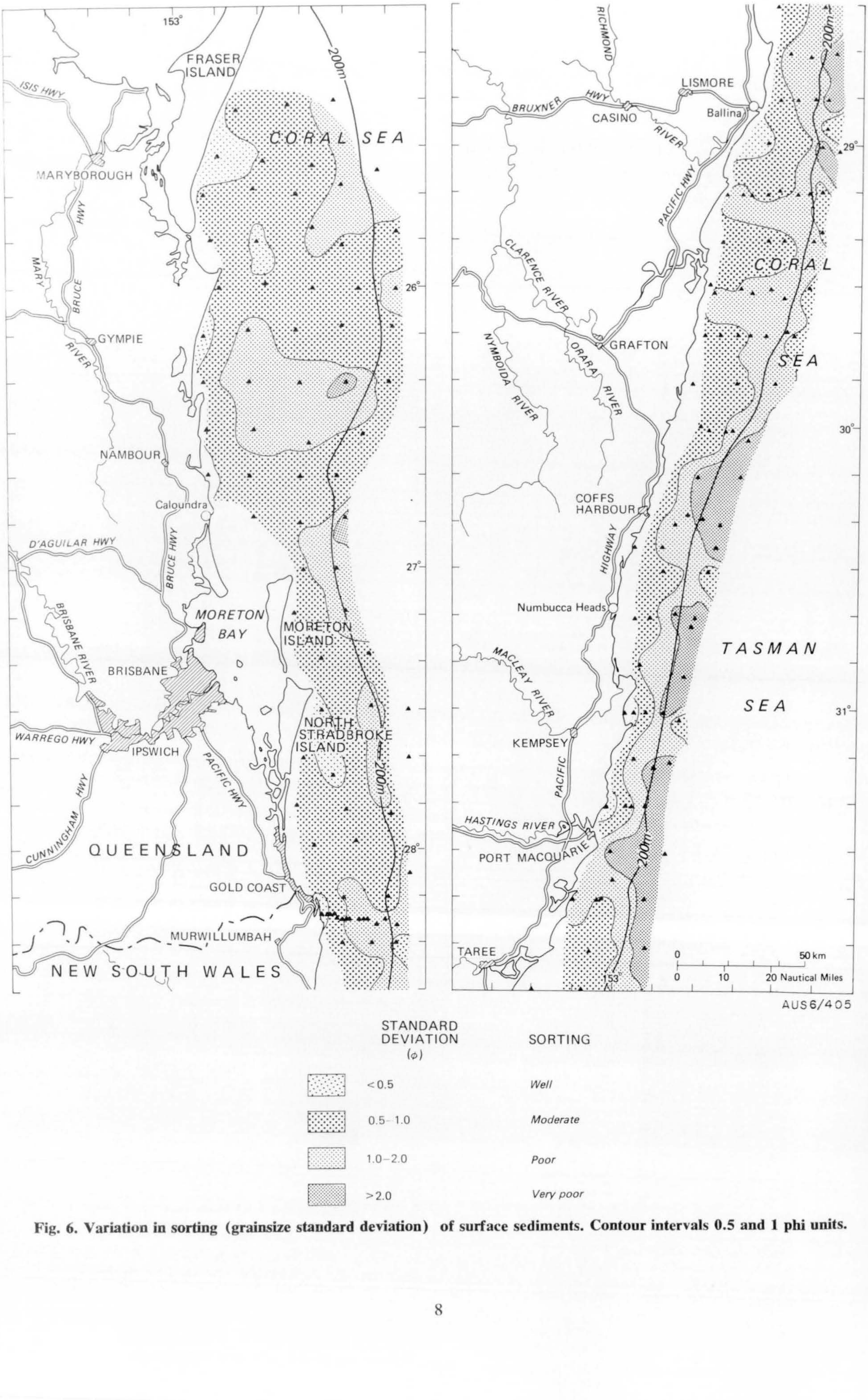

Fig. 6. Variation in sorting (grainsize standard deviation) of surface sediments. Contour intervals 0.5 and 1 phi units.

STATISTICAL GRAINSIZE PARAMETERS

Although almost all the shelf sediments are classified as sand, the grainsize parameters of these sediments show a somewhat complex pattern. Values of mean grainsize of the sediments (Fig. 5) show a rather haphazard distribution. On one part of the shelf values may indicate relatively fine sands nearshore becoming coarser offshore, while on another part of the shelf the reverse may occur. Figure 8 shows the trend of mean grainsize values across the shelf at various latitudes. In some traverses there is a decrease in grainsize from the inner shelf to the mid shelf, followed by an increase on the outer shelf. In other traverses there is an increase from the inner shelf to the inner part of the mid shelf followed by a decrease on the mid shelf and then another increase on the outer shelf. This complex pattern arises largely from variations in the amount of carbonate in the sediments. However, significant variations do occur on the inner shelf where carbonate values are generally low, indicating that the local energy regime has exerted some influence on the non-carbonate fraction.

The degree of sorting, as reflected by the standard deviation values, shows that well to moderately sorted sediments are present on the inner shelf while poorly to very poorly sorted sediments occupy the outer shelf and upper slope (Fig. 6). Exceptions to this general rule do occur, such as between 26° and 27°S, where there are moderately sorted sediments on the outer shelf and poorly sorted sediments on the inner shelf. In most places the trend of the standard deviation (sorting) follows the trend of mean grainsize and carbonate (Fig. 8). Usually an increase in grainsize and carbonate is reflected by an increasingly poor sorting coefficient, while well sorted sediments tend to have a low carbonate content and a relatively fine mean grainsize (usually about 2-3 phi).

Grainsize frequency curves show that sediments on the inner shelf are either unimodal or bimodal, whereas the majority of mid and outer shelf sediments are polymodal. This is a reflection of their carbonate content, sediments with high carbonate having three or more modes. Some outer shelf sediments do show unimodal or bimodal frequency curves. These sediments are considered to be relict and to have been subjected to size sorting processes during periods of lower sea level. On some parts of the outer shelf it could be postulated that the East Australian Current is exerting such an influence at the present time.

CARBONATE DISTRIBUTION

Marshall & Davies (1978) have shown that the sediments on the continental shelf off eastern Australia increase in carbonate content away from the present shoreline. This is generally true for the continental shelf off southern Queensland and northern New South Wales; however, while the inner shelf has low carbonate values (<30%) and the outer shelf generally high values (>60%), there are areas on the outer shelf where carbonate values are only moderately high (Fig. 7). Typical examples of this situation occur at 29°30'S and at about 31°S. In these areas the amount of carbonate has been diluted by authigenic minerals and/or their weathered products.

There are only small isolated areas where the carbonate content of the sediment exceeds 90 percent (e.g. Fig. 9D). Examples occur on the southern Queensland shelf where there are areas of algal banks towards the outer part of the shelf. Another area of high carbonate is Barwon Bank (26°33'S, 153°32'S), a small isolated bank which supports living corals. Small isolated patches of sediment on the inner shelf contain relatively high carbonate values in contrast to the surrounding areas. In some cases these sediments contain a varied fauna, but often molluscan skeletal fragments dominate.

SYNTHESIS OF TEXTURAL AND CARBONATE CONTENT DATA

The sediments of the continental shelf of southern Queensland and northern New South Wales are composed dominantly of sands while muds are a relatively rare component. Gravels have a random distribution on the shelf, but cover an extensive area of the outer shelf in the south. The mean grainsize values for the shelf sediments show a complex distribution with prominent latitudinal differences. This suggests that grainsize variation is a fairly local phenomenon, and that there is no single controlling factor, such as wind-induced currents on high-energy shelves, that is affecting the shelf as a whole. The carbonate content of the sediments shows an overall increase from the inner shelf to the outer shelf, and this is reflected to some extent by the standard deviation values. Profiles across the shelf of mean grainsize, standard deviation, and carbonate content show a good correspondence between these three parameters. This suggests that the amount and the type of carbonate material have a substantial bearing on the texture of the sediments, and that this masks any variations that occur in the terrigenous fraction.

MINERALOGY OF THE SEDIMENTS

TERRIGENOUS COMPONENTS

Quartz

Quartz is the main constituent of the terrigenous fraction and therefore the amount present in the sediments varies inversely with the carbonate content, except where authigenic minerals are a significant component. Thus in general terms the abundance of quartz decreases from the inner to the outer shelf. However, at 26°20'S and 28°20'S moderate quartz values (30-60%) occur on the outer shelf. Relatively low quartz values may occur on the inner shelf where there are high carbonate values. Most of the inner shelf sediments contain more than 60 percent quartz, and on the southern Queensland shelf values may exceed 90 percent (e.g. Fig. 9A). In this region high quartz values extend onto the mid shelf. Quartz values on the outer shelf are generally less than 10 percent.

Quartz types

Four types of quartz have been tentatively recognised, determined largely on the basis of grainsize, degree of roundness, and sorting. It was found impossible to distinguish groups based on a genetic classification of quartz types because most sediments contain varying proportions of nearly all types. While overlapping of the different quartz groups does occur, it is felt that a differentiation of the quartz types on this basis provides some insight into their depositional environ-

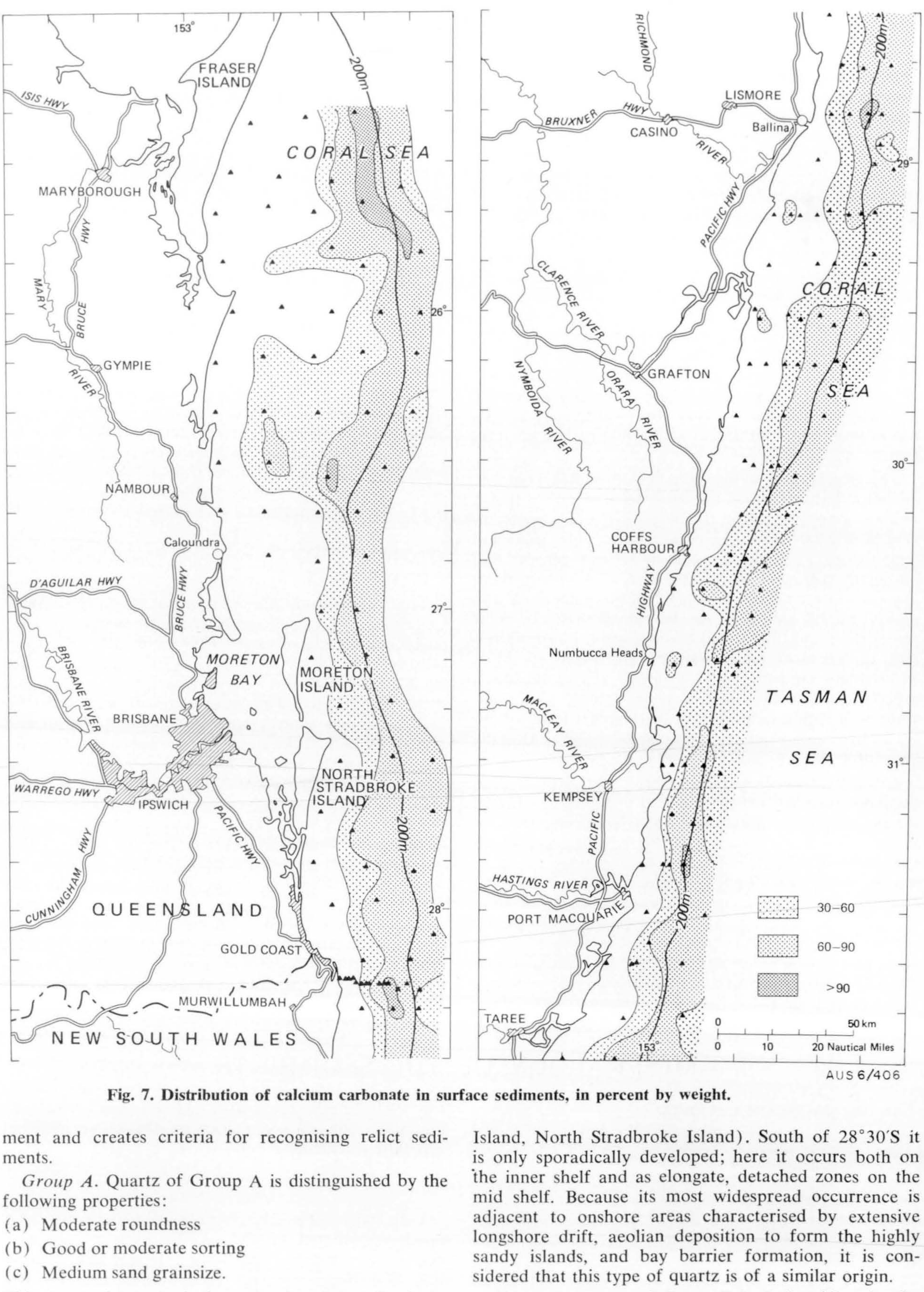

Fig. 7. Distribution of calcium carbonate in surface sediments, in percent by weight.

ment and creates criteria for recognising relict sediments.

Group A. Quartz of Group A is distinguished by the following properties:

(a) Moderate roundness
(b) Good or moderate sorting
(c) Medium sand grainsize.

This type of quartz is best developed on the inner shelf of southern Queensland (e.g. Fig. 9A). It occurs extensively offshore from areas that are characterised by long, unbroken stretches of sandy beaches, as well as large sandy islands (e.g. Fraser Island, Moreton Island, North Stradbroke Island). South of 28°30′S it is only sporadically developed; here it occurs both on the inner shelf and as elongate, detached zones on the mid shelf. Because its most widespread occurrence is adjacent to onshore areas characterised by extensive longshore drift, aeolian deposition to form the highly sandy islands, and bay barrier formation, it is considered that this type of quartz is of a similar origin.

Group B. Quartz of Group B is distinguished by the following properties:

(a) Moderate roundness
(b) Poor sorting
(c) Fine to coarse sand grainsize.

This type of quartz is present on the inner shelf offshore from Moreton Island, and seawards of Group A quartz. Between 28°30′S and 30°S it is present on the inner shelf, but south of 30°S it is only present on the outer shelf. Quartz of this group is the hardest to classify and it does not appear to have a common origin. It possibly represents mixing of other groups.

Group C. Quartz of Group C is distinguished by the following properties:

(a) Angular to subangular grains
(b) Moderate to poor sorting
(c) Fine to medium sand grainsize.

This type of quartz is extensively developed on the mid shelf between Moreton and Fraser Islands (e.g. Fig. 9B). In this area it extends onto the inner shelf, offshore from river mouths. From Moreton Island south to 29°S this quartz type is virtually absent. South of 29°S, however, it is the dominant quartz type over a wide area of the mid and inner shelf. In some places it is present on the inner shelf off river mouths, such as the Clarence River. This possibly indicates that this quartz type is fluvial in origin and that it was deposited directly onto the shelf without being subjected to intense littoral processes. There is no evidence of sand-size quartz being deposited on mid shelf areas at the present day, and such quartz is therefore relict.

Group D. Quartz of Group D is distinguished by the following properties:

(a) Angular grains
(b) Well sorted
(c) Fine sand grainsize.

This type of quartz is restricted to the outer shelf areas, where it forms a semi-continuous zone along the shelf edge. This quartz type represents the finer-grained fraction of the fluvial sands which were deposited on the shelf and have been progressively reworked into deeper water. The well-sorted nature of this quartz is probably a function of its fine grainsize, but it is also considered to be a result of reworking and deposition in a low-energy environment. Silt-size quartz is largely absent from the shelf, which suggests that it has by-passed, or been winnowed from, the shelf and been deposited on the continental slope.

Feldspar

The feldspar content is generally low (<5%), and decreases towards the edge of the shelf. Between Fraser Island and Moreton Bay there is an area on the mid shelf where feldspar makes up 5-10 percent of the sediment. The few samples collected on the inner shelf show low values, but more detailed sampling by Hekel (1977 and pers. comm.) between Bribie Island and Noosa Heads indicates that locally values as high as 15 percent are present. South of 27°30′S nearshore sediments commonly contain 5 to 10 percent feldspar, and offshore from Kempsey there are two areas where it exceeds 10 percent.

Most of the feldspar grains are altered, and it is difficult to identify particular feldspar minerals in thin section. Although fresh, unaltered orthoclase was not observed in thin section, some of the plagioclase grains were relatively unaltered.

Terrigenous rock fragments

Rock fragments are rare on the shelf in the northern part of the area, but they increase in abundance towards the south. The values are highest nearshore and decrease away from the shoreline. The highest values, exceeding 10 percent, were recorded on the inner shelf between Coffs Harbour and Kempsey. Between 31° and 32°S values on the inner shelf are as high as 5 percent.

An anomalous sample (70631492) immediately south of the entrance to the Clarence River contains up to 20 percent rock fragments. These rock fragments appear to be sedimentary or possibly volcanic in origin, and consist of quartz grains ranging in size from fine to coarse sand in a highly altered chloritic and iron-stained matrix. Thin, crosscutting quartz veins are present in some fragments. In a number of cases the matrix around the perimeter of the quartz grains has been removed, and void channels about 0.02 mm wide and lined with iron oxides have formed.

Elsewhere the rock fragments are predominantly sedimentary in origin, with lesser amounts of volcanic, plutonic, and metamorphic varieties. The sedimentary rock fragments are characterised by quartz of silt to fine sand size set in a dark iron-rich matrix and cut by numerous thin quartz veins. In transmitted light they sometimes impart a reddish colour.

CARBONATE COMPONENTS

Foraminifera

Foraminifera are the most abundant type of skeletal organism present on the shelf. The largest populations are present on the edge of the shelf, and values decrease towards the shore mainly because of the increase of terrigenous material. The high values near the shelf edge are attributed to the presence of abundant planktic foraminifera which add greatly to the existing benthic community. Towards the shore the ratio of benthic to planktic foraminifera increases.

Molluscs

Molluscs are moderately abundant on the edge of the shelf, and occur as isolated patches on the inner and mid shelf. Fewer are present on much of the mid shelf in the north, and on the inner shelf in the south. Pelecypods are the most common type of mollusc, and gastropods have a scattered distribution. Most shells are abraded and many are extensively bored and iron-stained; partial or complete recrystallisation to low-Mg calcite provides further evidence of the relict nature of some of this material.

Bryozoa

Skeletons of bryozoans increase in abundance from north to south on the outer shelf. Between 25° and 29°S their abundance is only low on the outer shelf, and they are rare or absent on the mid and inner shelf. South of 29°S bryozoans are moderately abundant on the outer shelf, present in small numbers on the mid shelf, and rare on the inner shelf. In many skeletons the autopores have been filled by carbonate or iron oxides.

Echinoderms

Fragments of echinoid plates and spines are present in the majority of samples. Some nearshore sediments do not contain any recognisable fragments, but farther offshore, echinoid fragments are a common component of the carbonate fraction. They are moderately abundant towards the edge of the shelf. Since the plates and spines are formed of a single crystal of high-Mg calcite, identification under the polarising microscope is relatively easy. The echinoid plates also show a characteristic fenestrate pore structure. These pores are usually filled with either micrite, glauconite, or goethite.

Calcareous red algae

Marshall & Davies (1978) have shown that the highest concentration of calcareous red algae (coralline algae) on the continental shelf of eastern Australia is on the outer shelf between Fraser Island and Brisbane. Apart from this area there are narrow, linear zones on the mid and outer shelf between Brisbane and Coffs Harbour where calcareous red algae are fairly abundant. On the inner shelf they are rare while seawards of the shelf break they are absent. In the northern part of the area, especially off Fraser Island, the calcareous red algae are associated with banks or hardgrounds, which they have presumably colonised. Such banks are not as extensively developed in the south. Usually in the northern area the algae are of an encrusting nature, binding other skeletal fragments and detrital grains to form nodules (rhodoliths). In the south the algae are present in the sediments as segmented fragments with a well developed cellular structure (Fig. 9C).

It is known that calcareous red algae extend from polar regions to the tropics (Adey & Macintyre, 1973), and that they are a common component of skeletal sands on the continental shelves of many continents. Adey & Macintyre (op. cit.) considered that light is the primary factor controlling the depth distribution of the algae, and that most species in polar to temperate waters have a limited depth range in this respect. Most coralline algae at water depths of 50 to 150 m on the continental shelves of other continents are relict (Milliman, 1974), and they formed during the last major period of glaciation or earlier. The highest concentrations of coralline algae on the continental shelf of eastern Australia occur in water depths of 60 to 160 m. This would suggest that they are likewise relict.

Halimeda

Rare fragments of the codiacean alga *Halimeda* are present on the mid to outer shelf regions east of Fraser Island. Marshall & Davies (1978) concluded that *Halimeda* is absent from the shelf sediments south of 24°S, the boundary between chlorozoan and foramol assemblages* on the east Australian shelf. This conclusion remains valid because the amount of *Halimeda* offshore from Fraser Island is negligible compared to the other skeletal components. It is also possible that it may be relict. The fragments of *Halimeda* are abraded and their utricles are generally filled with clear, fine-grained carbonate cement.

Intraclasts

The term intraclast is used here to describe rock fragments, mostly less than 2 mm in diameter, consisting of quartz and/or skeletal material in a carbonate cement. The quartz and skeletal components are similar to those in the surrounding sediments. The intergranular cements consist of either micrite (Fig. 10A, C) or sparite (Fig. 10B, D). Rocks of a similar composition are not present on the mainland, and it is considered that these intraclasts have originated on the shelf. This is supported by the absence of intraclasts on most of

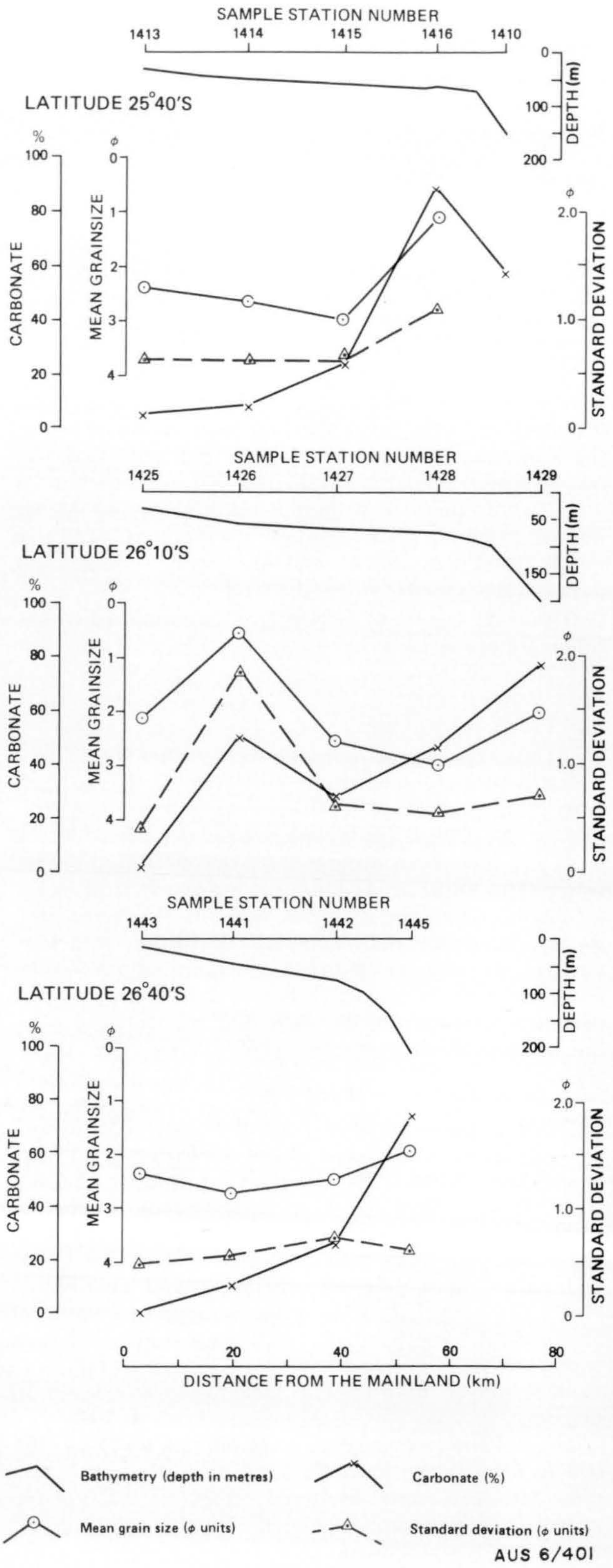

Fig. 8. Profiles across the shelf at different latitudes showing variation in mean grainsize, standard deviation, and carbonate content.

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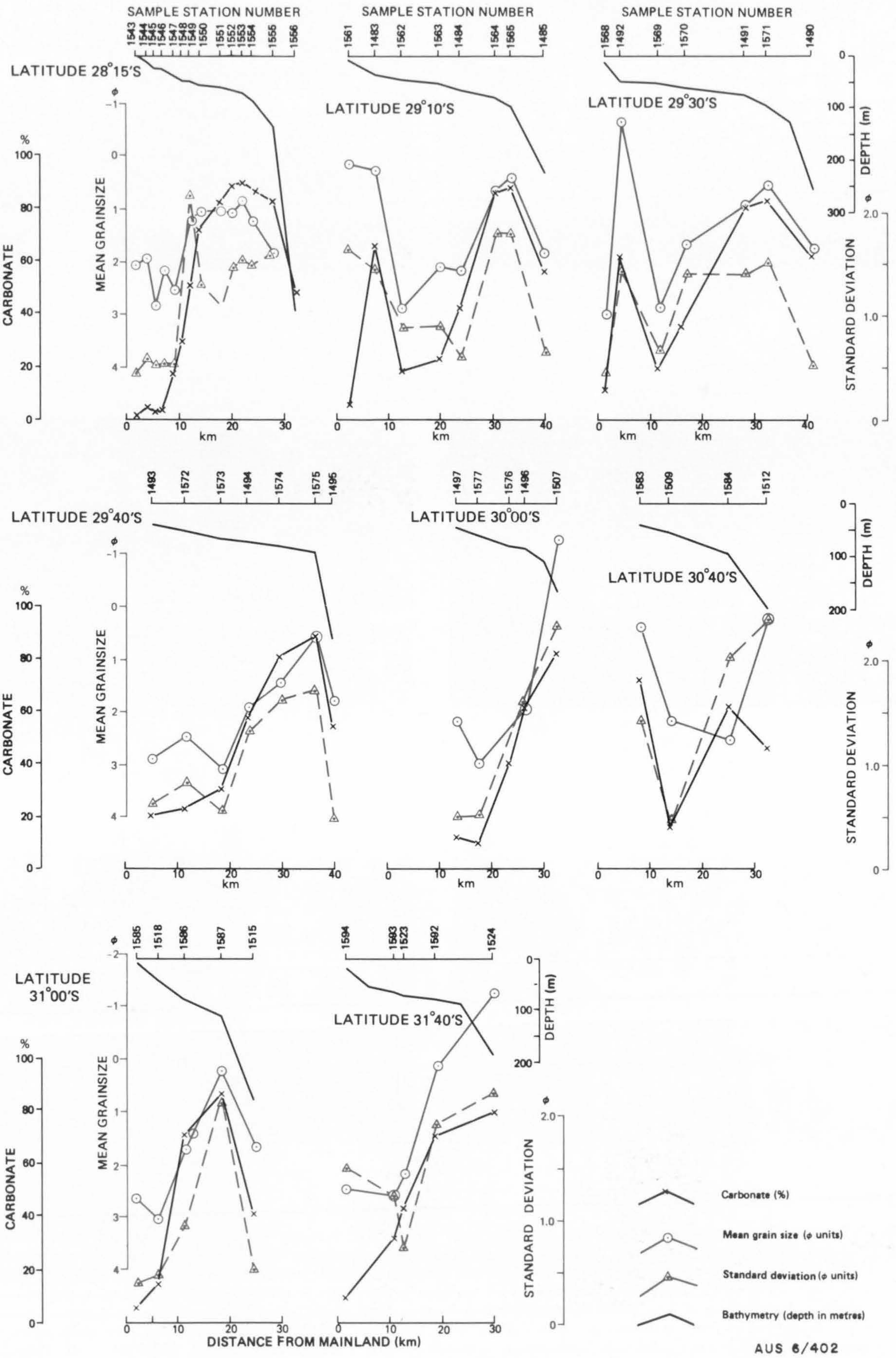
* Lees & Buller (1972) proposed these terms for different skeletal carbonate associations. Chlorozoan is defined as a tropical assemblage in which hermatypic corals and calcareous green algae are diagnostic types. Foramol represents temperate water assemblages in which the predominant constituents are foraminifera, molluscs, bryozoans, calcareous red algae, and barnacles. Lees (1975) considered the distribution of these two associations to be related primarily to water temperature and salinity.


SAMPLE STATION NUMBER
1543 1544 1545 1546 1547 1548 1549 1550 1551 1552 1553 1554 1555 1556
LATITUDE 28°15'S
1561 1483 1562 1563 1484 1564 1565 1485
LATITUDE 29°10'S
1568 1492 1569 1570 1491 1571 1490
LATITUDE 29°30'S
1493 1572 1573 1494 1574 1575 1495
LATITUDE 29°40'S
1497 1577 1576 1496 1507
LATITUDE 30°00'S
1583 1509 1584 1512
LATITUDE 30°40'S
1585 1518 1586 1587 1515
LATITUDE 31°00'S
1594 1593 1523 1592 1524
LATITUDE 31°40'S
CARBONATE
%
MEAN GRAINSIZE
φ
STANDARD DEVIATION
DEPTH (m)
km
DISTANCE FROM MAINLAND (km)
Carbonate (%)
Mean grain size (φ units)
Standard deviation (φ units)
Bathymetry (depth in metres)
AUS 6/402

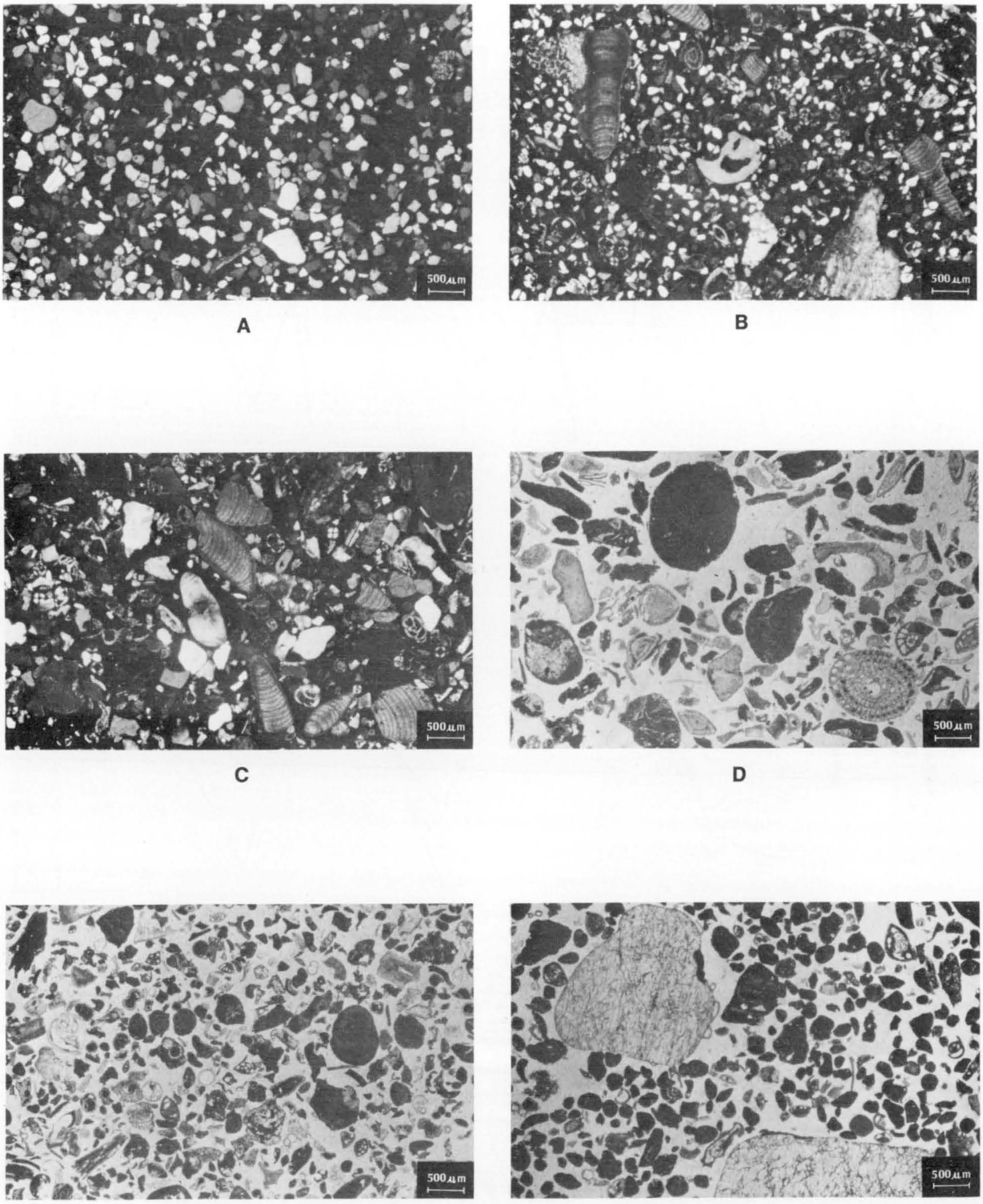


Fig. 9. Main sediment types. A. Well sorted sand from the inner shelf (sample 1443). Crossed nicols. (M/2160). B. Sand moderately high in terrigenous content, from the mid shelf with Group C quartz predominant. Skeletal fragments consist of calcareous red algae, molluscs, foraminifera, and echinoids (sample 1444). Crossed nicols. (M/2160). C. Sand from the mid shelf with roughly equal proportions of terrigenous and biogenic components (sample 1464). Crossed nicols. (M/2160). D. Coarse-grained carbonate sand from the outer shelf consisting of foraminifera, calcareous red algae, molluscs, echinoids, and Bryozoa (sample 1404). Plane polarised light. (M/2160). E. Outer shelf carbonate sand showing many skeletal chambers filled with dark micrite (sample 1473). Plane polarised light. (M/2160). F. Outer shelf relict sand with a high proportion of iron-stained skeletal material and coarse subrounded quartz grains (sample 1512). Plane polarised light. (M/2160).

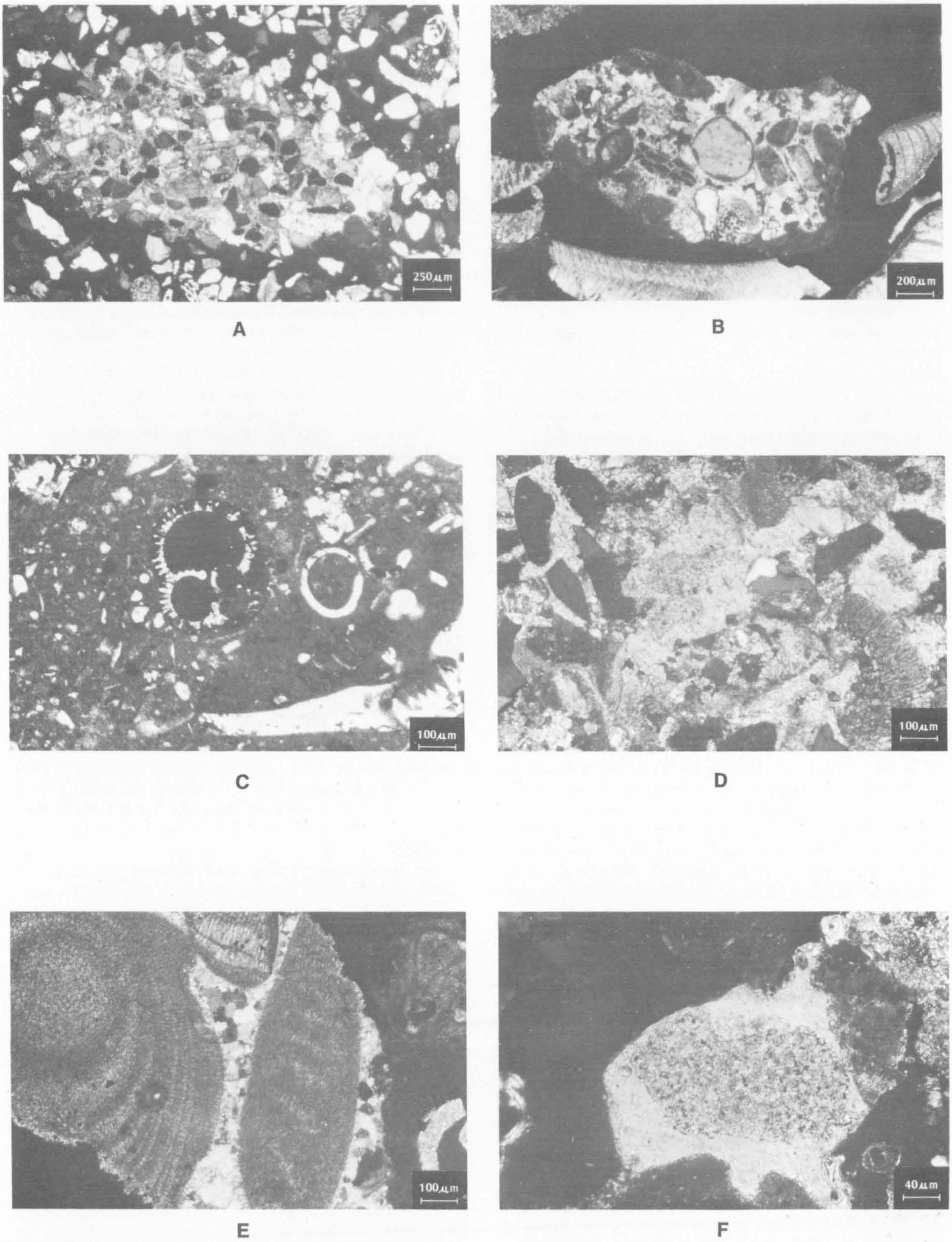


Fig. 10. Intraclasts. A. Intraclast consisting of quartz grains and skeletal material set in a micrite cement (sample 1415). Crossed nicols. (M/2158). B. Intraclast of quartz and skeletal material set in a sparry calcite cement. Note micrite fringe around central quartz grain (sample 1417). Crossed nicols (M/2158). C. Detail of intraclast showing dark micrite cement. Foraminiferal chamber is filled with goethite (sample 1439). Plane polarised light. (M/2158). D. Detail of intraclast showing interlocking sparite cement (sample 1432). Crossed nicols. (M/2158). E. Detail of intraclast showing fragments of calcareous red algae cemented by low-Mg calcite spar (sample 1417). Crossed nicols. (M/2160). F. Detail of intraclast; sparite cement shows echinoid plate with a syntaxial rim (sample 1576). Crossed nicols. (M/2158).

the inner shelf, and their increasing abundance towards the edge of the shelf.

The amount of quartz grains present in the intraclasts is variable, as is the ratio of quartz to skeletal carbonate. Compositions range from 100 percent quartz to exclusively skeletal carbonate. The types of intraclasts with micrite or sparite cement are also variable. Generally in deeper water the dominant type is that with a micrite cement. This is particularly noticeable between 29° and 32°S, where intraclasts with sparite cement (Fig. 10E) are common on the shelf, but near the 200-m isobath there is a mixture of the two types, while below 200 m the intraclasts have micrite cements. In some cases the sparite-cemented intraclasts include echinoid fragments with syntaxial overgrowths (Fig. 10F).

The presence of intraclasts with similar constituents suggests a common origin, but the different types of cement suggest that they have different diagenetic histories. It is considered that those intraclasts with micrite cement have remained exclusively within the marine environment, while those with sparite cement have been subaerially exposed at some stage, leading to dissolution and reprecipitation of calcite cement. The distribution of intraclasts with micrite or sparite cement suggests that this change took place as a result of eustatic sea level changes.

A possible source of the intraclasts is beachrock, which is known to be present on the sea-floor at depths of 128 to 137 m (Smith & Iredale, 1924). Radiocarbon ages of 12 900 ± 210 and 17 900 ± 600 years B.P. on material from the same area (Phipps, 1970) indicate that the beachrock formed during the last major glacial period. This would not necessarily explain the origin of those intraclasts with sparite cement, except to indicate that previous beachrocks at higher levels were subaerially exposed. Petrographic examination of the beachrocks shows that they have a similar composition to the intraclasts, but texturally they are quite different. Both quartz and skeletal carbonate grains in the beachrock are significantly coarser than those of the intraclasts, while the beachrock cement (high-Mg calcite) has a better developed crystal structure than the micrite cement of the intraclasts. The beachrock has a much greater porosity than the intraclasts.

This leaves the suggestion that the intraclasts have formed as a result of direct cementation on the sea-floor. Examples of submarine cementation quoted by Bathurst (1975) show that such processes can take place in various marine environments ranging from the intertidal zone to the deep sea-floor. Those intraclasts with a micrite cement are presumably fragments of cemented shelf sediments, whereas those with sparite cement have formed as a result of cementation on the sea-floor at higher levels, and have subsequently undergone transformation during periods of low sea level.

Carbonate cements

Various types of cement have developed within chambers of shells which form much of the carbonate fraction of the shelf sediments. The most common type of cement is that formed by the filling of chambers by impure lime mud which has subsequently been cemented (Fig. 12F). The result is a chamber filled with quartz and fragments of skeletal material floating in a micrite cement. This micrite cement is usually grey-brown in transmitted light, and shows very little birefringence because of its fine grainsize and dark colour. In some cases a microspar cement, rather than micrite, is present (Fig. 11B). Microspar cement has better defined crystal boundaries, is light grey, and shows birefringence. The mineralogy of the micrite cement is unknown, but presumably it is aragonite or high-Mg calcite, or a mixture of both.

Fringing cements are also well developed within skeletal chambers, particularly those of foraminifera, Bryozoa, and gastropods. Most shelf sediments with a high carbonate content contain porcellaneous foraminifera of the family Miliolidae, usually *Quinqueloculina* sp. and *Triloculina* sp. The majority of these miliolids have fringing calcite cement on the walls of the inner chambers, while the outer chambers are filled with micrite or iron oxides (Fig. 11A-E.) In some the cement in the inner chambers has developed to such an extent that it completely fills them. There are basically two types of cement within these inner chambers: (i) an isopachous outer rim of bladed calcite crystals 10-20 μm wide and 20-40 μm long (Fig. 11C); (ii) tabular, sparry calcite 40-50 μm wide, which may fill the chambers (Fig. 11D, E). From crystal morphology and substrate control, the first type of cement is considered to be high-Mg calcite, but it is not known if the tabular cement is high- or low-Mg calcite.

Some of the outer chambers of the miliolids have microspar cements while others show a gradation between micrite and microspar (Fig. 11B). Other foraminifera may have fringing cements, but less commonly than those with a porcellaneous wall structure. This suggests that foraminifera with this type of wall structure form better substrates for nucleation of calcite cement.

Fringing cements within bryozoan and gastropod chambers consist of aragonite and calcite (Fig. 12E). Bryozoan chambers commonly have a fringing cement consisting of bladed crystals 30-60 μm long and 5-20 μm wide (Fig. 12C, D). In some cases they form rosettes of crystals which have nucleated from a common point. The interior of the chamber is usually filled by micrite, but sometimes the cement completely fills the chambers.

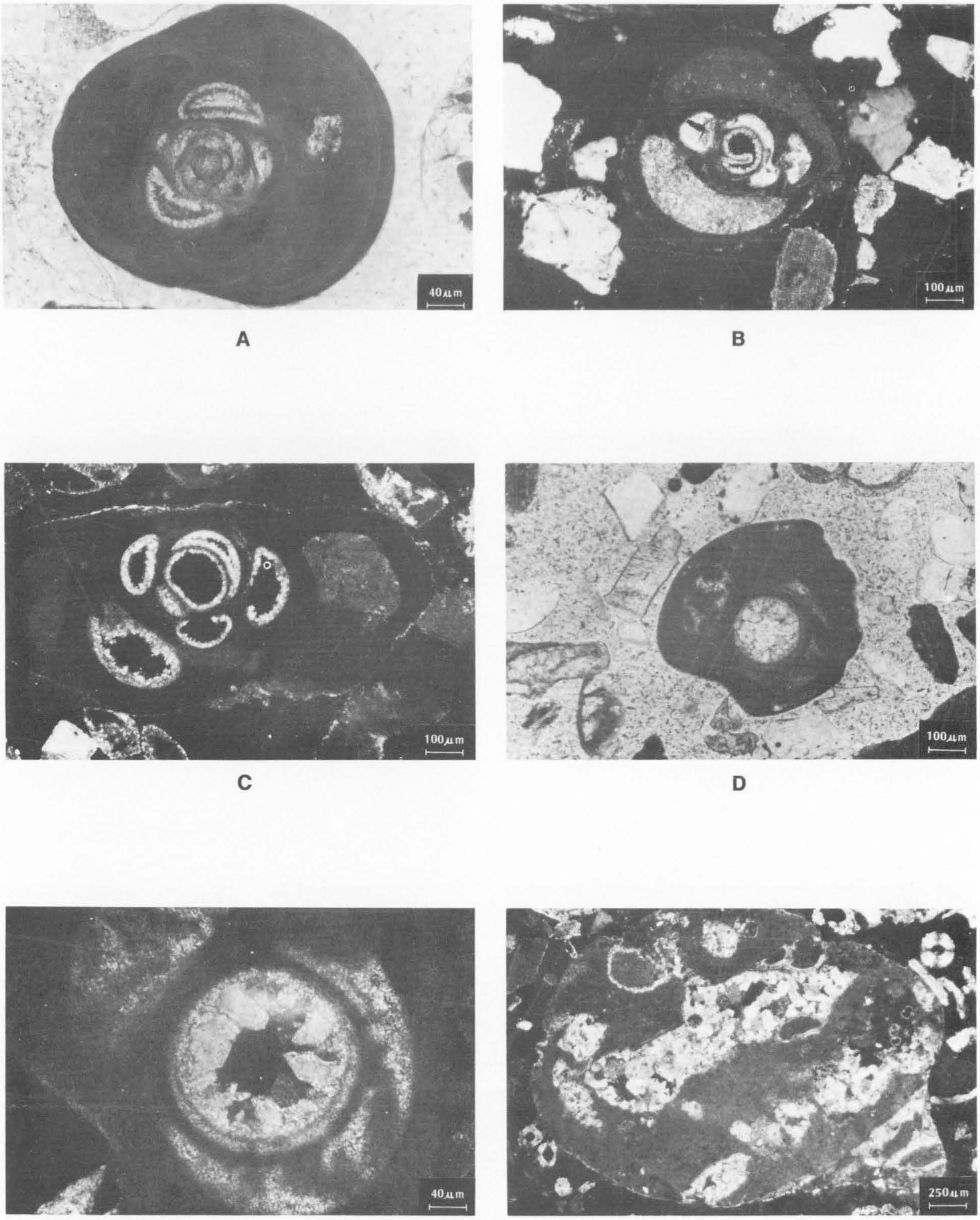
The interior of gastropod shells may be filled with acicular aragonite, cryptocrystalline high-Mg calcite, sparry calcite, or dark grey micrite. One particular example (Fig. 12A) has a fringing cement of acicular aragonite growing from the chamber wall. Towards the centre of the chamber there is cryptocrystalline cement, considered to be high-Mg calcite, while micrite fills another part of the chamber. Quartz grains and skeletal fragments 'float' in this cement. Other gastropods have sparry calcite cement completely filling their chambers (Fig. 12B). This type of cement is possibly low-Mg calcite; individual sparite crystals are up to 200 μm wide.

OTHER AUTHIGENIC COMPONENTS

Glauconite, hydrated iron oxides, and phosphorite form the major authigenic components on the shelf. On some parts of the shelf the three components are unrelated to each other, but on the outer shelf at the southern end of the area all three are closely associated. However, this does not necessarily imply that they originated within a similar environment or that they were formed at the same time.

Glauconite

Between Fraser Island and Brisbane glauconite is present in trace amounts on parts of the inner and mid



A B C D E F

Fig. 11. Carbonate cements. A. Foraminifer of the family Miliolidae showing inner chambers rimmed or filled with calcite cement and outer chambers filled with goethite (sample 1485). Plane polarised light. (M/2160). B. Miliolid showing fringing calcite cement in the proloculus, coarse calcite cement filling the inner chambers, microspar filling lower outer chamber, and micrite in upper outer chamber (sample 1479). Crossed nicols. (M/2158). C. Clear calcite cement (high-Mg calcite?) lining the inner chambers of a miliolid. Outer chambers filled with micrite (sample 1477). Crossed nicols. (M/2158). D. Calcite spar lining proloculus of miliolid (sample 1464). Plane polarised light. (M/2158). E. Detail of D showing finer-grained calcite lining the wall of the proloculus with coarse calcite filling most of the chamber (sample 1464). Crossed nicols. (M/2158). F. Fragment of encrusting coralline algae with calcite spar developed within voids (sample 1491). Crossed nicols. (M/2158).

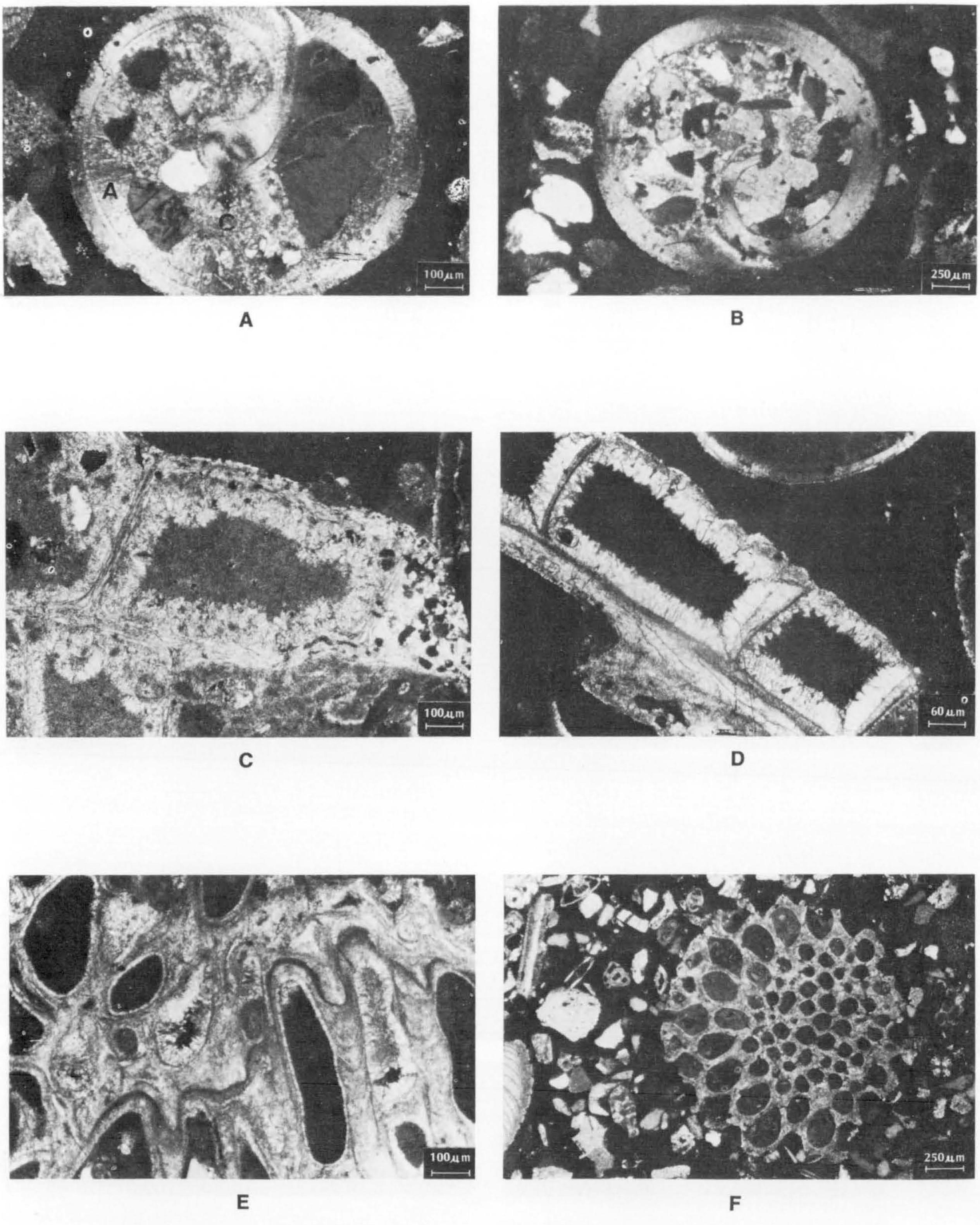


Fig. 12. Carbonate cements. A. Section through a gastropod shell filled with carbonate cement and quartz grains. Three types of cement are visible: acicular aragonite cement (A) lines part of the wall; crypto-crystalline, possibly high-Mg calcite cement (C) fills the central parts of the chamber; dark grey micrite (M) in top right-hand corner (sample 1430). Crossed nicols. (M/2158). B. Gastropod shell filled with quartz and low-Mg calcite (sample 1472). Crossed nicols. (M/2158). C. Bryozoan chamber rimmed by bladed calcite cement and later filled with micrite (sample 1504). Crossed nicols. (M/2158). D. Bryozoan chambers rimmed with a palisade of bladed calcite cement and filled with micrite (sample 1550). Crossed nicols. (M/2158). E. Bryozoan fragment showing some chambers rimmed, or filled, with aragonite cement and others lined with a fine fringe of calcite cement. Other chambers have been filled with micrite (sample 1417). Crossed nicols. (M/2158). F. Bryozoan fragment, the chambers filled with grey-brown micrite (sample 1494). Crossed nicols. (M/2158).

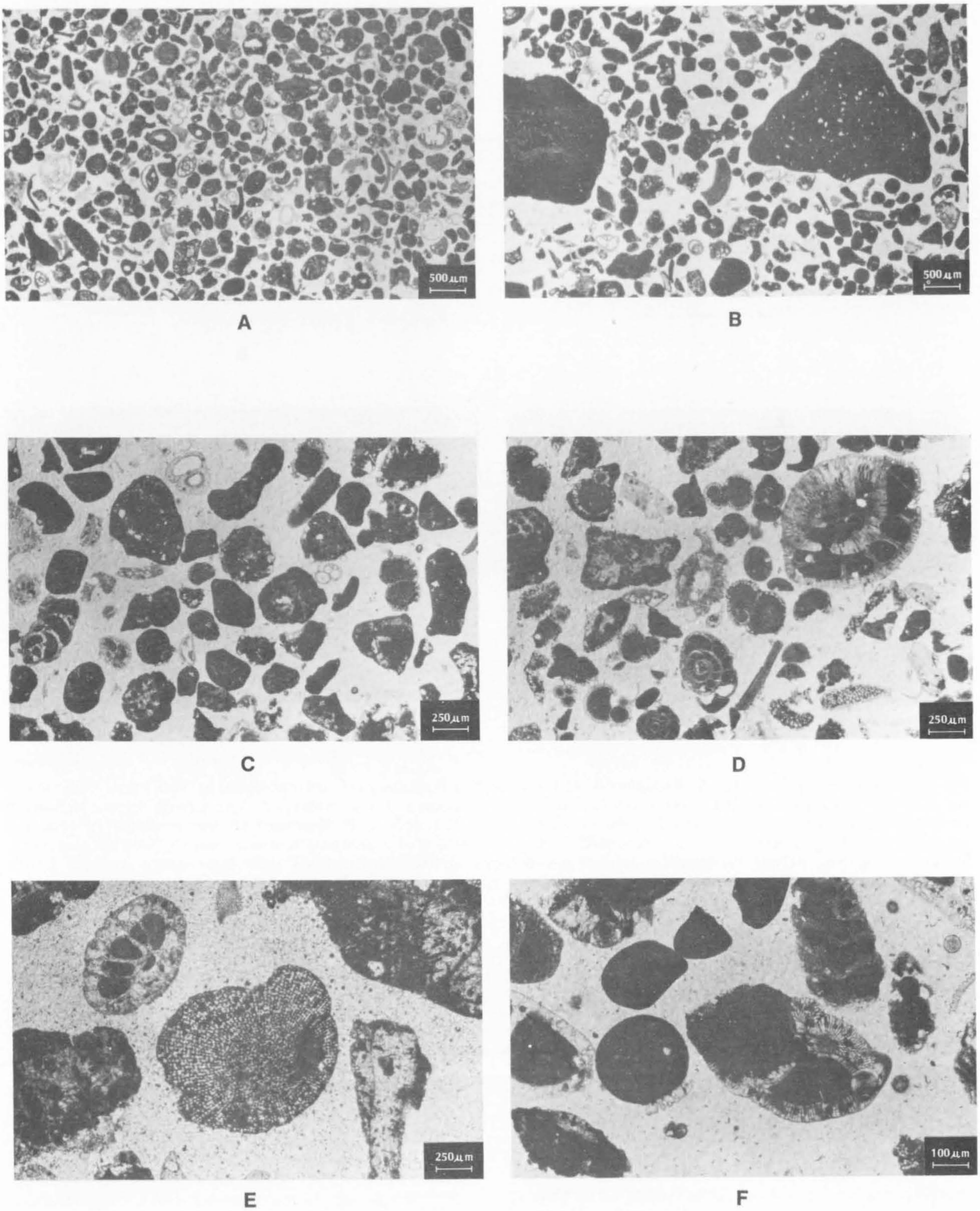


Fig. 13. High-Fe sediments. A. Chambers of foraminifera are predominantly filled by goethite (sample 1566). Plane polarised light. (M/2160). B. Development of goethite in skeletal chambers and clasts of quartz and skeletal material set in an iron oxide cement (sample 1512). Plane polarised light. (M/2160). C. Detail of high-Fe sediment showing infilling of chambers by goethite and minor glauconite. Mollusc fragment in lower right-hand corner shows ironstaining and filling of borings by goethite (sample 1515). Plain polarised light. (M/2160). D. High-Fe sediment with goethite and glauconite filling chambers (sample 1489). Plain polarised light. (M/2160). E. Fragment of an echinoid plate, pores filled with goethite (sample 1492). Plane polarised light. (M/2160). F. Detail of high-Fe sediment showing goethite filling the chambers of foraminifera, and goethite pellets which were originally enclosed within foraminiferal chambers (sample 1515). Plane polarised light. (M/2160).

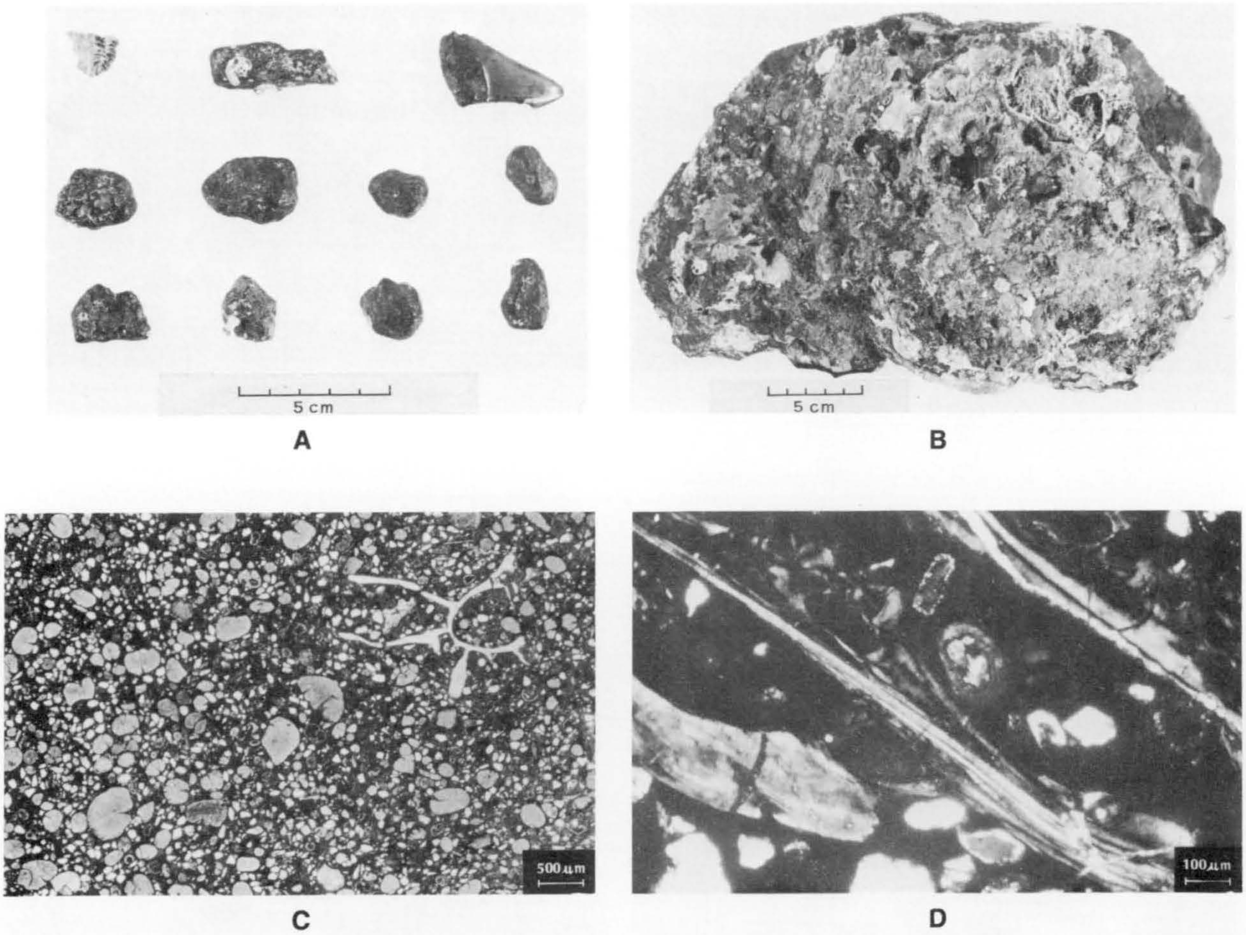


Fig. 14. Phosphatic sediments. A. Phosphorite nodules dredged from the outer shelf of northern New South Wales showing glazed goethite coatings and some encrustation. Coral fragments and a phosphatised shark's tooth (upper right-hand corner) were dredged from the same locality (sample 1516). (GA/4656). B. Encrusted boulder consisting of cemented phosphorite nodules (sample 1513). (GA/4645). C. Thin section of a phosphorite nodule showing detrital glauconite, fine-grained quartz, pelagic foraminifera, and a phosphatised skeleton set in a dark collophane matrix (sample 1516). Plane polarised light. (M/2161). D. Photomicrograph of part of a nodule showing skeleton of an unknown organism which consists entirely of carbonate-apatite (sample 1516). Crossed nicols. (M/1197).

shelf. Between 27° and 29°S it is absent from the shelf sediments, but south of 29°S it is a common constituent of the outer shelf sediments. Generally its abundance, in this area, varies from 5 to 20 percent, but in one or two places it is as high as 50 percent. The glauconite varies from pale greenish yellow to dark green. Most of it occurs as filling of the chambers of organisms, particularly foraminifera.

Iron oxides

On the outer continental shelf and upper continental slope between 29° and 32°S the sediments have a characteristic dark yellowish brown colour (10YR4/2) which is due to the presence of iron oxides. Up to 25 percent Fe_2O_3 may be present in these sediments, which otherwise consist of almost pure carbonate.

Thin sections show abundant iron staining of the skeletal carbonate, and the filling of skeletal chambers and borings by a dark reddish brown material. Rock fragments consisting of quartz and/or skeletal material in an iron oxide cement are also present. X-ray diffraction analysis indicates that goethite is a prominent mineral phase, but it is possible that amorphous iron oxides are also present. Since mineral species such as limonite are considered to be cryptocrystalline forms of goethite (Borchert, 1965), the term *goethite* will be used throughout when discussing the iron oxide.

Goethite, like glauconite, is most commonly found filling the chambers of organisms (Fig. 13A-F), and this suggests that the two have a common origin. In most sediments on the outer shelf between 29° and 32°S the two coexist, but goethite is usually more abundant than glauconite. Skeletal chambers may be filled with either one or the other, and only rarely are both present within the same chamber. However, a skeletal fragment may have some of its chambers filled with glauconite and others with goethite. More commonly a skeletal fragment will have all its chambers filled with only one type.

Intraclasts or rock fragments containing quartz and/or skeletal carbonate in an iron oxide cement make up a small proportion of these iron-rich sediments (Fig. 13B). Other intraclasts contain glauconite and goethite pellets as well. In a few intraclasts collophane is present in the cement. The intraclasts are in places rimmed by a lighter coloured goethite which in part is colloform.

Phosphorite

Phosphatic sediments were dredged from a number of stations on the outer continental shelf between 29° and 32°S. Von der Borch (1970) has previously reported the occurrence of phosphatic concretions, nodules, and cemented nodules at depths of 210 to 385 m in the same area. The phosphatic material occurs where bedrock or gravel is common on the outer shelf, and little or no fine material is being deposited.

The phosphatic material ranges in size from granules to boulders; pebble-size nodules were dredged from two stations (1512 and 1516), and cobbles and boulders of cemented nodules from one station (1513). On two occasions (station 1514) the heavy rock dredge hit a hard surface, but no sample was recovered. The seismic reflection traverses in this area do not show bedrock cropping out on the sea-floor. It is likely that the gravel is a surface or near-surface feature, and does not continue to any great depth.

The nodules range from 1 to 3 cm across and they have a 'polished' goethite coating (Fig. 14A). The nodules are associated with softer goethite-coated clastic pebbles and cobbles, some of which appear similar to the nodules except that they are flatter, less rounded, and less highly polished. Sediments dredged from station 1516 also included granules of abraded nodules, a phosphatised shark's tooth, and a rounded quartzite pebble.

In thin section it can be seen that the nodules consist of glauconite, quartz, goethite pellets, skeletal material, rock fragments, and traces of feldspar set in a cement consisting of varying proportions of goethite and collophane (Fig. 14C). Glauconite is present as pellets and, less commonly, fills chambers of organisms. The glauconite pellets are rounded to elliptical in shape, and they have diameters ranging from 0.1 to 0.3 mm. Most are light green, but some show signs of alteration, especially around rims and along cracks, which imparts a brownish colour. Although most of the glauconite pellets are spheroidal or lobate (terminology of Triplehorn, 1966), some do show evidence that they were once enclosed within skeletal chambers and subsequently liberated. The quartz has an average grainsize of 0.1 mm, and it is usually angular and subelongate. Some quartz grains are rimmed by glauconite, and in others the glauconite appears to be replacing quartz. The skeletal material in the nodules consists predominantly of planktic foraminifera with minor benthic forminifera, molluscs, and Bryozoa. The chambers of foraminifera are filled with goethite or calcite, and on rare occasions collophane. One large bryozoan fragment in one of the nodules has its carbonate skeleton replaced almost completely by goethite, and its chambers filled with goethite. Mollusc fragments are heavily bored, and the borings are filled with goethite. In one nodule a relatively large skeletal fragment of an unknown species consists entirely of carbonate-apatite (Fig. 14D). Von der Borch (1970) reported that two of the nodules examined by him contained parts of the phosphatic shell of the crab *Ommatocarcinus corioensis* (Early Miocene to Early Pliocene). It is possible that the phosphatic shell in the nodule belongs to the same species. Rock fragments make up a small proportion of some nodules. One particularly large fragment, about 8 mm wide, consists of quartz, goethite and glauconite pellets, and pelagic foraminifera in a cement of goethite and subordinate collophane. The fragment has a goethite coating about 0.3 mm thick. This is probably a smaller nodule which became incorporated into a much larger nodule.

Most phosphate in the nodules is present as cement, along with goethite. The cement consists of microcrystalline collophane which binds the grains into a fairly loose framework. There appears to be a gradation between collophane and goethite, with possibly an intermediate stage of iron-rich collophane.

The cobble and boulder size material recovered from station 1513 has a glazed, dark brown goethite coating (Fig. 14B). The upper surfaces of the rocks are encrusted by corals, Bryozoa, algae, and serpulid tubes, whereas the lower surface is relatively free of encrustation. Some of the rocks have smooth, glazed protuberances, which are nodules cemented into the rock. Freshly broken surfaces show nodules and fragments of nodules set in a dense, fine-grained matrix. The ratio of matrix to nodules is quite high; most of the nodules are completely separated from each other. One cobble consisted of a fossil bone in which the original microstructure is still preserved. In thin section the nodules are similar to those described previously. However, some of the more ferruginous nodules show dissolution of skeletal carbonate. Another atypical group comprise rounded goethite and collophane coated nodules consisting of fine quartz and skeletal material (foraminifera and echinoids) in a grey-brown micrite cement. In the centre of the nodule the micrite has been replaced by collophane, but the skeletal carbonate remains unaffected (Fig. 15C, D).

The matrix of the conglomeratic aggregates of cemented nodules from station 1513 consists of quartz, goethite pellets, glauconite, nodule fragments, and skeletal carbonate in a calcite, goethite, and collophane cement (Fig. 15A). Quartz is usually in the very fine sand-size range, but some coarse sand-size grains are also present. The quartz grains are subangular, and they make up as much as 30 percent of the matrix. They are often rimmed by goethite or calcite. Where they are rimmed by calcite, it can be seen that the calcite is replacing quartz. The calcite rim is usually sparite, but there are some micrite rims. Goethite is present as pellets and infilling of chambers of foraminifera. The pellets are 0.1-0.2 mm in diameter, and make up about 10 percent of the matrix. Glauconite occurs as green, rounded pellets about 0.1 mm in diameter. Sometimes the outer rims of the glauconite pellets show alteration to goethite. A small amount of glauconite is present filling chambers of foraminifera.

The skeletal material in the matrix consists predominantly of planktic foraminifera, with lesser amounts of benthic foraminifera, molluscs, and echinoids. The foraminifera have their chambers filled with goethite and calcite, and sometimes glauconite. Some mollusc shells show alteration to low-Mg calcite, while others have been replaced by collophane (Fig. 15E).

The cement of the matrix consists of calcite, collophane, and goethite (Fig. 15B). The calcite cement varies from micrite to microspar to sparite. Often calcite cement has been replaced by collophane, and to a lesser extent by goethite. Some micrite cement is present filling what appear to be large borings. However, a large part of the micrite within these borings has been replaced by collophane (Fig. 15F). The colour of the cement varies considerably. Where goethite is present it is dark brown, but where calcite is present it is clear. Small cross-cutting veins of calcite, sometimes partly replaced by goethite, are present throughout the matrix.

HEAVY MINERALS

The heavy-mineral fraction of the surface samples collected during the 1970 and 1972 surveys has been examined by J. Smart of BMR and the following de-

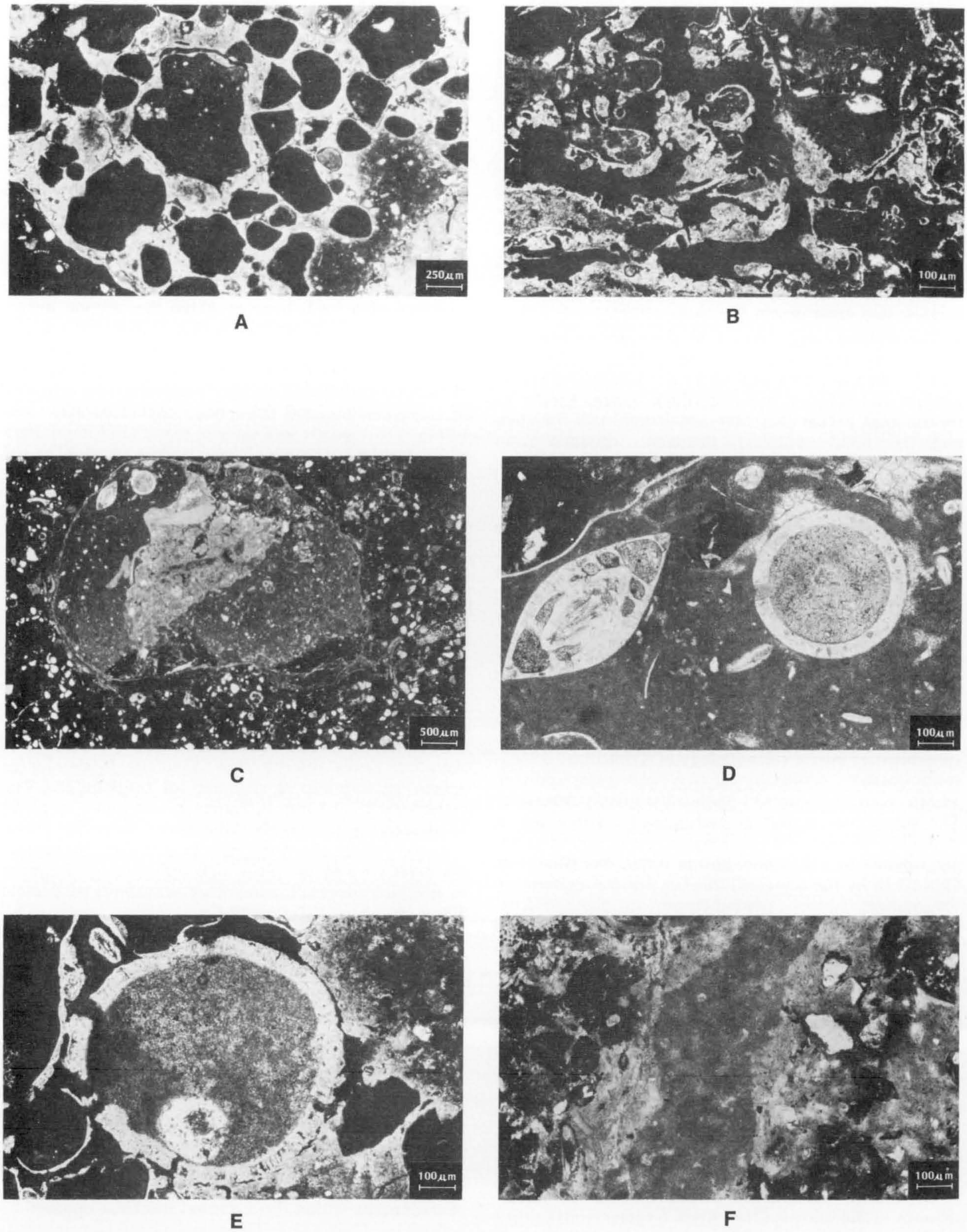


Fig. 15. Phosphatic sediments. A. Iron-rich clasts and pellets set in a predominantly collophane cement (sample 1513). Plane polarised light. (M/2160). B. Unusual texture exhibited by collophane (light) and goethite (dark) within the matrix of a cemented nodule boulder (sample 1513). Plane polarised light. (M/2161). C. Phosphatised pellet within matrix of cemented nodules. Light coloured collophane (centre) has replaced darker micrite (sample 1513). Plane polarised light. (M/2161). D. Detail of top left-hand corner of C. Chambers of larger skeletons are filled with collophane (sample 1513). Plane polarised light. (M/2161). E. Photomicrograph showing replacement of skeletal calcite by collophane; interior of chamber filled with micrite (sample 1513). Plane polarised light. (M/2161). F. Replacement of micrite cement (dark, centre) by collophane (light) possibly within a large boring (sample 1513). Plane polarised light (M/2161).

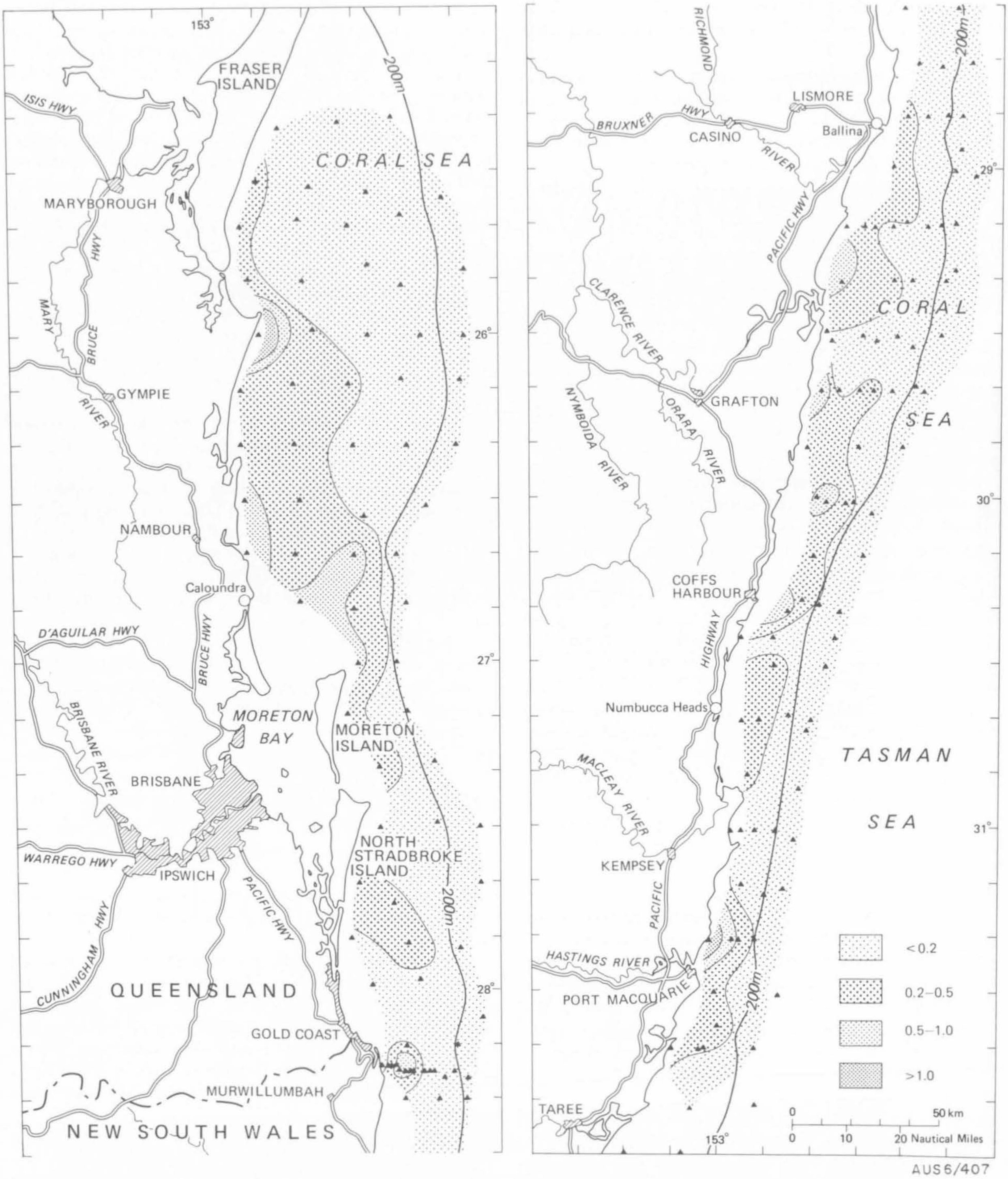


Fig. 16. Distribution of total heavy-mineral content expressed as a percentage of the total sand fraction.

scriptions are based on his unpublished report. Heavy minerals from weighed splits of each sample were separated using bromoform, and grain amounts of the minerals were examined with a petrographic microscope. Mineral proportions were determined by counts of up to 300 grains. The opaque varieties were identified using reflected light, and proportions were determined from counts of about 50 grains. The distribution of total heavy minerals on the shelf is shown in Figure 16. The results show that the overall level of heavy-mineral content is low. Only a few scattered areas have values higher than 0.5 percent. Highest values, of up to 2 percent, are from sites off Double Island Point and north of Port Macquarie (Fig. 16). At these sites zircon and rutile collectively make up only 8 to 14 percent of the total heavy minerals. Some of the types of heavy minerals and their relative abundances are discussed below:

Magnetite and ilmenite form the largest fraction of the heavy minerals in all samples. Both occur as irregular grains and minor subhedral crystals, with a metallic or submetallic lustre. Some of the ilmenite is partly altered to leucoxene. Magnetite and ilmenite are most abundant north of Tweed Heads, where they make up

30 to 50 percent of the heavy mineral fraction. They are presumably derived from Tertiary volcanics (Whitworth, 1959).

Leucoxene is an alteration product of ilmenite and is chemically similar to rutile. It occurs as pseudomorphs after ilmenite and as irregular masses. Leucoxene is present in most samples, and it usually makes up 10 to 15 percent of the heavy-mineral fraction.

Rutile is present in most samples, but the proportion is generally low. The higher values occur north of the Clarence River, but even these are generally less than 4 percent of the total heavy-mineral fraction. The rutile grains are generally rounded and range in colour from yellow-brown to reddish brown to opaque.

Zircon is present in nearly all samples, but in low concentrations. The higher values tend to be in samples with a relatively high rutile content. This roughly constant ratio of zircon to rutile has been noted in the onshore deposits (Whitworth, 1959; Paterson, 1965). The zircon is generally clear and occurs mainly as elongate prisms with rounded ends.

Tourmaline is common throughout the area and it generally makes up 5 to 10 percent of the heavy-mineral fraction. It is mainly yellow-brown, but some samples contain very dark brown or blue varieties.

Amphiboles are present in most samples, and proportions range from less than 1 percent to over 20 percent; the highest average is north of 27°S. There is a trend towards higher values on the outer shelf, similar to that noticed by Davies (1979) to the south. Most of the amphibole is a green hornblende.

Epidote is a common constituent, but it is everywhere less than 10 percent, and generally less than 5 percent. No obvious pattern in its distribution is apparent. Epidote occurs as irregular greenish yellow grains, commonly partly altered.

Garnet of a pale pink variety is a common, but minor, constituent. It is prominent in some of the coarser sediments. Grains are generally anhedral and angular or subangular.

Alumino-silicates such as andalusite, staurolite, kyanite, and sillimanite are common minor constituents, usually totalling less than 10 percent of the heavy-mineral fraction. Andalusite and staurolite are the most common.

Minor constituents include traces of altered pyroxenes, glaucophane, monazite, corundum, and spinels.

Economic aspects

The coastal sands along the southern Queensland and northern New South Wales coast contain one of the world's largest deposits of rutile, zircon, and monazite. The heavy-mineral concentrations onshore occur as seams in the present-day beaches and in former strandlines farther inland. Extensive low-grade accumulations are also present in the large aeolian dunes along the southern Queensland coast and on the high sandy islands, such as Fraser and North Stradbroke Islands. Aspects of these heavy mineral deposits have been discussed by Beasley (1948; 1950), Gardner (1955), Whitworth (1959), Connah (1962), and Winward (1974).

Offshore exploration for heavy minerals by mining companies has involved the use of seismic reflection and bathymetric profiling, and shallow drilling; Jones & Davies (1979) provide a comprehensive review of offshore exploration activities. The offshore work has indicated that the total content of heavy minerals is lower, and the proportion of rutile and zircon in the heavy fraction much lower, than in the onshore deposits.

Jones & Davies (1979) concluded that surface sampling was one method of delineating offshore heavy-mineral deposits. However, on the basis of the present survey it is doubtful if widely-spaced surface sampling is of much use. Jones & Davies (op. cit.) considered that submerged shorelines present the best target for future exploration, particularly if they are present in the vicinity of a marked disconformity detected by seismic reflection profiling. Several submerged shorelines are believed to exist in waters deeper than about 40 m, but none have been tested by drilling.

One important factor militates against the existence of large economic concentrations of heavy-mineral sands offshore. The major mineral seams onshore occur in the beach deposits of the Inner and Outer Barriers. These bay barriers have formed as the culmination of substantial marine transgressions and relatively constant sea level during interglacial periods. Jones & Davies (op. cit.) considered that during a transgression heavy-mineral concentrations are likely to migrate landwards until they reach the maximum level of transgression. If a regression follows then the bulk of the heavy minerals will be left behind as sea level falls; reworking, and possible further concentration, will occur only when sea level once more reaches or exceeds the original elevation.

Although there is a good possibility that heavy-mineral concentrations occur offshore, either as buried seams which escaped destruction during marine transgressions or as reworked deposits, such concentrations are perhaps unlikely to match those onshore in size and grade.

PRESENT-DAY SEDIMENTATION PATTERNS

There is no evidence on sediment deposition and transport from direct observation of bottom currents, movement of sediment, and deposition rates, but some conclusions on the present-day regime can be drawn from data on the nature of the bottom sediments themselves.

Very little terrigenous material is at present being deposited on the shelf. Present-day fluvial deposits are confined to the estuaries with only minor leakage of fine-grained material to the open marine environment during periods of heavy runoff. The dominant littoral process along the coast is longshore drift in a northerly direction, although onshore-offshore transport can occur during heavy storms. However, the seaward migration of nearshore sediments does not appear to extend much beyond a depth of about 20 m.

The terrigenous sediments on the mid shelf are considered to be largely fluvial in origin, but these were probably deposited during periods of lower sea level. Marshall & Davies (1978) showed that there is a correlation between areas of low carbonate on the east Australian shelf and the position of river mouths. This is believed to be a result of dilution of carbonate by fluvial sediments during periods of lower sea level.

Much of the outer shelf carbonate sediment on the mid and outer shelf is considered to be relict, although recent contributions to the sediment are being provided from the skeletons of foraminifera, bryozoans, molluscs, and echinoids. However, the recrystallisation of much of the skeletal material, and development of low-Mg calcite cement, have resulted from previous subaerial

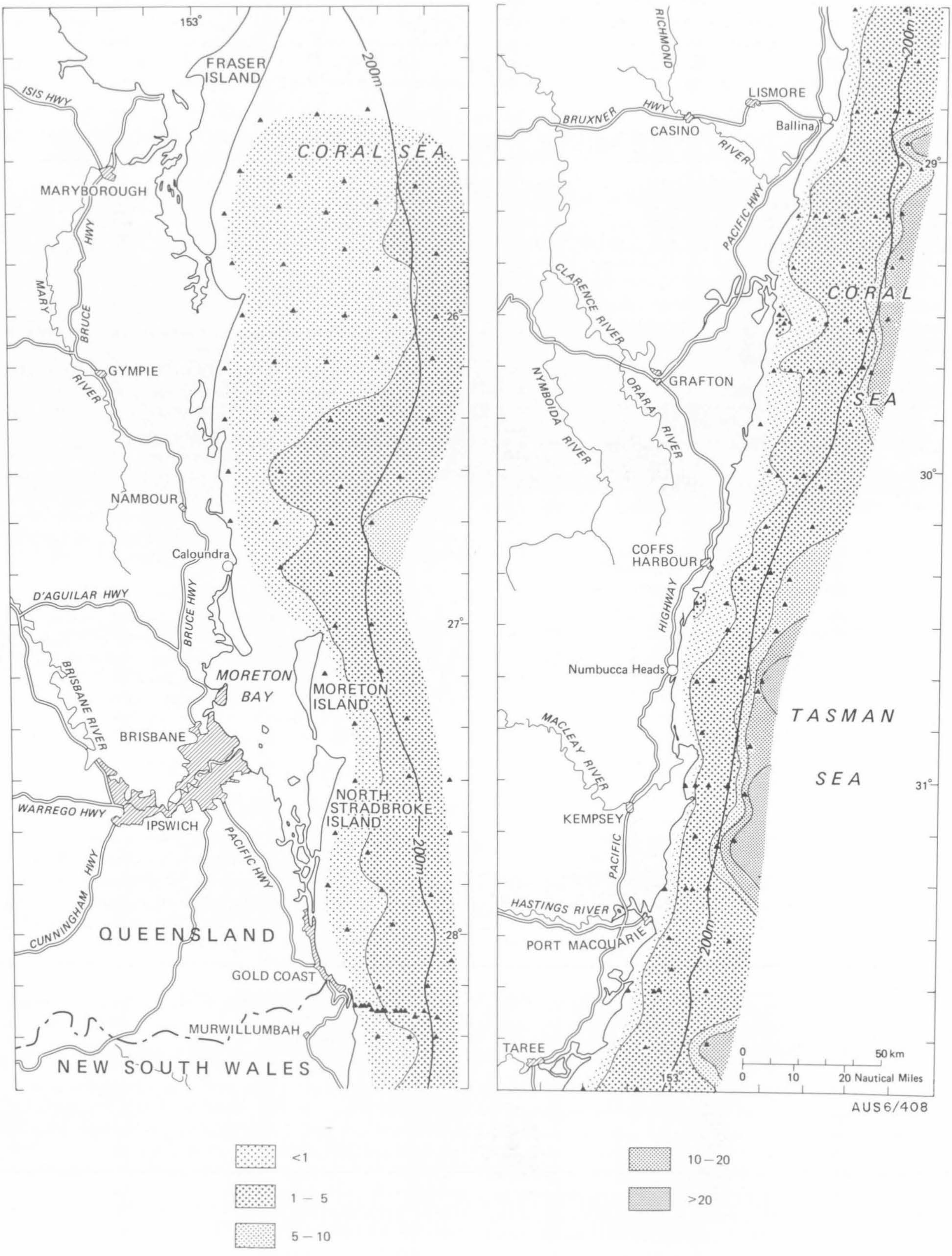


Fig. 17. Distribution of iron (expressed as percent Fe_2O_3).

exposure of a large proportion of the surficial carbonates. The presence of algal banks in deep water (60-160 m) has also been cited as evidence for relict sediments.

From the data available it would appear that relict sediments on the continental shelf of southern Queensland and northern New South Wales are widespread. Some modern sediments are probably being deposited on the inner shelf, especially in water less than 20 m deep, but it is considered that their contribution is relatively insignificant. Other modern sediments are presumably being deposited as a result of biogenic carbonate production and perhaps authigenesis. However, the main conclusion is that very little sediment is being deposited on the shelf at the present time.

GEOCHEMISTRY OF THE SEDIMENTS

Sediment samples collected during the 1970 survey were analysed for Fe, As, P_2O_5, and Ti. Samples collected during the 1972 survey were also analysed for Cu, Pb, Zn, Co, Ni, Mn, Cd, Sr, and organic C (Davies, 1979). In both cases the chemical analyses were carried out by the Australian Mineral Development Laboratories (AMDEL)). The results of these analyses are presented in Appendices 3 & 4. Only Fe, As, P_2O_5, and Ti are discussed in this study.

GENERAL DISTRIBUTION

Iron

Values are generally low (<1 percent Fe_2O_3) on the inner shelf and increase towards the edge of the shelf (Fig. 17). On the southern Queensland shelf, especially offshore from Fraser Island, Fe values are low over most of the shelf. The only high values (up to 6.4 percent Fe_2O_3) in this area occur on the outer shelf north of Moreton Island, where the dominantly calcareous sediments are strongly ironstained, and contain numerous intraclasts which have a goethite cement.

Iron values are highest on the outer shelf and upper slope between 29° and 32°S (Fig. 17). In this area values range from 3.0 to 26.5 percent Fe_2O_3, with an average value of 11.5 percent. The high Fe values are associated with those sediments which have high proportions of glauconite and goethite, mainly filling foraminiferal tests, and phosphatic nodules.

Arsenic

Values range from 3 to 390 ppm As, with an average value of 36 ppm. Values are highest on the outer shelf and upper slope (Fig. 18), especially between 29° and 32°S where they average about 125 ppm. Data relating to the arsenic content of continental shelf sediments in other parts of the world are almost negligible, but it appears that the values on the outer shelf and upper slope reported here are exceedingly high. Davies (1974) recorded arsenic contents on the middle and outer shelf between Port Kembla and Newcastle (central NSW shelf) of 50 to 100 ppm. These high values are considered to be related to pollutants discharged into the ocean from urban and industrial sources.

The only other type of sediment with comparable values and from a similar environment comprises shallow marine ferromanganese nodules (Calvert & Price, 1977a). It is well known that deep-sea nodules contain arsenic to the extent of 70-200 ppm (Calvert & Price, 1977b). While many minor elements are much lower in shallow marine ferromanganese nodules than in oceanic nodules, some elements, in particular As and P, are more concentrated in the shallow water varieties (Calvert & Price, 1977a). In the Black Sea the As content of ferromanganese concretions is as high as 687 ppm. In both the shallow marine ferromanganese nodules and the sediments with high arsenic reported here, the iron content is also relatively high.

Phosphate

P_2O_5 values are generally low (<0.1 percent) on the inner shelf and increase towards the edge of the shelf (Fig. 19). Areas of high P_2O_5 (>1.0 percent) coincide with areas where the sediments contain relatively abundant amounts of Fe and As. On the outer shelf between 29° and 32°S the high P_2O_5 values are associated with the phosphatic nodules and boulders of cemented nodules described previously. Table 2 shows that these rocks range from 4.8 to 26.2 percent P_2O_5. Generally the phosphate content of the boulders of cemented nodules is lower than that of the individual nodules. Fragments of nodules and collophane cement in the matrix of the cemented nodules contribute about 6.3 percent P_2O_5. Analyses of two nodules gave results of 9.5 and 10.0 percent P_2O_5. The highest value, 26.2 percent, was obtained from a fragment of bone. Von der Borch (1970) has reported P_2O_5 values ranging from 7.8 to 21.2 percent from the same area.

Titanium

Values range from 0.01 to 0.84 percent TiO_2, with an average value of 0.15 percent. Highest values occur on the inner shelf south of Fraser Island and near Kempsey (Fig. 20). Large areas of the mid shelf have low values (<0.1% TiO_2), while on the outer shelf, especially between 29° and 31°S, there are relatively high values. The only area of low values on the inner shelf is off Moreton and North Stradbroke Islands.

GEOCHEMISTRY OF THE HIGH-FE SEDIMENTS

Geochemical analyses show high concentrations of Fe in the sediments on the outer shelf between 29° and 32°S. Most of the Fe resides in the goethite and glauconite which fill the chambers of foraminifera and other organisms. It is also apparent, when comparing Figures 18 and 19, that concentrations of As and P are also relatively high within these sediments. However, it is uncertain what inter-relationships exist between the three elements. As and P probably occur in anionic form in the marine environment. As^{5+}, as the arsenate As_2O_5, has a very close relation with phosphate, and can easily substitute for it. The arsenate ion is also readily adsorbed onto ferric hydroxide. Phosphorus concentrations are well correlated with the Fe phase of shallow marine and lacustrine ferromanganese nodules (Calvert & Price, 1970; Calvert & Price, 1977a) where phosphate is either adsorbed by hydrous ferric oxides or forms ferric phosphate. Although evidence of adsorption is largely circumstantial, removal of P_2O_5 from seawater by adsorption onto hydrous ferric oxides has been proposed by several authors (Berner, 1973; Froelich & others, 1977).

To test the relation between Fe, As, and P, an R-mode factor analysis was carried out both on outer shelf sediments with low Fe contents and on those with high Fe. The results are shown in Table 3. Factor 1 in

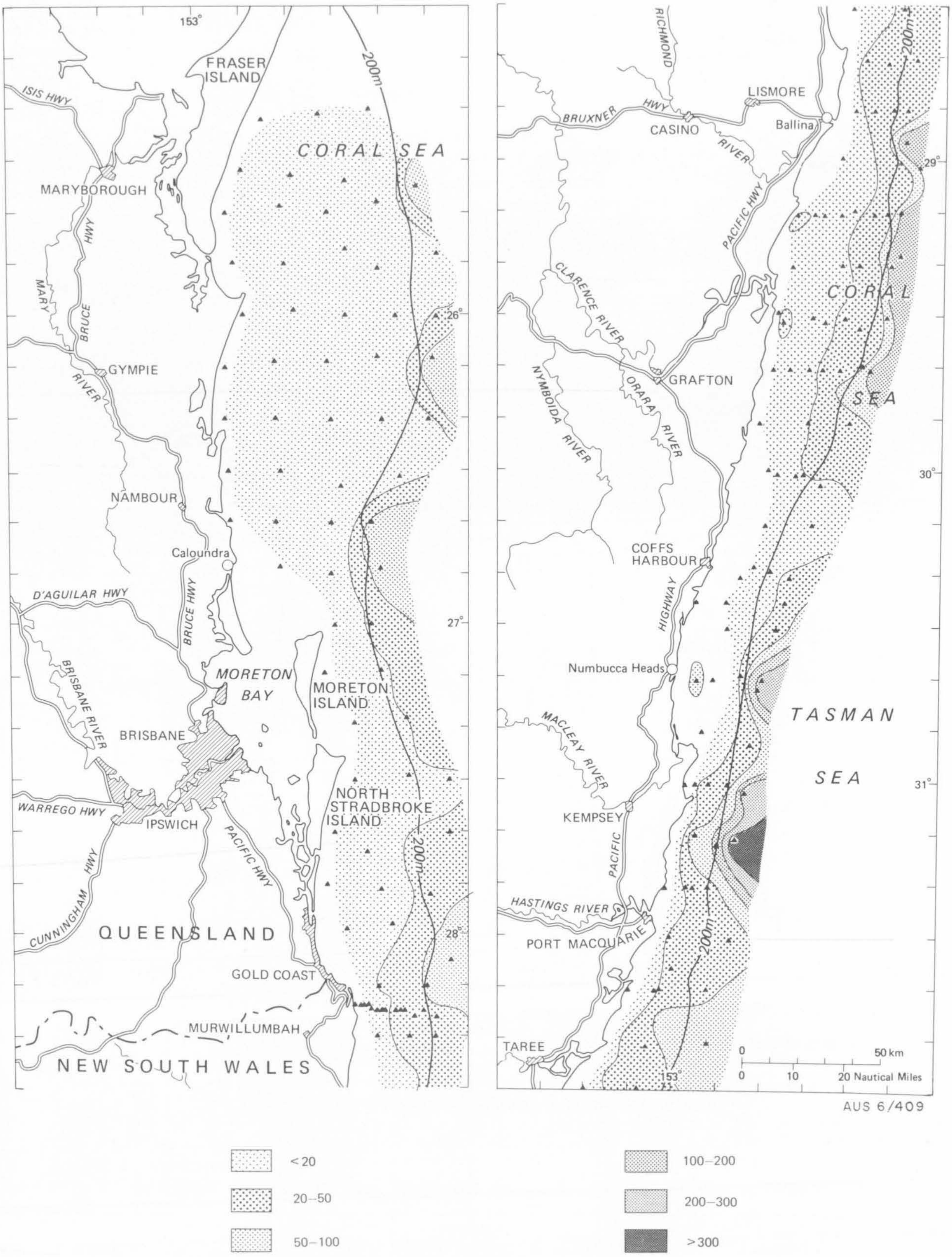


Fig. 18. Distribution of arsenic (ppm).

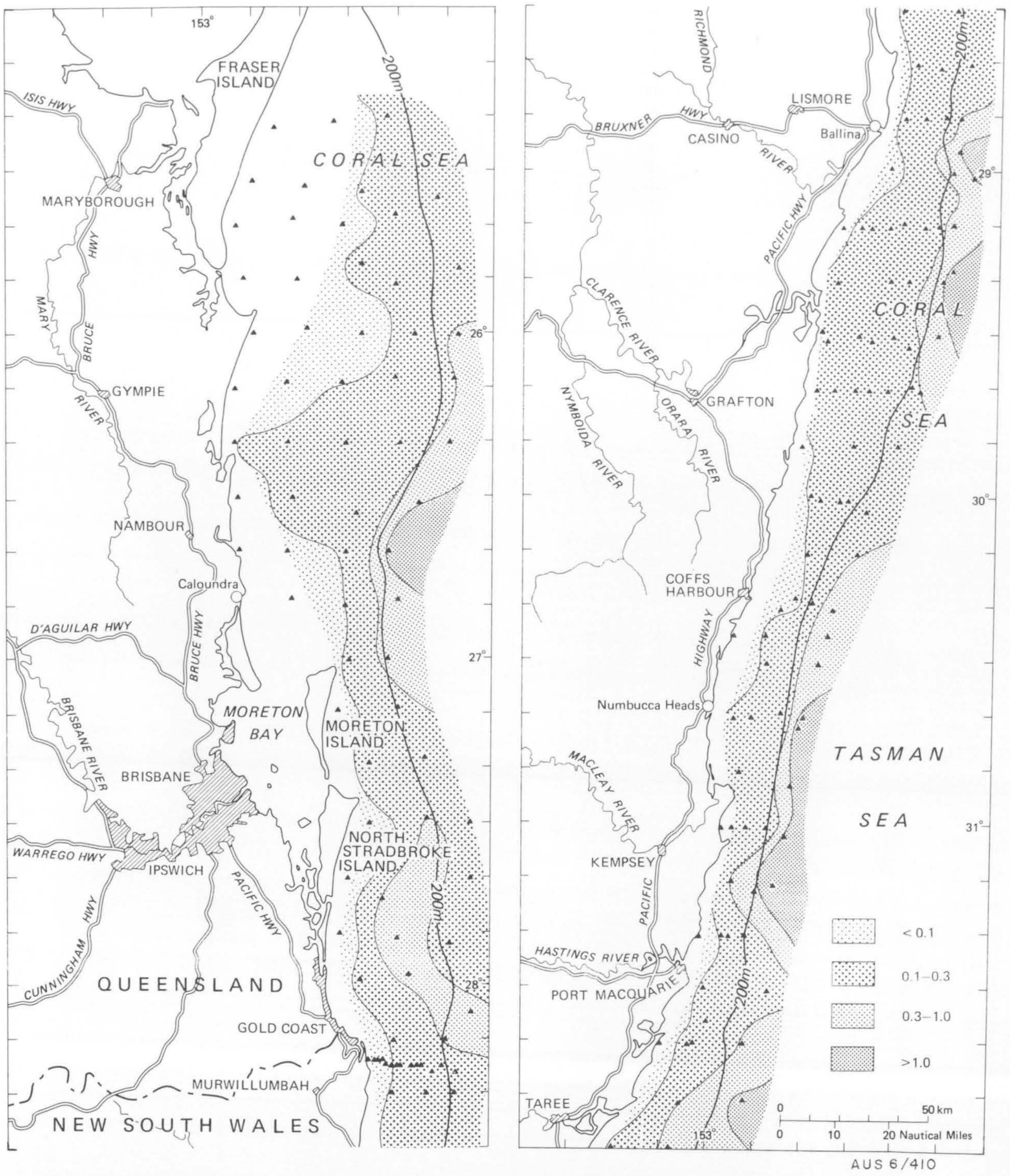


Fig. 19. Distribution of phosphate (expressed as percent P_2O_5).

TABLE 2. PHOSPHATE ANALYSES OF NODULES AND CEMENTED NODULES

Station number	*Latitude*	*Longitude*	*Depth m*	*P_2O_5 %*	*Description*
1506	29°01.0′S	153°54.0′E	229	4.8	Nodule
1512	30°39.6′	153°19.8′	197	6.3	Nodule
1513	30°43.4′	153°18.6′	200	26.2	Bone
1513	30°43.4′	153°18.6′	200	6.3	Matrix of cemented nodules
1516	30°10.6′	153°13.9′	241	9.5-10.0	Nodules

both the high and low-Fe sediments forms a closed array of the grainsize variables. However, in the high-Fe sediments P_2O_5 does show some relation with gravel, presumably in that P_2O_5 is mainly concentrated in gravel-size nodules and cemented nodules.

Within Factor 2 for the high-Fe sediments the factor scores show a definite relation between Fe, Ti, As, and P_2O_5, and an antipathetic relation between these elements and calcium carbonate. A relation between Ti and Fe has previously been observed in the Fe phase of ferromanganese nodules (Calvert & Price, 1977b) and in deep-sea sediments (El Wakeel & Riley, 1961). In the low-Fe sediments Ti is strongly correlated with silt and clay (Table 3). The association between Ti and clay minerals has been noted previously (Hirst, 1962; Moore, 1963). However, it is generally agreed that Ti is not adsorbed or incorporated into the crystal lattice, but occurs as very finely crystalline or amorphous titanium dioxide deposited with the clay minerals (Goldschmidt, 1954; Degens, 1965). Davies (1979) has also suggested that Ti could occur in silt-size heavy minerals.

The strong relation between Fe, As, and P_2O_5, as shown by the factor analysis (Table 3), not only exists for the high-Fe sediments, but is also significant for

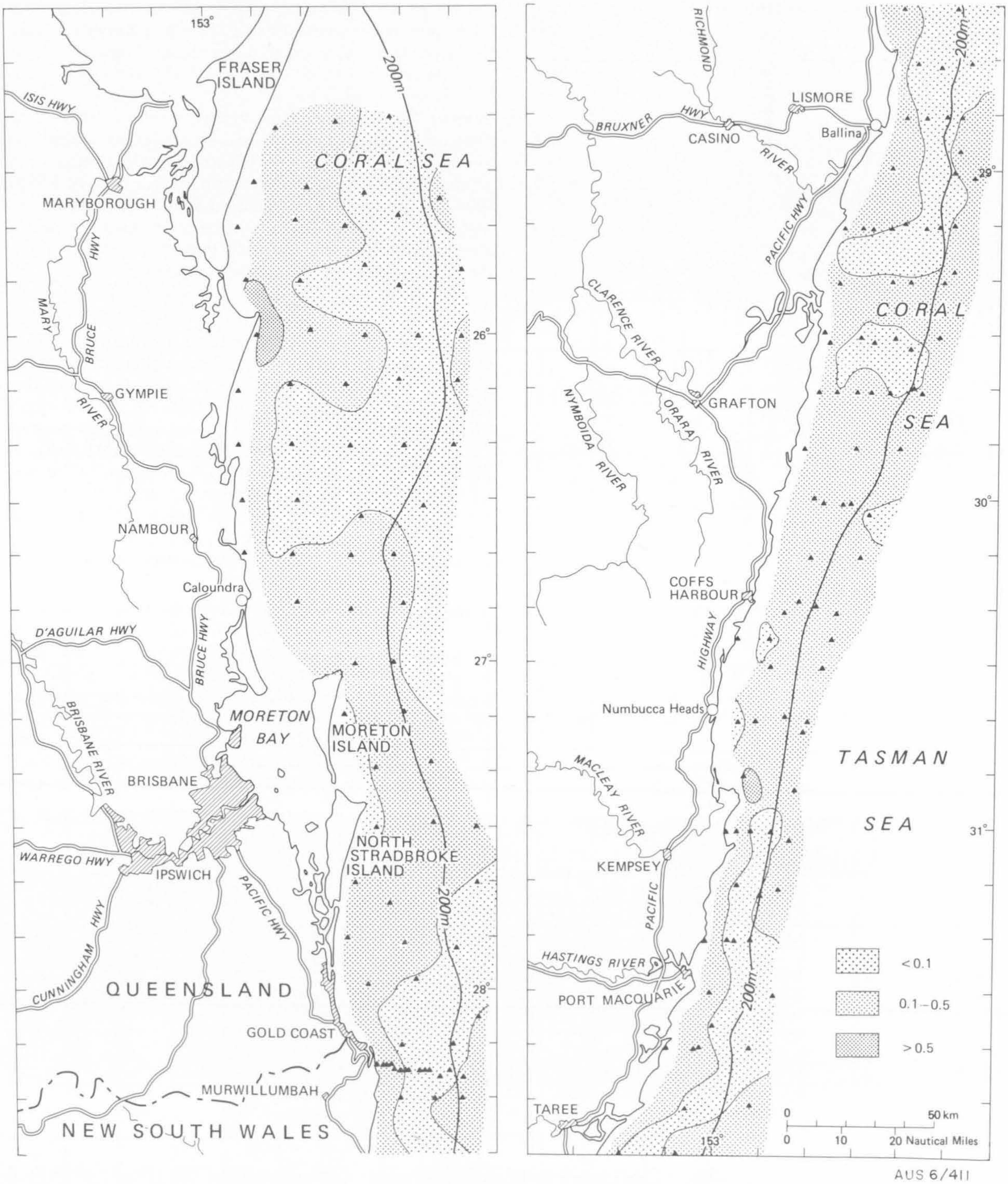


Fig. 20. Distribution of titanium (expressed as percent TiO_2).

those outer shelf sediments with relatively low Fe contents. Calvert & Price (1977a) in a detailed review of the adsorptive capacities of ferric and manganese oxides and/or hydroxides suggested that the charge characteristics of hydrous oxides of manganese and iron may be of fundamental importance in controlling the adsorption of minor elements from seawater. They suggest that in the shallow marine environment hydrated iron oxides are weakly positively charged, and, therefore, have a greater capacity for anion adsorption. The good correlation between As, P_2O_5, and Fe in both types of sediments from the outer shelf suggests that adsorption of arsenate and phosphate ions onto hydrated ferric oxides occurs at all concentrations, and that the amount adsorbed is limited by the concentration of iron.

TABLE 3. VARIMAX-ROTATED FACTOR MATRIX FOR SEDIMENTS ON THE OUTER CONTINENTAL SHELF

A. HIGH-IRON SEDIMENTS (>5%)

Variable	*Factor 1*	*Factor 2*	*Factor 3*
Depth	+		+
Gravel	— — —		
Sand	+ + +		
Silt			— — —
Clay			— — —
Mean	+ + +		
Std Dev.	— — —		
$CaCO_3$		— — —	
P_2O_5	—	+ +	
Fe		+ + +	
Ti		+ + +	
As		+ + +	

B. LOW-IRON SEDIMENTS

Variable	*Factor 1*	*Factor 2*	*Factor 3*
Depth			
Gravel	— — —		
Sand	+ + +		
Silt			— — —
Clay			— — —
Mean	+ + +		
Std Dev.	— — —		
$CaCO_3$			+ + +
P_2O_5		+ + +	
Fe		+ + +	—
Ti			— — —
As		+ +	+

+ + + — — — Factor scores between 0.8-1.0
+ + — — Factor scores between 0.6-0.8
+ — Factor scores between 0.4-0.6

Additional analyses of the high-Fe sediments were undertaken to try to determine their origin. The coexistence of glauconite and goethite and their similar location within the tests of foraminifera suggest that the goethite has formed as a result of oxidation of glauconite. Results of the analyses are presented in Table 4. This shows that apart from calcium carbonate and Fe, there are relatively high amounts of Si and Al. Si is known to be present in silt-size quartz and glauconite. The amount of quartz present in the sediments is relatively small, usually less than 5 percent. Glauconite contains on average about 50 percent SiO_2. On a carbonate-free basis the high-Fe sediments contain 16.6 to 33.9 percent SiO_2. These low values, when compared to glauconite, suggest that Si is also present within the goethite-filled chambers. Analyses of oxidised glauconite grains off the west coast of South Africa (Birch, 1975) show that about 14 to 23 percent SiO_2 is present. Allowing for 5 percent quartz and the presence of minor amounts of glauconite, these figures are comparable with the silica content of the high-Fe sediments.

The Fe^{3+}/Fe^{2+} ratio of glauconite has a narrow range of 4.1 to 6.3 (Hendricks & Ross, 1941). In the high-Fe sediments this ratio ranges from 14.3 to 79.3. If most of the infilling of skeletal chambers was originally glauconite, then the Fe^{3+}/Fe^{2+} ratio shows that there has been extensive oxidation since it formed. Chemical analyses of oxidised glauconite grains indicate that there is a loss in all elements other than Fe (Birch, 1975). On a carbonate-free basis the amount of Fe present in the high-Fe sediments ranges from 19.6 to 26.2 percent compared with 5.8 to 9.5 percent Fe for glauconite. Chemical analyses of oxidised glauconite pellets off the west coast of South Africa range from 18.3 to 21.7 percent Fe (Birch, 1975).

There is a noticeable increase in the amount of phosphorus in the oxidised glauconite samples from South Africa compared with normal glauconite, and the high-Fe sediments are similarly enriched. This is possibly a post-oxidation process of seawater phosphate being adsorbed onto the hydrated ferric oxide.

Most of the trace-elements in the high-Fe sediments show a slightly higher concentration than the other shelf sediments (see Appendix 4). Arsenic shows the most increase, followed by Mn; Cu, Co, and Ni are only slightly enriched.

TABLE 4. CHEMICAL ANALYSES OF SELECTED HIGH-FE SEDIMENTS

Major elements are expressed in percentages, minor elements in ppm

	1485	*1489*	*1490*	*1495*	*1505*	*1512*	*1515*	*1516*	*1525*
SiO_2	10.70	11.70	10.90	14.60	14.20	15.30	15.60	16.90	16.10
Al_2O_3	2.72	3.28	2.78	3.34	3.48	3.80	4.64	4.10	3.20
TiO_2	0.20	0.20	0.17	0.22	0.27	0.23	0.26	0.29	0.16
FeO	0.52	0.81	0.69	0.86	0.49	0.45	0.43	0.43	0.43
Fe_2O_3	11.50	12.90	11.50	14.30	21.90	24.70	23.60	36.10	11.20
P_2O_5	0.77	1.42	1.16	1.49	1.38	1.23	1.48	5.96	1.18
As	100	130	100	120	200	200	260	390	100
Ba	20	10	20	30	40	40	40	30	50
Co	12	15	15	15	10	15	18	18	8
Cu	8	8	8	5	8	8	8	10	8
Mn	260	230	310	300	220	240	290	400	170
Ni	28	32	32	32	25	30	35	38	28

ORIGIN OF THE HIGH-FE SEDIMENTS

The presence of glauconite and goethite within the chambers of foraminifera and other organisms suggests that these minerals have a common origin, and that goethite might have formed as a result of oxidation of glauconite. It is known that under extreme oxidation the glauconite structure breaks down and that Fe is liberated and forms hydrated ferric oxide (McRae, 1972). Wolff (1967) considers that the end product of the weathering of glauconite is pseudomorphs of goethite and authigenic kaolinite.

Most workers agree that subaerial weathering does not cause all glauconite to oxidise (McRae, 1972). In many cases a rim of oxidised glauconite forms and then protects the grain against further weathering. The presence of both glauconite and goethite in the outer shelf sediments supports this conclusion. However, the dominance of goethite over glauconite is anomalous; normally the opposite is true.

The lack of cementation of the high-Fe sediments suggests that they have not been exposed to subaerial weathering processes. The carbonate fraction of the sediments shows neither cementation nor the effects of vadose diagenesis. X-ray diffraction analysis shows that the dominant carbonate mineral is calcite but a considerable proportion is high-Mg calcite. The only cementation that occurs is in the intraclasts where quartz and skeletal material are cemented by goethite. These intraclasts make up usually less than 5 percent of the sediment. Lack of subaerial diagenetic effects suggests that oxidation of glauconite has taken place in the marine environment.

It is known that glauconite formation requires slightly alkaline conditions (pH 7-8) and a slightly reducing environment (Eh 0 to −200 mV). The tests of foraminifera are considered to provide a suitable micro-environment even though the macro-environment is strongly oxidising. Oxygenation requirements are provided by bacterial decomposition of organic matter (McRae, 1972).

If the glauconite was subsequently subjected to a more oxygenated environment it could be possible that over a period of time the glauconite structure would start to break down. Such a situation could be brought about by a lowering of sea level. Increased turbulence and mixing of sea water would produce the oxygenated environment, but whether this would be sufficient to cause glauconite to break down and form goethite is at this stage speculative.

ORIGIN OF THE PHOSPHORITES

Two mechanisms have been proposed for the formation of marine sedimentary phosphorites. One theory advocates direct inorganic precipitation of apatite from sea water associated with coastal upwelling (Kazakov, 1937; McKelvey et al., 1953). The second theory proposed replacement of existing calcium carbonate by phosphate-rich interstitial solutions to form carbonate fluorapatite (Ames, 1959; Parker & Siesser, 1972; Birch, 1975).

Studies in areas of upwelling off South-West Africa and Chile/Peru (Baturin, 1969; Burnett, 1977) show that inorganic precipitation of apatite within pore waters of anoxic sediments has occurred within recent times, and is taking place at the present day (Baturin & others, 1972; Burnett & Veeh, 1977). Winnowing of the fine fraction of the sediments, probably in response to eustatic sea level fluctuations, has resulted in concentration of the indurated phosphatic nodules (Burnett, 1977).

The nodules and cemented nodules on the outer shelf of New South Wales show attributes of processes involving both precipitation of apatite and replacement of micrite. In the nodules the matrix is almost exclusively collophane and goethite. Very little calcite cement is present and there is no evidence to suggest that collophane or goethite have replaced any pre-existing calcite. The goethite cement is mainly located towards the exterior of the nodules, and diagenetic evidence suggests that Fe was introduced after collophane (Marshall, 1971). Therefore, a precipitational mechanism for the formation of apatite within the matrix of the nodules is a distinct possibility. One drawback is that precipitated apatite forming off South-West Africa and Chile/Peru is mainly associated with diatomaceous oozes whereas Birch (1975) considered that the association of glauconite and apatite is indicative of replacement. He considered the association of glauconite and apatite to be a direct result of conversion of clay minerals to glauconite and phosphatisation of lime mud. No finely disseminated glauconite was observed in the collophane cement of the nodules from eastern Australia, where glauconite occurs only as pellets. If the presence of diatomaceous oozes is unnecessary then precipitation of apatite in other types of sediments could occur.

The significance of diatoms in the South-West African and South American phosphorites is that they provide large quantities of phosphorus, and therefore generate a high concentration of organic phosphate within the pore waters. Stumm & Leckie (1970) have also suggested that phosphate may be supplied to anoxic pore waters from the reduction of hydrous ferric oxides that contain adsorbed phosphate. Therefore, it is possible that the high-Fe sediments that are associated with the phosphorites on the outer shelf off northern New South Wales were the source of the phosphate. This would eliminate the necessity to invoke intense upwelling along the northern New South Wales shelf. Present-day upwelling does occur off Evans Head (29°S) with associated nutrient enrichment (Rochford, 1972), but it is only moderate compared to that occurring off South-West Africa and Chile/Peru.

Within the matrix of the cemented nodules evidence of replacement of micrite by collophane is quite apparent. In addition to collophane and goethite, calcite is a prominent cementing material. Two types of calcite exist: sparry calcite and micrite. Replacement of calcite by phosphate is observed only in the micrite. Some replacement of skeletal material by collophane is also evident, but is relatively uncommon.

A two-stage development of phosphate formation is proposed for the phosphatic rocks on the outer shelf off northern New South Wales. The first stage involves the direct precipitation of apatite within presumably anoxic pore waters of the sediments. A possible source of phosphate could have been the high-Fe sediments that had formed on the outer shelf. These collophane-cemented sediments were then reworked during a period of lower sea level to form nodules, a process similar to that described by Burnett (1977). Some of the nodules were subsequently cemented by calcium carbonate. During a second stage parts of the micritic portion of this cement were replaced by collophane.

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APPENDIX 1

POSITION OF SAMPLE STATIONS, WATER DEPTH, AND SEDIMENT COLOUR

Sample No.	*Latitude S*	*Longitude E*	*Depth m*	*Colour **	*Sample No.*	*Latitude S*	*Longitude E*	*Depth m*	*Colour **
7063-					1478	28°40′	153°53.7′	234	10YR5/4
1404	25°20′	153°38.5′	55	5YR8/1	1479	28°40′	153°42.3′	58	5Y5/6
1405	25°21′	153°27′	51	5Y6/1	1480	28°50′	153°40′	58	10YR5/4
1406	25°22′	153°15′	37	10YR5/4	1481	28°41.5′	153°47.5′	99	10YR6/2
1407	25°32′	153°10′	27	10YR5/4	1482	28°59.5′	153°37.5′	48	10YR4/2
1408	25°33′	153°21′	48	5Y5/2	1483	29°10.5′	153°31′	42	10YR4/2
1409	25°34.5′	153°33′	58	10YR6/2	1484	29°09.5′	153°40′	71	10YR4/2
1410	25°35′	153°48′	154		1485	29°09.5′	153°50′	219	10YR4/2
1411	25°48′	153°53.5′	196	10YR5/4	1486	29°00′	153°50′	179	10YR4/2
1412	25°51′	153°40′	69	10YR6/2	1487	29°20′	153°26′	42	5Y3/2
1413	25°40′	153°07.5′	35	10YR4/2	1488	29°20′	153°37.4′	77	10YR4/2
1414	25°39.7′	153°19′	51	10YR5/4	1489	29°20′	153°48.6′	240	10YR2/2
1415	25°40′	153°29′	59	5Y5/2	1490	29°30′	153°47′	256	10YR4/2
1416	25°38′	153°40.5′	64	5Y7/2	1491	20°30′ 29°.	153°37.9′	77	10YR4/2
1417	25°47′	153°33′	64	5Y5/2	1492	29°31.1′	153°24.1′	51	10YR2/2
1418	25°50′	153°20.4′	51	5Y5/2	1493	29°40′	153°21.7′	42	10YR4/2
1419	25°50′	153°09.3′	35	5GY3/2	1494	29°40.2′	153°33.1′	77	10YR4/2
1420	26°00′	153°11.5′	55	5GY3/2	1495	29°40′	153°43.4′	260	10YR4/2
1421	25°59.2′	153°22.5′	59	5GY5/2	1496	30°00.2′	153°29.2′	88	10YR4/2
1422	26°00′	153°33.5′	64	5Y5/2	1497	29°59.8′	153°21.2′	49	10YR6/2
1423	26°30′	153°08.5′	27	10YR5/4	1498	29°49.9′	153°19.1′	31	10YR6/2
1424	26°20′	153°07.5′	27	10YR4/2	1499	29°50.3′	153°30.8′	80	10YR4/2
1425	26°10′	153°07′	27	10YR5/4	1500	30°20′	153°14.6′	59	5Y5/2
1426	26°09.5′	153°18.5′	56	5Y5/2	1501	30°20′	153°26.2′	201	5Y4/4
1427	26°09′	153°29.5′	64	10Y4/2	1502	30°10′	153°31′	187	5Y5/2
1428	26°08′	153°40.5′	71	5Y6/1	1503	30°10′	153°19.6′	66	5Y5/2
1429	26°08′	153°52′	201	10YR5/4	1504	29°50′	153°39′	165	10YR4/2
1430	26°00′	153°44.5′	64	10YR7/4	1505	28°56.4′	153°50.7′	220	10YR4/2
1431	26°00′	153°53.5′	230	10YR5/4	1506	29°01′	153°54′	229	10YR6/2
1432	26°20.4′	153°18.5′	55	5Y5/2	1507	30°02.3′	153°32.5′	164	10YR4/2
1433	26°20′	153°30′	64	5Y5/2	1508	30°49.8′	153°07.3′	69	5Y5/2
1434	26°20′	153°41′	113	5GY3/2	1509	30°40′	153°08.7′	58	10YR4/2
1435	26°20′	153°51′	293	5Y5/2	1510	30°30′	153°12′	55	10YR4/2
1436	26°31′	153°45′	283	5Y5/2	1511	30°30′	153°23′	219	10YR4/2
1437	26°33′	153°32′	60		1512	30°39.6′	153°19.8′	197	10YR4/2
1438	26°30′	153°19.3′	59	5Y5/2	1513	30°04.4′	153°18.6′	200	
1439	26°49′	153°41′	329	10YR6/2	1514	30°52.5′	153°17.5′	278	
1440	26°49.7′	153°19.2′	46	5Y4/1	1515	31°01.9′	153°15.6′	274	10YR4/2
1441	26°40′	153°18.5′	49	5Y5/2	1516	31°10.6′	153°13.9′	241	10YR4/2
1442	26°40′	153°30′	79	5Y5/2	1517	31°10′	153°05′	82	10YR4/2
1443	26°40′	153°08′	18	10YR6/2	1518	31°00.4′	153°04.7′	46	5Y4/4
1444	26°50′	153°30′	84	5Y5/2	1519	31°20′	153°02.7′	64	10YR4/2
1445	26°40′	153°39′	220	10YR5/4	1520	31°22′	153°10.4′	174	10YR4/2
1454	27°00′	153°39.2′	184	5Y5/2	1521	31°30′	153°12.8′	274	
1455	27°00′	153°31.5′	102	5Y5/2	1522	31°29.5′	152°59.8′	62	5Y4/4
1456	27°09.8′	153°28.6′	42	5Y5/6	1523	31°40′	152°57′	71	10YR4/2
1457	27°09.7′	153°41.0′	170	5Y5/2	1524	31°39.7′	153°07.6′	183	10YR4/2
1458	27°18.7′	153°47.4′	220	10Y6/2	1525	31°50.5′	153°07.6′	220	5Y5/2
1459	27°19.5′	153°35.5′	75	5Y5/6	1526	32°01′	153°02.7′	164	
1460	27°30′	153°35′	31	10YR6/2	1527	31°59.6′	152°51.8′	108	10YR4/2
1461	27°29.8′	153°47.7′	137	5Y5/2	1528	31°59.4′	152°40.1′	42	10YR5/4
1462	27°30′	153°56.7′	392	5Y7/2	1529	31°51.2′	152°54.4′	91	10YR5/4
1463	27°40′	153°56.6′	225	5Y5/6	7263-				
1464	27°44.5′	153°38.8′	86	5Y6/1	1543	28°14.4′	153°34.5′	8	10YR7/2
1465	27°40′	153°31′	42	10YR4/2	1544	28°15′	153°36′	20	5Y6/2
1466	27°50.5′	153°29.5′	47	10YR5/4	1545	28°15′	153°38′	32	5Y6/2
1467	27°51′	153°41′	80	10YR6/2	1546	28°15′	153°39′	35	5Y6/2
1468	27°52.5′	153°52′	190	10YR5/4	1547	28°15′	153°40′	46	10YR7/4
1469	28°05′	153°56′	256	10YR5/4	1548	28°15′	153°41.5′	57	10YR4/2
1470	27°58.5′	153°43.5′	86	10YR5/4	1549	28°15′	153°43′	58	10YR7/4
1471	27°59.5′	153°33′	47	10YR5/4	1550	28°15′	153°44′	67	10YR6/4
1472	28°10.1′	153°40.2′	62	5Y5/2	1551	28°15′	153°45′	69	10YR6/4
1473	28°10.5′	153°51.8′	184	10YR5/4	1552	28°15′	153°46′	73	10YR6/4
1474	28°20.2′	153°53.5′	338	5Y5/2	1553	28°15′	153°47′	79	10YR6/4
1475	28°20′	153°40.5′	58	10YR5/4	1554	28°15.6′	153°48.2′	91	10YR6/4
1476	28°30′	153°39.5′	49	5Y5/6	1555	28°15.2′	153°50.8′	146	10YR6/4
1477	28°30′	153°50.2′	157	5Y5/6	1556	28°16′	153°53.2′	494	5Y7/2
					1557	28°49.6′	153°51.3′	185	5Y5/2
					1558	28°49.8′	153°47.8′	91	10YR6/4
					1559	28°49.7′	153°54.2′	73	10YR6/4

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* Comparison of fresh sample with Rock Color Chart, Geological Society of America

Sample No.	*Latitude S*	*Longitude E*	*Depth m*	*Colour **	*Sample No.*	*Latitude S*	*Longitude E*	*Depth m*	*Colour **
1560	28°20.4′	153°47.1′	82	10YR6/4	1578	30°18.6′	153°22′	97	5Y5/2
1561	29°10.1′	153°26.6′	18	10YR5/4	1579	30°18.4′	153°17.7′	76	5Y5/2
1562	29°09.7′	153°33.5′	51	5Y5/2	1580	30°25.3′	153°05.4′	22	10YR5/4
1563	29°10′	153°36.8′	59	10YR5/4	1581	30°25.5′	153°11.6′	47	10YR5/4
1564	29°10.2′	153°43.7′	86	10YR5/4	1582	30°24.8′	153°24.6′	247	5Y6/1
1565	29°10′	153°47′	103	10YR5/4	1583	30°39.8′	153°04.8′	41	10YR5/4
1566	29°18.4′	153°50.1′	300	10YR4/2	1584	30°39′	153°15′	98	5Y5/2
1567	29°20′	153°41′	84		1585	31°00′	153°03′	15	10YR6/2
1568	29°30′	153°22′	13	5Y6/1	1586	31°00′	153°08.2′	88	5Y5/2
1569	29°30′	153°26.3′	53	5Y3/2	1587	31°00′	153°11.7′	113	10YR5/4
1570	29°30′	153°31.2′	61	10YR5/4	1588	31°20′	152°58.4′	16	5Y6/1
1571	29°31.7′	153°41.3′	97	10YR5/4	1589	31°20.4′	153°04.8′	77	10YR5/4
1572	29°39.8′	153°26.4′	55	5Y5/2	1590	31°20.5′	153°07.6′	113	10YR5/4
1573	29°40.3′	153°30.4′	71	5Y5/2	1591	31°11′	153°13.6′	240	
1574	29°39.8′	153°37.4′	82	10YR5/4	1592	31°36.3′	162°59.6′	79	10YR5/4
1575	29°39.1′	153°41.7′	95	10YR5/4	1593	31°40′	152°56.3′	63	5Y5/2
1576	30°00′	153°27′	84	5Y5/2	1594	31°40′	152°50.4′	20	5Y5/2
1577	30°00′	153°23′	61	5Y5/2					

152°

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APPENDIX 2

GRAINSIZE DATA

Sample No.	*Gravel %*	*Sand %*	*Silt %*	*Clay %*	*Mean phi*	*Standard deviation phi*
7063-						
1404	23.2	76.8	—	—	0.00	1.44
1405	—	100	—	—	2.77	0.54
1406	—	100	—	—	2.19	0.52
1407	—	100	—	—	2.07	0.45
1408	—	100	—	—	3.11	0.54
1409	4.6	95.4	—	—	2.04	0.86
1410						
1411	100	—	—	—	−4.14	0.53
1412	1.2	98.8	—	—	2.90	0.51
1413	—	98.0	0.2	1.8	2.40	0.62
1414	—	100	—	—	2.65	0.61
1415	0.8	99.2	—	—	2.98	0.61
1416	7.8	92.2	—	—	1.07	1.10
1417	45.5	54.5	—	—	−0.49	1.23
1418	—	100	—	—	1.89	0.49
1419	—	95.0	1.7	3.8	2.82	0.62
1420	—	96.0	2.5	2.2	2.90	0.70
1421	1.6	98.4	—	—	2.52	0.58
1422	1.0	99.0	—	—	2.71	0.61
1423	—	100	—	—	2.36	0.52
1424	2.0	98.0	—	—	2.21	0.90
1425	—	100	—	—	2.16	0.40
1426	25.7	74.3	—	—	0.54	1.86
1427	—	96.0	2.5	1.8	2.60	0.63
1428	—	100	—	—	3.01	0.54
1429	—	100	—	—	2.04	0.70
1430	0.7	99.3	—	—	1.45	0.84
1431	6.5	93.5	—	—	1.69	1.44
1432	24.5	75.5	—	—	0.33	1.53
1433	12.5	87.5	—	—	0.84	1.33
1434	—	61.4	28.6	11.4	4.99	2.70
1435	—	100	—	—	3.06	0.65
1436						
1437						
1438	17.6	82.4	—	—	0.50	1.24
1439	62.0	38.0	—	—	−1.27	2.36
1440	—	100	—	—	2.42	0.72
1441	—	100	—	—	2.72	0.53
1442	—	100	—	—	2.45	0.72
1443	—	100	—	—	2.39	0.46
1444	—	100	—	—	2.47	0.98
1445	—	100	—	—	1.90	0.60
1454	6.2	89.8	2.9	2.3	1.91	1.39
1455	3.6	96.4	—	—	2.34	0.94
1456	—	100	—	—	1.63	0.55
1457	11.5	84.5	—	—	1.23	1.45
1458	5.0	95.0	—	—	2.18	0.92
1459	2.4	97.6	—	—	2.02	0.80
1460	—	100	—	—	1.56	0.47
1461	3.9	96.1	—	—	1.89	1.10
1462	—	100	—	—	2.32	0.88
1463	4.3	95.7	—	—	1.68	0.86
1464	3.3	96.7	—	—	1.66	0.42
1465	—	100	—	—	2.05	0.58
1466	—	100	—	—	1.82	0.59
1467	—	100	—	—	1.70	0.78
1468	—	100	—	—	2.03	0.96
1469	7.4	92.6	—	—	1.35	1.58
1470	—	100	—	—	1.72	0.81
1471	—	100	—	—	2.16	0.54
1472	10.0	90.0	—	—	1.40	1.49
1473	3.2	96.8	—	—	1.73	0.84
1474	—	95.0	2.8	2.9	2.70	0.80
1475	—	100	—	—	1.79	0.61
1476	—	100	—	—	2.35	0.59
1477	18.3	81.7	—	—	0.91	1.58
1478	47.5	52.5	—	—	−1.48	2.72
1479	18.0	82.0	—	—	0.90	1.66
1480	—	100	—	—	2,29	0.59
1481	12.7	86.3	—	—	0.87	1.30
1482	—	100	—	—	2.57	0.45
1483	25.8	74.2	—	—	0.22	1.44
1484	1.3	98.7	—	—	2.15	0.59
1485	2.6	97.4	—	—	1.80	0.67
1486	29.8	70.2	—	—	−0.23	2.13
1487	1.0	99.0	—	—	2.67	0.57
1488	—	100	—	—	1.77	0.72
1489	8.2	91.8	—	—	1.31	1.12
1490	—	100	—	—	1.69	0.53
1491	12.5	87.5	—	—	0.84	1.41
1492	42.5	57.5	—	—	−0.66	1.45
1493	2.0	98.0	—	—	2.90	0.62
1494	5.5	92.1	1.1	2.2	2.00	1.28
1495	—	100	—	—	1.72	0.49
1496	7.3	91.4	0.3	2.7	1.90	1.52
1497	1.5	98.5	—	—	2.11	0.51
1498	—	100	—	—	2.27	0.42
1499	2.5	97.5	—	—	2.30	0.86
1500	—	90.5	6.6	4.0	3.36	1.61
1501	16.0	79.6	2.8	2.9	1.77	2.11
1502	1.7	85.0	7.0	6.4	2.63	2.47
1503	—	86.9	9.1	5.4	3.83	2.01
1504	27.1	72.9	—	—	0.81	1.95
1505	—	97.8	1.2	2.1	1.86	0.72
1506	11.4	88.6	—	—	1.20	1.85
1507	60.4	39.6	—	—	−1.28	2.36
1508	0.8	91.7	4.7	4.2	3.36	1.82
1509	—	100	—	—	2.10	0.50
1510	—	100	—	—	1.98	0.55
1511	1.7	98.3	—	—	1.97	0.67
1512	22.6	77.4	—	—	0.27	2.37
1513						
1514						
1515	4.8	95.2	—	—	1.53	0.51
1516	52.0	48.0	—	—	−1.19	2.81
1517	5.9	94.1	—	—	1.41	1.22
1518	—	100	—	—	3.03	0.45
1519	6.8	93.2	—	—	1.04	0.97
1520	58.0	42.0	—	—	−0.90	2.32
1521						
1522	3.8	96.2	—	—	1.83	0.27
1523	—	100	—	—	2.18	0.68
1524	53.8	46.2	—	—	−1.34	2.23
1525	63.7	36.3	—	—	−1.68	2.74
1526						
1527	3.9	96.1	—	—	1.39	0.80
1528	2.2	97.8	—	—	1.43	0.51
1529	4.3	94.7	—	—	1.26	0.55
7263-						
1543	—	100	—	—	2.05	0.45
1544	0.1	99.9	—	—	1.91	0.58
1545	0.1	99.9	—	—	2.89	0.52
1546	0.1	99.9	—	—	2.16	0.54
1547	—	100	—	—	2.58	0.54
1548						
1549	16.4	83.6	—	—	1.20	2.15
1550	3.0	97.0	—	—	1.04	1.30
1551	2.3	97.7	—	—	1.02	1.07
1552	5.1	94.9	—	—	1.07	1.43
1553	9.7	90.3	—	—	0.87	1.54
1554	4.6	95.4	—	—	1.21	1.47
1555	4.8	95.2	—	—	1.88	1.58
1556						
1557	1.5	86.5	7.7	4.3	2.71	2.25
1558	14.1	85.9	—	—	0.14	1.86
1559	5.5	94.5	—	—	0.84	1.35
1560	19.9	80.1	—	—	0.65	1.75

Sample No.	*Gravel %*	*Sand %*	*Silt %*	*Clay %*	*Mean phi*	*Standard deviation phi*	*Sample No.*	*Gravel %*	*Sand %*	*Silt %*	*Clay %*	*Mean phi*	*Standard deviation phi*
1561	10.2	89.8	—	—	0.13	1.62	1578	4.3	91.1	2.3	2.3	2.28	
1562	0.9	99.1	—	—	2.91	0.87	1579	2.0	86.3	7.8	3.9	3.47	
1563	1.1	98.9	—	—	2.02	0.90	1580						
1564	11.4	88.6	—	—	0.62	1.80	1581	5.9	94.1	—	—	1.19	
1565	10.5	89.5	—	—	0.38	1.79	1582						
1566	0.3	99.7	—	—	1.58	0.59	1583	13.4	86.6	—	—	0.38	1.45
1567							1584	1.7	89.9	5.5	2.9	2.46	2.07
1568	—	100	—	—	2.94	0.51	1585	—	100	—	—	2.68	0.38
1569	—	100	—	—	2.81	0.66	1586	—	100	—	—	1.73	0.92
1570	4.9	95.1	—	—	1.63	1.43	1587	15.7	84.3	—	—	0.24	2.15
1571	8.0	92.0	—	—	0.48	1.53	1588	—	100	—	—	2.97	0.39
1572	—	100	—	—	2.45	0.84	1589	2.6	97.4	—	—	1.56	1.23
1573	—	100	—	—	3.08	0.55	1590	21.0	79.0	—	—	−0.03	2.08
1574	5.4	94.6	—	—	1.48	1.60	1591	57.7	42.3	—	—	−0.50	2.18
1575	9.2	90.8	—	—	0.55	1.70	1592	19.8	80.2	—	—	0.08	1.92
1576							1593	2.7	97.3	—	—	2.55	1.25
1577	0.3	99.7	—	—	2.93		1594	4.8	95.2	—	—	2.38	1.51

APPENDIX 3

GEOCHEMICAL DATA—1970 SAMPLES

Sample No.	*$CaCO_3$ %*	*P_2O_5 %*	*Fe_2O_3 %*	*TiO_2 %*	*As ppm*
7063-					
1404	97.2	0.10	0.18	0.01	7
1405	26.1	0.05	0.48	0.13	9
1406	3.3	0.05	0.21	0.11	6
1407	1.4	0.05	0.33	0.13	4
1408	14.8	0.05	0.76	0.19	4
1409	65.4	0.10	0.82	0.05	12
1410	59.5	0.20	4.45	0.16	65
1411	87.4	0.15			
1412	37.2	0.10	0.70	0.08	5
1413	5.3	0.05	0.95	0.14	9
1414	8.8	0.05	0.53	0.10	6
1415	24.1	0.05	0.68	0.11	7
1416	91.0	0.10	0.23	0.01	6
1417	87.6	0.15	1.19	0.02	17
1418	39.0	0.05	0.86	0.08	5
1419	12.3	0.05	2.00	0.47	11
1420	13.3	0.10	2.10	0.84	12
1421	19.8	0.05	0.68	0.11	6
1422	21.5	0.05	0.79	0.13	6
1423	4.3	0.05	0.52	0.12	8
1424	17.8	0.10	0.62	0.13	7
1425	2.7	0.05	0.27	0.13	3
1426	50.4	0.05	0.29	0.02	4
1427	27.7	0.10	0.70	0.15	4
1428	46.3	0.10	0.61	0.08	6
1429	77.4	0.30	4.05	0.11	70
1430	86.3	0.15	0.47	0.02	7
1431	66.3	0.35	3.20	0.14	42
1432	57.4	0.10	0.53	0.02	6
1433	51.3	0.10	1.20	0.05	10
1434	64.0	0.20	1.30	0.02	2
1435	54.9	0.45			
1436	73.6	1.00			
1437					
1438	66.1	0.15	1.30	0.02	9
1439	86.9	0.35	4.55	0.10	65
1440	16.6	0.05	1.00	0.22	4
1441	11.4	0.05	0.65	0.17	8
1442	26.7	0.10	1.25	0.22	6
1443	1.4	0.05	0.28	0.10	6
1444	25.2	0.10	1.05	0.26	7
1445	74.7	1.25	6.40	0.14	65
1454	80.8	0.35	2.80	0.11	36
1455	39.5	0.10	1.20	0.37	17
1456	12.0	0.05	0.33	0.08	5
1457	84.4	0.20	1.80	0.11	19
1458	84.0	0.20	1.60	0.11	20
1459	39.5	0.15			
1460	14.3	0.05	0.30	0.06	6
1461	79.2	0.30	1.90	0.13	19
1462	83.5	0.25	1.95	0.11	18
1463	88.8	0.20	1.75	0.07	30
1464	61.7	0.35	1.50	0.13	17
1465	8.9	0.05	0.78	0.16	8
1466	10.9	0.05	0.69	0.12	8
1467	55.2	0.40	0.97	0.10	10
1468	86.9	0.25	2.30	0.08	44
1469	86.7	0.35	3.55	0.11	70
1470	88.8	0.30	1.20	0.05	19

Sample No.	*$CaCO_3$ %*	*P_2O_5 %*	*Fe_2O_3 %*	*TiO_2 %*	*As ppm*
1471	10.0	0.10	0.82	0.10	13
1472	43.8	0.10	1.30	0.08	22
1473	87.6	0.30	2.95	0.07	55
1474	50.6	0.80	4.30	0.32	19
1475	21.8	0.10	0.88	0.08	18
1476	10.9	0.10	0.95	0.15	12
1477	87.9	0.20	1.90	0.07	28
1478	88.1	0.25	1.45	0.08	26
1479	37.9	0.10	1.15	0.08	22
1480	47.9	0.10	1.35	0.15	18
1481	86.5	0.10	1.60	0.05	22
1482	7.7	0.05	1.10	0.14	12
1483	66.5	0.15	1.10	0.01	16
1484	43.4	0.20	1.75	0.12	18
1485	57.7	0.60	11.50	0.20	105
1486	80.6	0.35	3.60	0.10	50
1487	11.6	0.10	1.25	0.24	15
1488	23.4	0.15	1.40	0.15	19
1489	41.8	1.00	12.90	0.20	110
1490	63.1	0.85	11.50	0.17	95
1491	82.4	0.30	1.85	0.07	34
1492	64.0	0.20	10.70	0.10	230
1493	20.7	0.65	1.25	0.32	12
1494	58.6	0.20	2.30	0.16	44
1495	54.3	0.30	14.30	0.22	110
1496	63.1	1.20	1.85	0.16	22
1497	13.5	0.10	1.05	0.12	14
1498	7.0	0.05	0.54	0.12	10
1499	64.0	0.20	2.05	0.13	20
1500	40.2	0.15	1.65	0.36	9
1501	66.7	0.45	5.85	0.19	40
1502	57.7	0.30	3.65	0.31	11
1503	29.7	0.10	1.90	0.38	8
1504	74.7	0.25	3.05	0.16	38
1505	47.2	1.10	21.90	0.27	185
1506	80.1	0.35	8.40	0.11	100
1507	83.8	0.25	1.65	0.07	17
1508	29.7	0.15	2.00	0.78	11
1509	18.3	0.15	1.65	0.12	12
1510	14.8	0.10	1.10	0.10	9
1511	71.5	0.70			
1512	47.9	1.45	24.70	0.29	240
1513					
1514					
1515	41.1	1.25	23.60	0.26	240
1516		5.00	36.10	0.29	390
1517	78.3	0.30	2.85	0.08	60
1518	15.0	0.15	1.20	0.15	28
1519	15.0	0.10	1.55	0.08	22
1520	78.3	0.50	5.60	0.10	125
1521					
1522	19.1	0.15	1.90	0.11	22
1523	44.3	0.25	3.30	0.18	48
1524	81.7	0.30	2.40	0.08	48
1525	54.5	0.90	11.20	0.16	90
1526					
1527	72.2	0.35	2.75	0.10	46
1528	13.9	0.15	0.84	0.06	17
1529	27.2	0.30	2.30	0.07	42

APPENDIX 4

GEOCHEMICAL DATA—1972 SAMPLES

Sample No.	$CaCO_3$ %	P_2O_5 %	Fe_2O_3 %	TiO_2 %	*Corg.* %	*As* ppm	*Cd* ppm	*Co* ppm	*Cu* ppm	*Mn* ppm	*Ni* ppm	*Pb* ppm	*Sr* ppm	*Zn* ppm
7263-														
1543	1.4	0.05	0.1	0.11	0.03	15	1	5	5	20	5	5	75	5
1544	5.5	0.05	0.3	0.10	0.03	5	1	5	5	30	5	5	80	5
1545	2.8	0.05	0.4	0.14	0.04	5	1	5	5	50	5	5	205	5
1546	3.5	0.05	0.3	0.10	0.03	3	1	5	5	40	5	5	105	5
1547	17.3	0.05	0.6	0.23	0.04	5	1	5	5	65	5	5	465	5
1548	29.5	0.05	0.7	0.10	0.22	15	2	5	5	50	10	5	670	10
1549	49.0	0.05	0.7	0.08	0.08	15	2	5	5	35	10	5	1470	10
1550	72.2	0.15	1.0	0.06	0.13	20	5	10	5	65	15	5	1700	10
1551	83.8	0.15	0.9	0.04	0.14	25	6	10	5	55	20	5	1770	5
1552	89.4	0.10	0.9	0.03	0.07	20	5	15	5	40	20	5	2890	5
1553	90.4	0.10	0.8	0.02	0.08	30	5	10	5	40	20	5	2910	5
1554	87.2	0.15	0.8	0.04	0.09	20	6	10	5	65	20	5	2310	10
1555	82.2	0.15	1.3	0.05	0.15	30	6	10	5	70	20	5	2140	10
1556	48.6	0.15	2.1	0.39	0.25	15	4	10	15	130	20	5	1010	60
1557	70.1	0.30	2.1	0.13	0.35	15	4	15	5	75	20	5	1780	35
1558	90.8	0.10	0.7	0.02	0.12	20	5	10	5	70	20	5	2160	15
1559	81.3	0.15	1.0	0.04	0.16	30	4	10	5	85	20	5	1900	10
1560	91.0	0.10	0.8	0.11		25	4	10	5	40	20	5	2760	40
1561	5.8	0.05	0.7	0.04	0.03	20	1	5	5	65	10	5	160	5
1562	19.1	0.05	0.8	0.13	0.11	5	1	5	5	65	10	5	625	15
1563	23.8	0.05	0.8	0.04	0.05	4	1	5	5	55	10	5	765	10
1564	86.7	0.15	1.0	0.06	0.09	30	6	10	5	110	20	5	2330	10
1565	88.5	0.15	1.1	0.04	0.09	25	5	10	5	110	20	5	2490	15
1566	42.9	1.60	11.0	0.16	0.13	150	3	30	5	220	50	5	1100	130
1567														
1568	14.1	0.05	0.3	0.10	0.06	5	1	5	5	25	5	5	520	10
1569	19.0	0.05	0.8	0.16	0.23	8	1	5	5	70	5	5	725	15
1570	37.0	0.05	0.6	0.05	0.06	5	1	15	5	65	5	5	760	15
1571	85.6	0.15	1.1	0.05	0.09	25	3	10	5	170	15	5	2160	15
1572	23.6	0.05	0.6	0.09	0.14	10	1	5	5	50	5	5	580	15
1573	31.1	0.10	1.1	0.12	0.12	5	1	5	5	100	5	10	940	20
1574	81.7	0.20	1.1	0.06	0.13	30	4	15	5	95	10	5	1800	15
1575	88.3	0.15	1.0	0.09	0.07	20	4	15	5	120	15	30	2250	10
1576	42.0	0.10	1.1	0.15	0.15	8	3	10	5	140	10	5	1500	20
1577	10.4	0.05	0.6	0.14	0.08	5	1	5	5	65	5	5	455	15
1578	41.9	0.10	1.0	0.10	0.16	10	3	5	5	100	10	10	1740	15
1579	37.7	0.05	1.1	0.19	0.36	5	1	5	5	85	10	10	1180	20
1580	10.0	0.05	1.3	0.10	0.06	10	1	5	5	150	5	5	415	30
1581	64.0	0.10	0.8	0.03	0.11	10	4	10	5	85	10	5	2330	10
1582	61.1	0.60	5.8	0.09	0.15	45	6	15	5	120	20	5	1580	85
1583	72.4	0.20	2.5	0.08		70	4	15	5	380	20	5	2230	25
1584	62.4	0.10	1.0	0.11		10	4	10	5	85	10	10	1670	20
1585	6.4	0.05	0.3	0.15	0.08	5	4	5	25	15	5	5	320	10
1586	71.3	0.15	1.4	0.07	0.17	20	4	10	5	120	15	5	1980	15
1587	86.7	0.15	1.3	0.04	0.12	35	4	10	5	140	15	10	2320	15
1588	11.4	0.05	0.4	0.27	0.03	5	4	5	5	35	5	5	240	5
1589	77.6	0.15	1.7	0.07	0.17	30	4	15	5	160	15	5	1980	20
1590	94.7	0.15	1.2	0.03	0.21	30	6	15	5	120	20	5	2380	10
1591	48.1	3.55	19.0	0.14	0.13	350	3	30	5	270	40	20	945	100
1592	72.2	0.20	1.5	0.06	0.10	40	5	10	5	200	25	10	1930	15
1593	32.5	0.10	1.3	0.14	0.19	8	3	5	5	85	10	5	900	15
1594	10.6	0.05	0.4	0.14	0.05	2	1	5	5	50	5	5	390	10

CONTINENTAL SHELF SEDIMENTS

SOUTHERN QUEENSLAND AND NORTHERN NEW SOUTH WALES

1979

Scale 1:1 000 000

10 0 10 20 30 40 50 60 70 80 KILOMETRES
10 0 10 20 30 40 50 NAUTICAL MILES

Lambert Conformal Conic Projection

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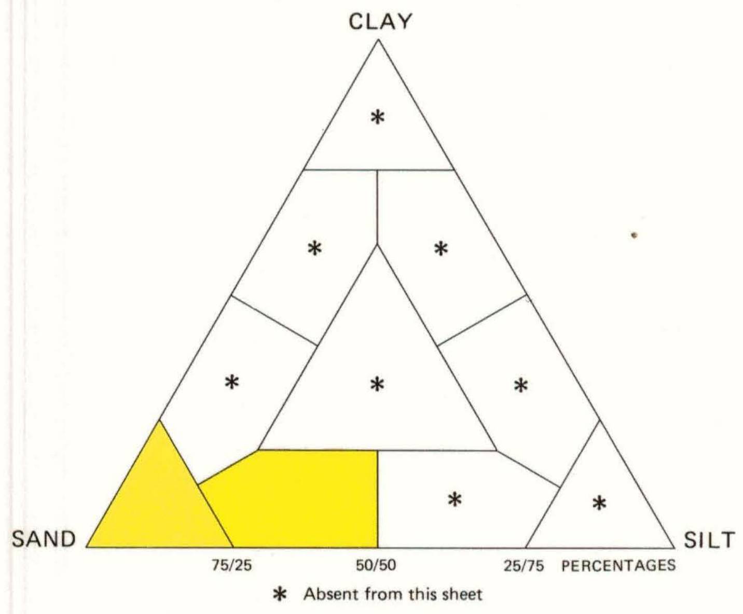


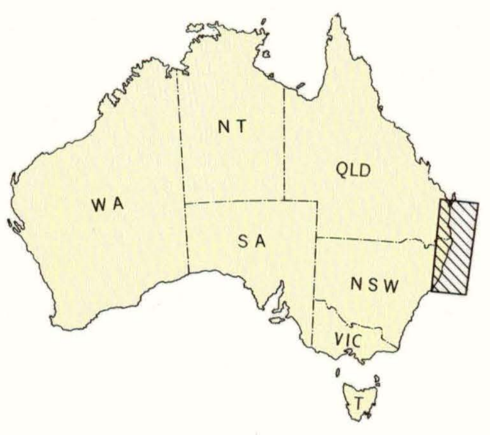
* Absent from this sheet

SEDIMENT CLASSIFICATION

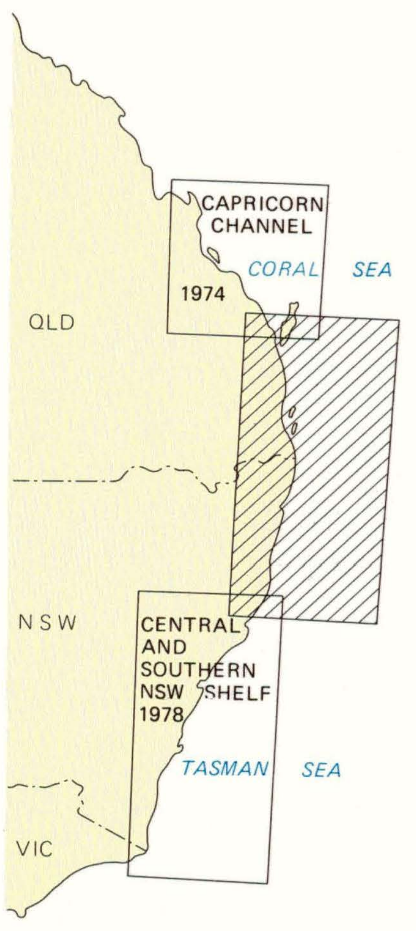
Note: The triangular diagram classifies the sediments according to the proportion of sand-, silt- and clay-sized particles they contain. The Wentworth scale is used. The corners of the inner triangle represent 60/20/20 percentages

- 🟨 *Sand*
- 🟨 *Silty sand*
- 🟥 *Rock*
- ▨ *> 60% gravel*
- ▨ *30-60% gravel*
- ▨ *10-30% gravel*
- ▨ *> 90% carbonate*
- ▨ *60-90% carbonate*
- ▨ *30-60% carbonate*
- ▨ *0-30% carbonate*

- • *Sea bed sample station*
- 500 *Bathymetric contour in metres*
  Contour intervals 20m (0-100), 100m (100-500m)
- *Swamp*
- *Highway*
- *Road*
- *Railway*



INDEX TO ADJOINING MAPS



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Geological reliability: The distribution of sediments is based on analyses of sea bed samples from stations whose positions are marked. Extrapolation between stations, and outside the area sampled, has been guided by bathymetry and by sediment notations on British Admiralty and Australian charts

Bathymetric reliability: Bathymetric contours have been compiled from published and unpublished R.A.N. Hydrographic Service charts and from surveys by the Division of National Mapping, Department of National Development

NOT TO BE USED FOR NAVIGATION

SOUTHERN QUEENSLAND AND
NORTHERN NEW SOUTH WALES
1 : 1000 000

FIRST EDITION 1979