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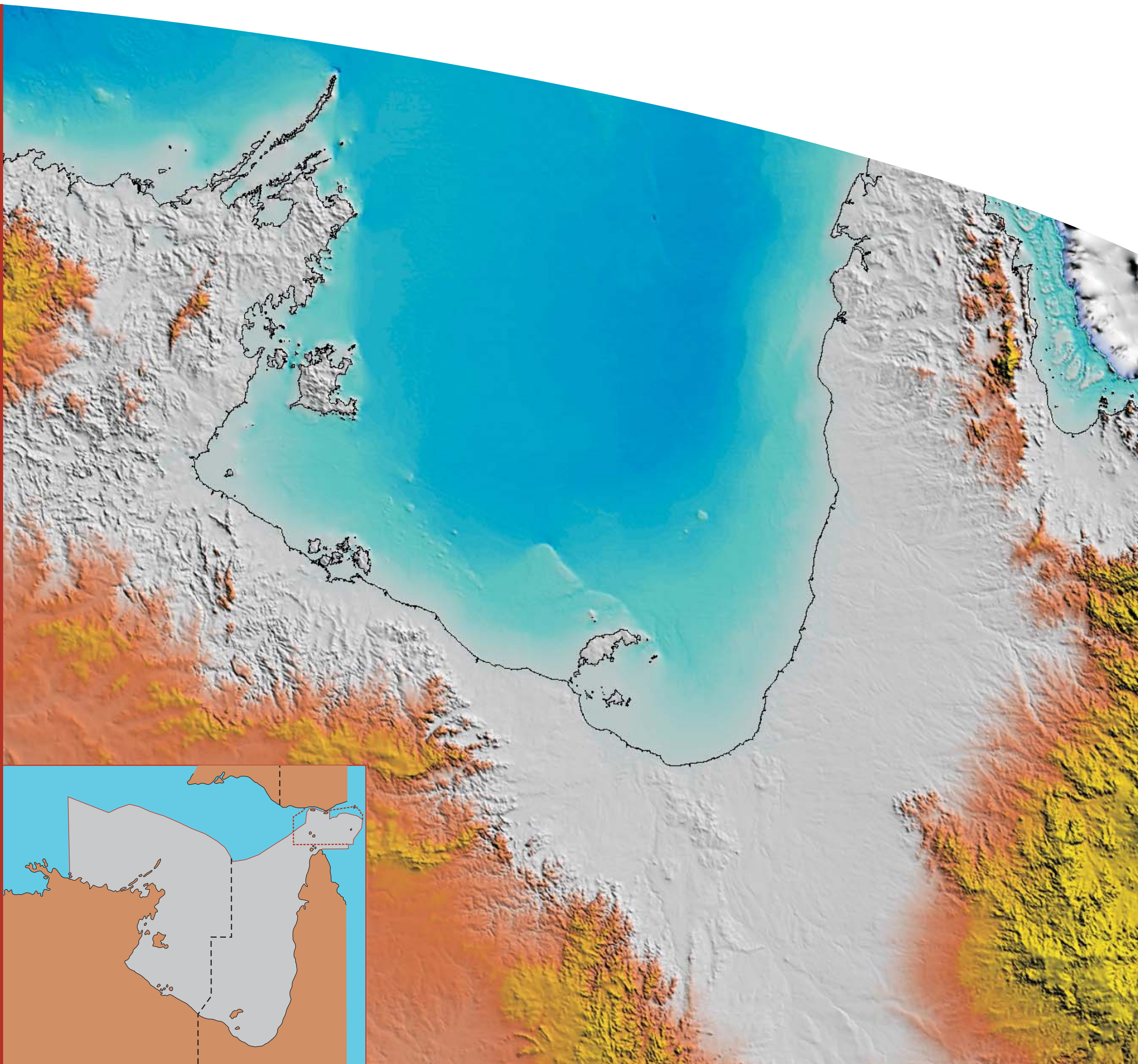
Geomorphology and Sedimentology of the Northern Marine Planning Area of Australia

Review and Synthesis of Relevant Literature in Support of Regional Marine Planning

Andrew Heap, James Daniell, Dena Mazen, Peter Harris, Laura Sbaffi, Melissa Fellows and Vicki Passlow

Record

2004/11



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Andrew Heap, James Daniell, Dena Mazen, Peter Harris,
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Australian Government

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Executive Summary

This record is a review and synthesis of geological research undertaken along the northern margin of Australia. The record has been written in support of regional marine planning and provides fundamental baseline scientific information for the Northern Planning Area. The Northern Planning Area (as defined by the National Oceans Office) extends from the Goulburn Islands in the west to Torres Strait in the east, and includes the seabed and ocean from the coast to the outer limit of the Exclusive Economic Zone. The information synthesised in this record can be used to define and characterise benthic (seabed) habitats for the purposes of contributing to a measure or description of habitat diversity.

The Northern Planning Area is conveniently divided into three major physiographic provinces: (1) Arafura Shelf; (2) Gulf of Carpentaria; and (3) Torres Strait, all of which were drowned about 18,000 years ago by the latest post-glacial marine transgression. The shelf is continuous between Australia and Papua New Guinea and formed a land bridge during the last glacial maximum. Its geological history has greatly influenced sea level and the physiography and type of sedimentary environments found in the region.

The Arafura Shelf is characterised by:

- A broad seaward-sloping platform of generally low relief that contains banks and reefs with gentle slopes in the south and is heavily dissected in the northeast by subaerially eroded channels;
- Oceanographic processes, dominated by tides, that are relatively uniform over the shelf but variably influenced by moderate wave energy and seasonal wind-driven and oceanographic currents. The shelf is occasionally affected by tropical cyclones that mobilise sediment across the entire area. This oceanographic regime produces the most uniform distribution of sediment mobility in the Northern Planning Area;
- A thin veneer of surface sediments consisting of poorly-sorted mixed siliciclastic sandy muds and carbonate sands that show relatively uniform patterns across the shelf in samples and acoustic records; and
- A Late Quaternary history dominated by the accumulation of sediment from northern Australia, which mostly came from the Gulf of Carpentaria over the Arafura Sill and was deposited in the Arafura Depression.

The Arafura Shelf contains some of the deepest water shelf habitats on the Australian margin.

The Gulf of Carpentaria is characterised by:

- A broad, shallow basin that is bordered in the north by shallow sills. The sills have regulated the transport of sediment and water into the basin over many sea level cycles. The floor is a low-gradient plain that is punctuated in the south by widespread areas of hard-grounds and sand banks, as well as steep-sided pinnacles and flat-topped platforms, at least three of which are submerged patch reefs;
- Oceanographic processes that are dominated by tides in the deeper central regions and waves in the shallow coastal waters. This oceanographic regime produces a pattern of sediment mobility with nearly equal areas dominated by waves and tides that causes Gulf waters to be well-mixed. The Gulf is also occasionally affected by tropical cyclones that mobilise sediment across the entire area, and also contains the largest region of negligible sediment mobility in the Northern Planning Area;
- Surface sediments that consist of poorly-sorted mixed terrigenous and carbonate muddy sands in the central gulf, with widespread ooids, and marginal terrigenous muds and sandy muds. The southern Gulf of Carpentaria is Australia's largest shelf province of terrigenous dominated sediments; and
- A Late Quaternary history dominated by multiple transitions between lacustrine, marginal marine and open marine conditions, associated with eustatic sea level cycles. A large freshwater to brackish lake occupied the Gulf during sea level lowstands.

Because of the relatively flat floor and low-sedimentation rates, the Gulf of Carpentaria has some of the most stable seabed habitats in the Northern Planning Area.

Torres Strait is characterised by:

- A shallow low-relief plain that contains a discontinuous chain of granitic islands, and is covered by widespread mobile sandwaves in the west. Isolated volcanic islands and relict fluvial channels up to 60 m deep occur in the east. More than 600 well-developed fringing and patch coral reefs occur in Torres Strait along with extensive *Halimeda* banks;
- Oceanographic processes that are strongly dominated by tides. Tidal velocities are high due to the constricted geometry of the region. Torres Strait is also occasionally affected by tropical cyclones that mobilise sediment across the entire area. The

resulting pattern of sediment mobility is highly variable and greater around reefs and islands due to local tidal streams;

- A diverse range and complex distribution of surface sediments. Well sorted sands and gravels make up the bedforms, while most of the shelf is covered by a (<1-2 m) veneer of poorly-sorted terrigenous mud and carbonate sand and gravel that forms four major facies. Coarse-grained sediments occur in regions of strong tidal currents and fine-grained sediments occur in regions of weaker tidal currents; and
- A Late Quaternary history of subaerial and fluvial erosion during lowstand, and widespread reef development and sediment reworking into bedforms during transgression and highstand.

The complex distribution of seabed habitats in Torres Strait reflects the complex bathymetry, distribution of substrates and variable hydrodynamic conditions.

As with all areas offshore of Australia, geomorphic and sedimentary data will always play a vital role as surrogates for habitat and biological diversity in regional marine planning, because we can never have a complete inventory of benthic biota. Consequently, further resources should be committed to expanding and enhancing databases that contain baseline geological and biological information on Australia's offshore areas.

1. Introduction

1.1. BACKGROUND

This record is a review and synthesis of geological research undertaken along the northern margin of Australia. The record has been compiled in support of regional marine planning to provide background scientific information for the development and implementation of regional marine plans. The information will also contribute to the National Oceans Office (NOO) national work program of constructing a bioregionalisation system for the north Australian margin. The region covered coincides with the Northern Planning Area, as defined by the NOO (Fig. 1.1). It extends from the Goulburn Islands in the west to Torres Strait in the east, and encompasses the ocean and seabed from the coast out to the outer limit of the Australian Economic Exclusive Zone (EEZ).

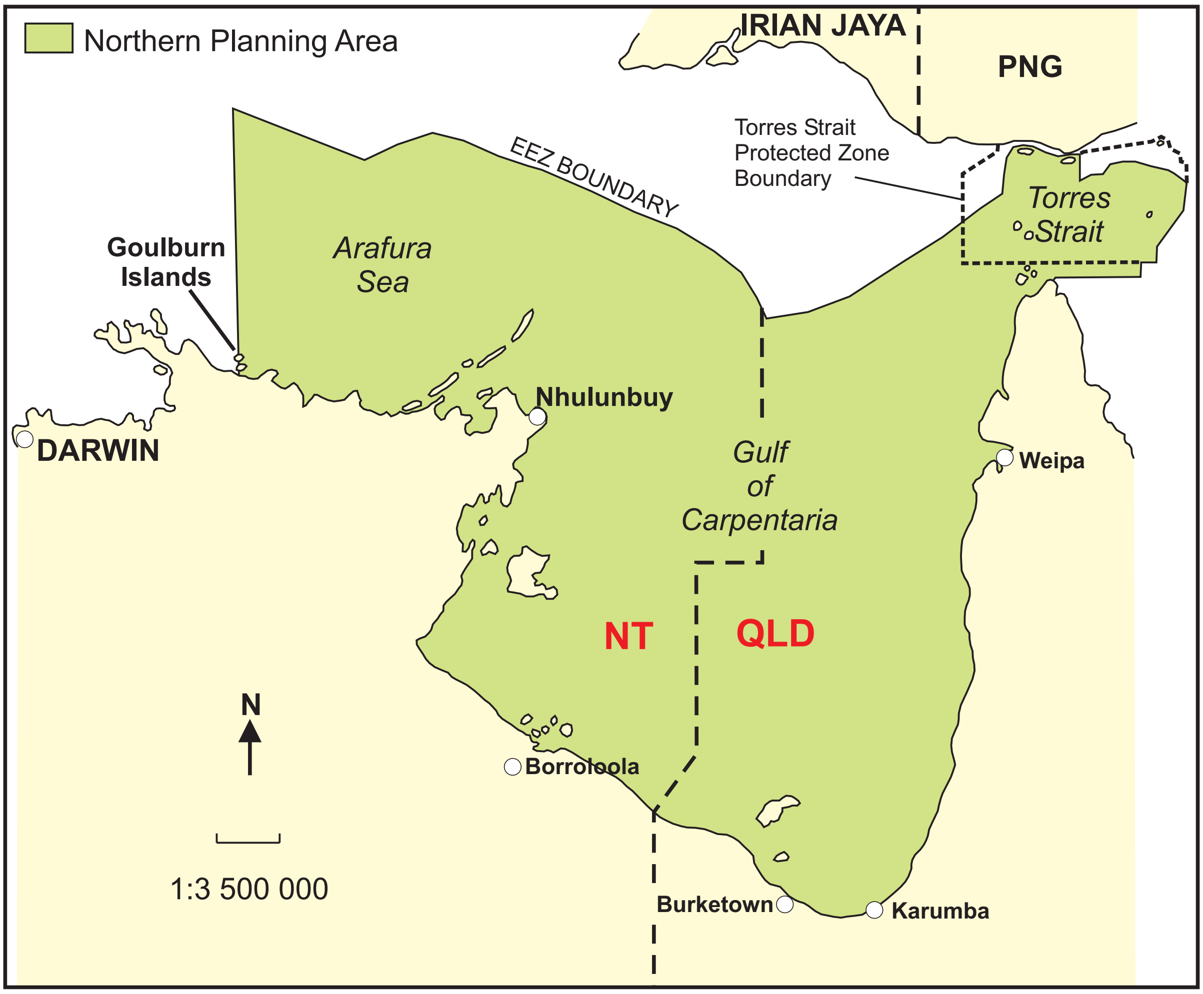

Figure 1.1. Map showing the boundaries of the Northern Planning Area, as defined by the National Oceans Office. The boundaries extend from the Goulburn Islands in the west to Torres Strait in the east, and the region encompasses the ocean and seabed from the coast out to the edge of the Economic Exclusive Zone (from National Oceans Office, 2003).

1.1.1. Oceans Policy and Regional Marine Planning

The Federal Government's commitment to an integrated ecosystem-based approach to planning and management of Australia's ocean resources saw the introduction, in December 1998, of Australia's Oceans Policy. At the heart of Oceans Policy is the preservation and maintenance of biodiversity via regional marine planning (National Oceans Office, 2003). Regional marine planning will allow ecosystem-based management of Australia's ocean resources, through the development of regional marine plans by the NOO.

The construction of a bioregionalisation system is a key component of the regional marine plan for the Northern Planning Area. The final bioregionalisation will rely in large part on the geologic information contained in this record. It will consist of a comprehensive, agreed and representative set of benthic and pelagic regions. Each region is based on physical and biological characteristics that reflect biogeography and ecosystem processes. A major outcome of this work will be the improved use of information in planning and managing of human uses and interaction with the marine environment. The results will be used to update, extend and refine the current national ecologically-based planning framework, the Interim Marine and Coastal Regionalisation of Australia (IMCRA), which presently covers the Northern Planning Area.

1.1.2. Scope and Relevance

The scope of this record is the synthesis of geomorphic, sedimentary and oceanographic information and knowledge published in the scientific literature for the Northern Planning Area (Fig. 1.1), although other supporting information, such as the distribution of seagrasses, is also summarised where relevant. This information is relevant for ocean management because the nature of the seabed can be important for determining the diversity and dynamics of marine biological communities. Geomorphic and sedimentary information has been used already to construct a bioregionalisation for the southeast margin (Butler et al., 2002).

The information synthesised here can be applied to the definition and characterisation of benthic (seabed) habitats. Habitat diversity, stability and water quality are some of the most significant environmental issues that must inform the management of ocean resources in the Northern Planning Area. This report emphasises geological information and includes a discussion of the implications of this information for regional marine planning in the Northern Planning Area. The discussion stresses the major differences in the abundance, distribution and nature of benthic habitats, and the hydrodynamic and sedimentary processes that affect them, and provides examples of the relationship between sediment/substrate types and biota.

1.2. NORTHERN PLANNING AREA

The Northern Planning Area can be conveniently divided into three major physiographic provinces: (1) Arafura Shelf; (2) Gulf of Carpentaria; and (3) Torres Strait (Fig. 1.2). Features mentioned in the text are shown in Figure 1.3, and a variety of geomorphic units have been mapped in the region (Fig. 1.4). In the region, the continental shelf is continuous between Australia and Papua New Guinea and formed a land bridge during the last glacial maximum (Harris, 1994a).

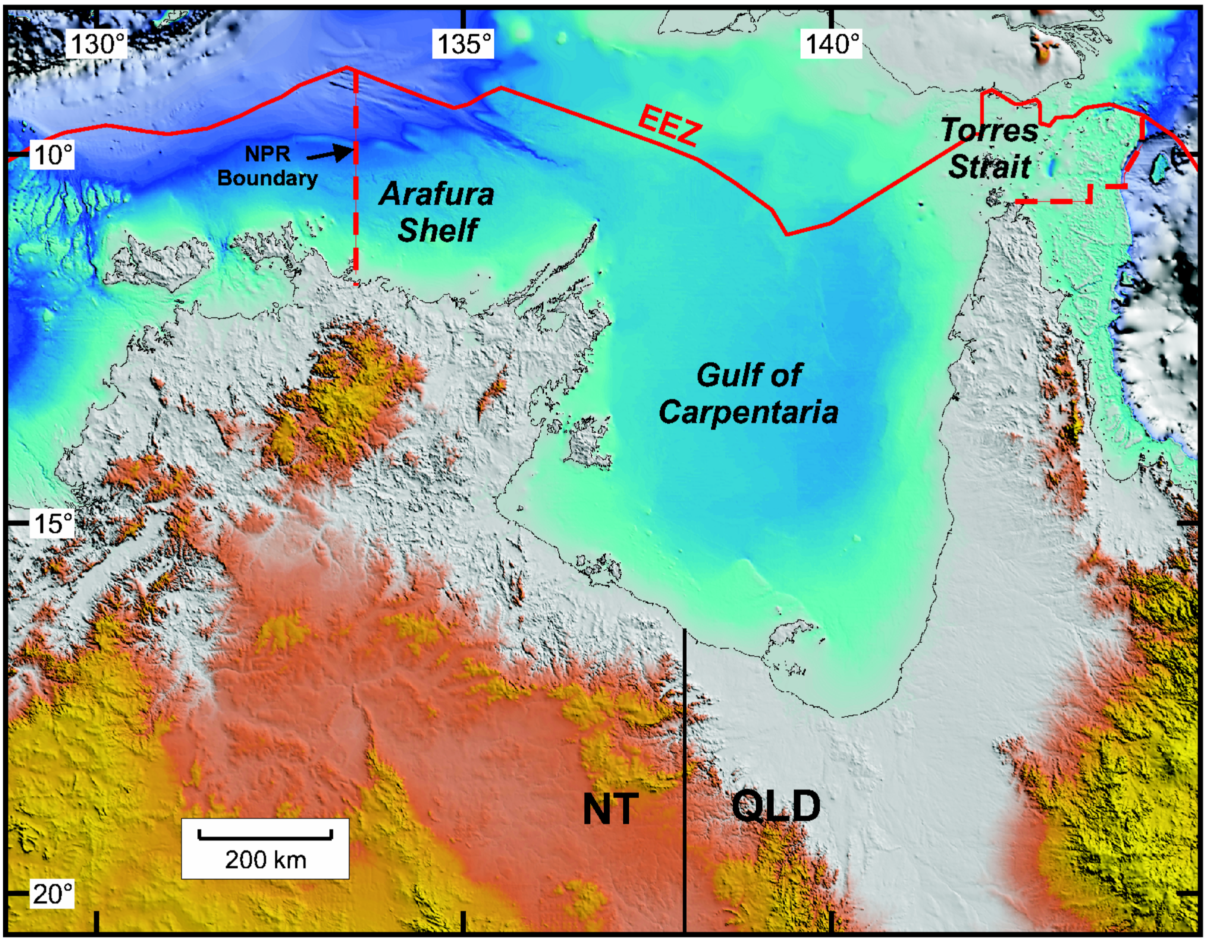

Figure 1.2. False-colour image showing the gross geomorphology and bathymetry of the northern margin of Australia. The region can be conveniently divided into three main physiographic provinces: (1) Arafura Shelf; (2) Gulf of Carpentaria; and (3) Torres Strait. The boundary of the Northern Planning Area is also shown.

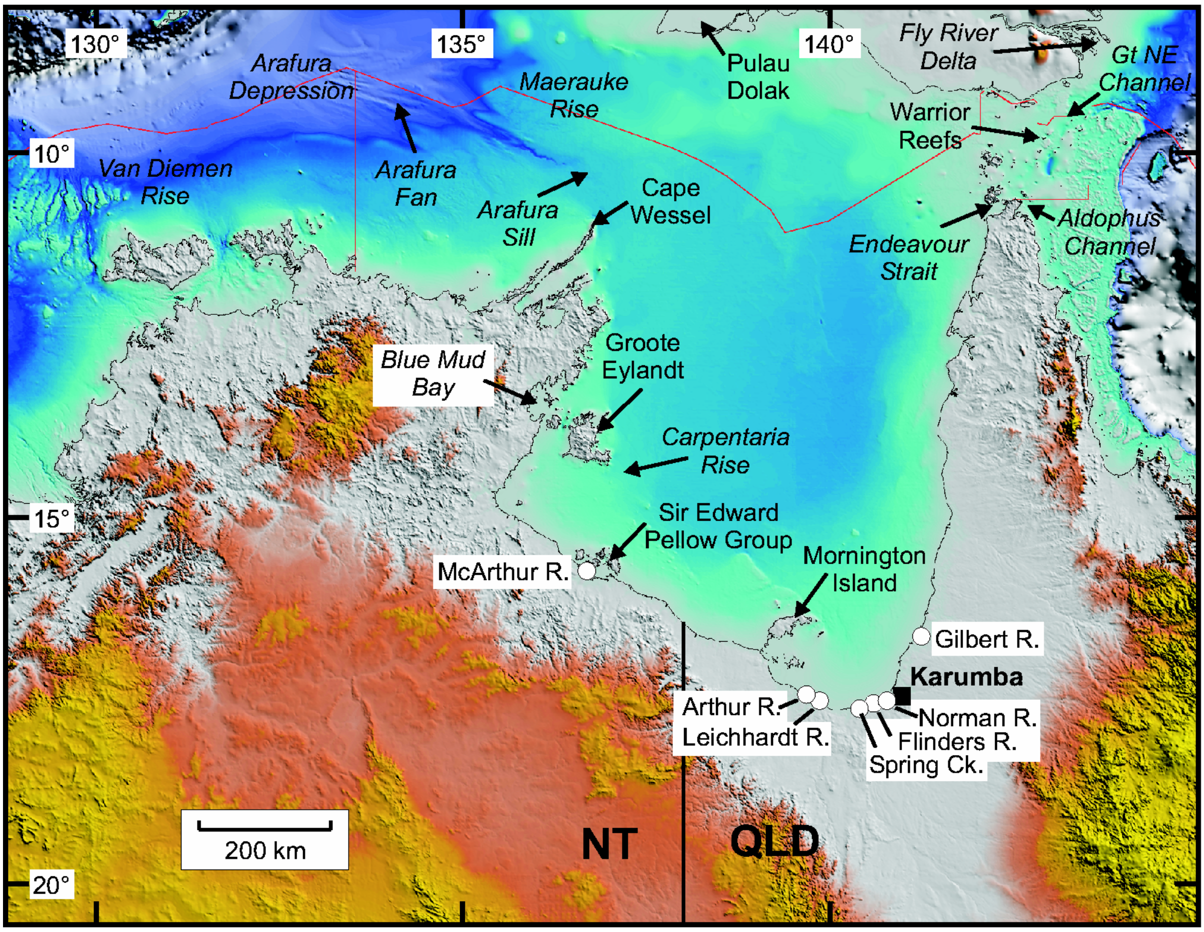

Figure 1.3. False-colour image showing the gross geomorphology and bathymetry of the northern margin of Australia with the location of features mentioned in the text.

1.2.1. Arafura Shelf

The Arafura Shelf is a major shipping seaway that connects the Indian Ocean with the Gulf of Carpentaria and Coral Sea. It was a primary depocentre for sediment and fluvial drainage for the northern margin and Papua New Guinea during the last glacial period. The outer shelf contains some of the deepest shelfal benthic habitats on the Australian margin. From a marine geological perspective, the Arafura Shelf is the most poorly-studied province in the Northern Planning Area.

1.2.2. Gulf of Carpentaria

The Gulf of Carpentaria is a shallow epicontinental sea of >400,000 km^2. The Gulf supports a major prawn fishery which yields >10,000 tonnes annually, and contains extensive seagrass habitats along its southern margins that are a principal feeding ground for Dugong and Green Turtle, which themselves are a traditional food source for the indigenous Torres Strait Islanders and Aborigines. Throughout much of the Late Quaternary, the Gulf was an isolated basin separated from the Indian and Pacific Oceans. Environments within the Gulf regularly fluctuated between terrestrial, lacustrine, coastal and open marine, in response to sea level cycles. Marine benthic habitats in the Gulf of Carpentaria were probably stable during the interglacial periods, particularly in the 60–70 m deep central regions.

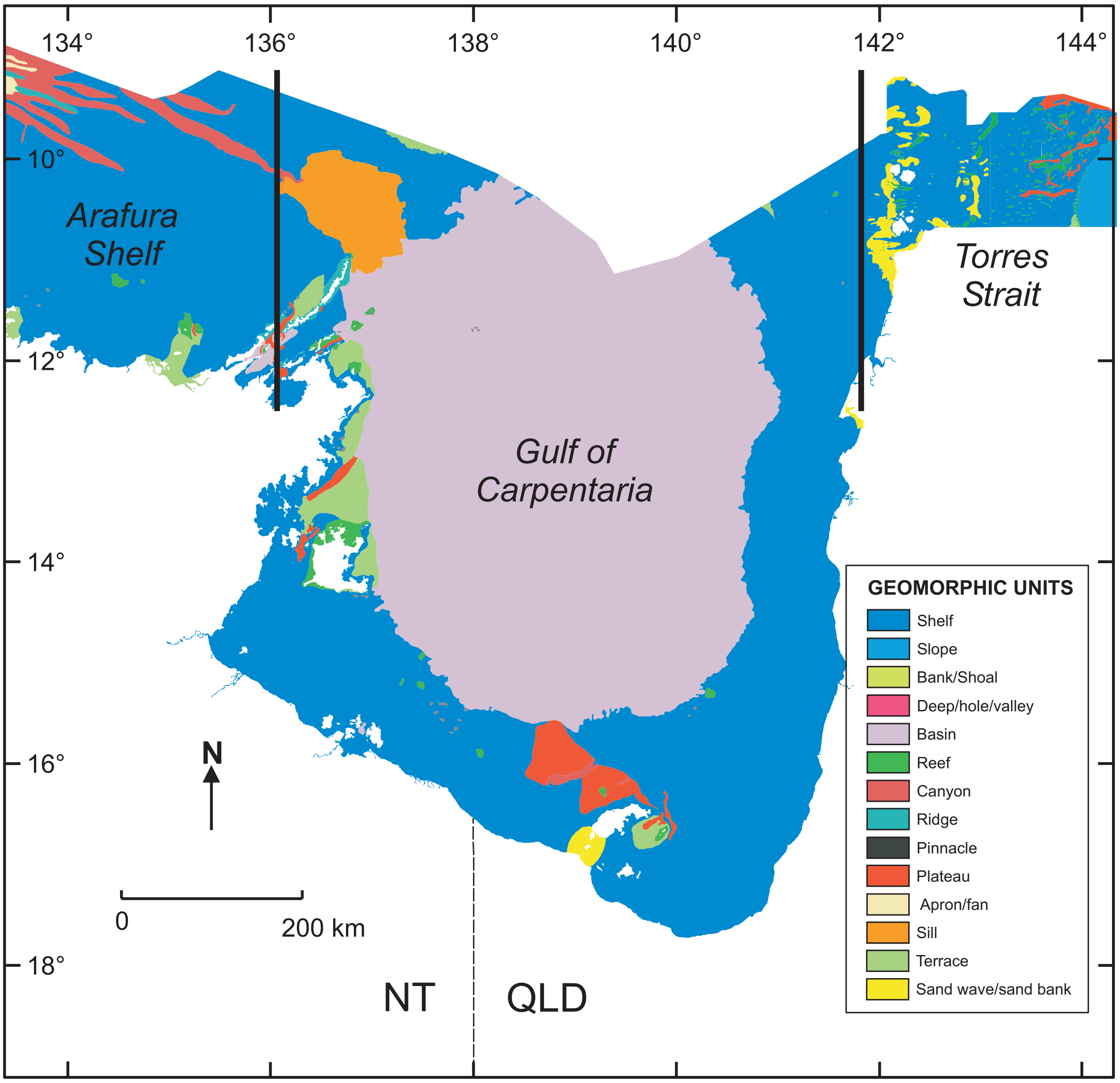

Figure 1.4. Map showing the major geomorphic units in the Northern Planning Area (from Harris et al., 2004a). The Arafura Shelf is dominated by a wide flat shelf and several northwest-trending channels in the north that bisect the shelf and connect the Gulf of Carpentaria with the Timor Trough. The Gulf of Carpentaria is dominated by a wide, flat basin and pinnacles and reefs in the south. In the north, the Gulf basin is separated from the Arafura Shelf by the Arafura Sill. Torres Strait is characterised by numerous islands and reefs. In the central and western regions, the seabed is covered by numerous large sand waves/sand banks that move around in response to changes to wind, waves and tide conditions.

1.2.3. Torres Strait

Torres Strait is at the northern end of the Great Barrier Reef (GBR). It is a major shipping seaway connecting the northern ports of Australia with Southeast Asia and the Pacific. Its significant biological diversity includes valuable fisheries resources (Williams and Staples,

1990) and sensitive seagrass habitats that also support Dugong and Green Turtle populations. Torres Strait is the oceanographic boundary between the Gulf of Carpentaria and Coral Sea. It is a biological barrier corresponding to the northern limit of the GBR. It is also a principal geological mixing zone, sandwiched between the largest modern tropical carbonate province on Earth (i.e., GBR) and a margin suppling vast amounts of terrigenous sediment to the ocean (Papua New Guinea). The distribution of benthic habitats is complicated and their stability over time and space is highly variable.

2. Arafura Shelf

The Arafura Shelf region of the North Planning Area extends from the Goulburn Islands in the west to Cape Wessel in the east, an area of approximately 130,000 km² (Fig. 1.2), and is the northern extension of the Australian continental platform (Nicol, 1970). The geologic structure, geomorphology and sedimentology of the Arafura Shelf can be directly attributed to the collision of the Australian platform with Papua New Guinea and Indonesia.

2.1. Tectonic Setting

The Arafura Shelf is a submerged part of the Australian continent that is bounded to the north by an extinct accreting plate margin (Jongsma, 1974; Nicol, 1970). To the north and northwest, this margin reflects some of the movements that have occurred in the tectonically active Tertiary orogenic belts of the Banda Arcs, Timor, and New Guinea border of the Arafura Sea. The principal geological provinces of the Arafura Shelf are the Goulburn Graben and Arafura Basin (Fig. 2.1).

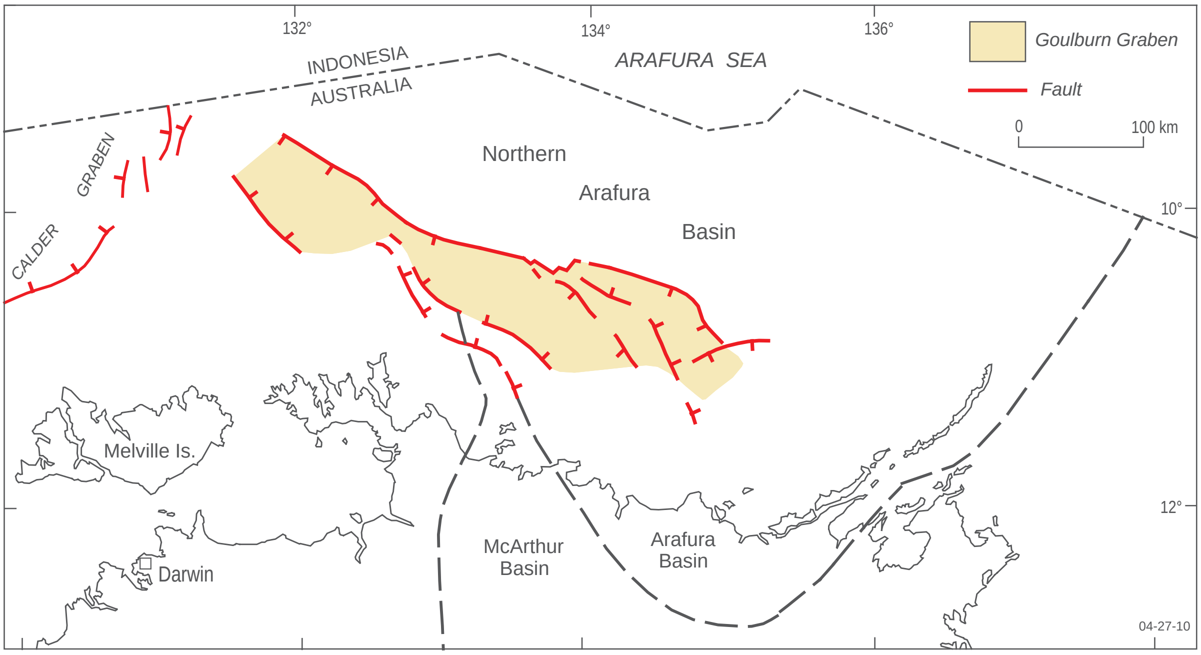

Figure 2.1. Map showing the geologic setting of the Arafura Shelf (from Moore, 1995). The shelf is underlain by the represents a submerged part of the Australian continent.

The Arafura Basin is an extension of the stable pericratonic area lying in the northern Australia Shield region. Structurally, the basin consists of a northern and southern platform separated by a northwest trending Goulburn Graben. The basin is filled with Cambrian to Permo-Triassic sediment unconformably overlain by middle Jurassic sediments of the Money Shoal Basin (Bradshaw et al., 1990).

2.2. Geomorphology

Due to its shallow depths, the geomorphology of the Arafura Shelf is largely the product of low sea-level erosional processes (Fig. 2.2; Jongsma, 1974). The shelf is a broad gently seaward-sloping platform up to 350 km wide of generally low relief. However, in the far southwest, banks with gentle slopes occur locally, and in the northeast, the surface is extensively dissected by subaerially eroded channels (Jongsma, 1974).

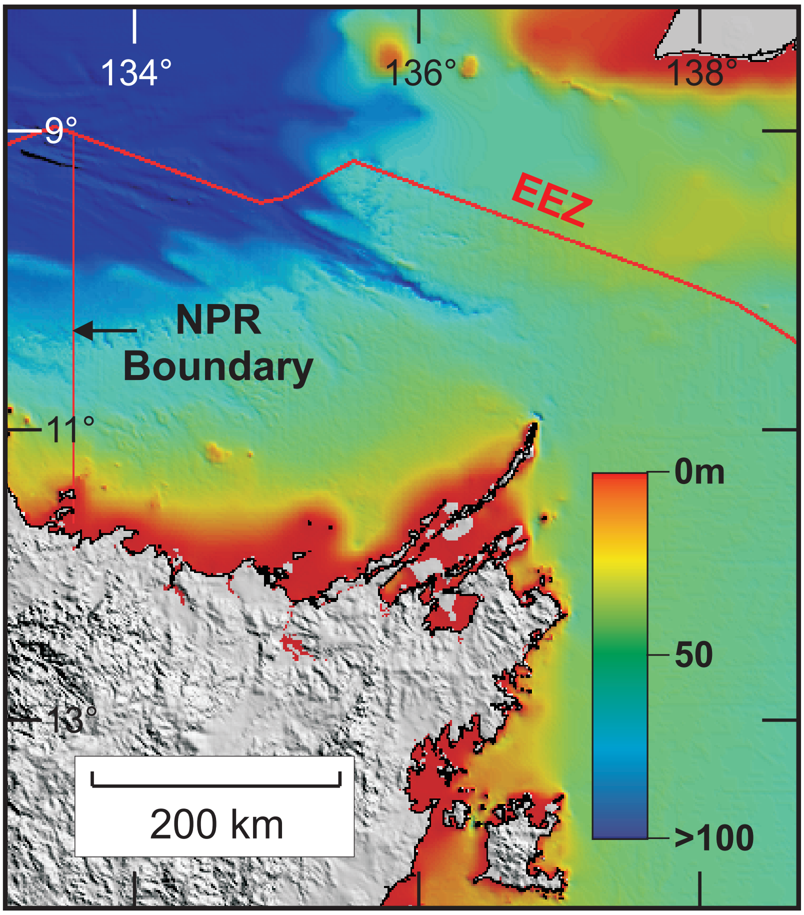

Figure 2.2. False-colour image showing the geomorphology and bathymetry of the Arafura Shelf. The shelf is characterised by a broad gently seaward-sloping platform up to 350 km wide of generally low relief. In the southwest, banks with gentle slopes occur locally, and in the north the shelf is extensively dissected by subaerially eroded channels.

The shelf can be broadly divided into two main morphological regions (Fig. 1.4). In the north, the shelf is characterised by a drowned fluvial system, which existed during the Pleistocene (and possibly older) sea level lowstands (Jongsma, 1974). Echo sounder profiles collected in 1969 during a Bureau of Mineral Resources survey to the region reveal a complex pattern of canyons, terraces, and ridges. The canyons, which are >8,704 km^2 in area (Table 2.1), are steep sided, with slopes of between 7° to 19°. The largest of these submarine channels extends northwestward for 400 km from Cape Wessel to the Arafura Depression (Jongsma, 1974). In the central and southern sections of the shelf is the Arafura Depression

(Fig. 1.3) which, in contrast to the northern fluvial system, is of generally low relief with few distinguishing features (Harris et al., 1991).

At the base of the Arafura Depression is a submarine fan (Arafura Fan?). Only the southern most edge of the fan or 427 km² is in Australian waters (Figs 1.3 & 2.2; Table 2.1). The surface of the fan is hummocky, and given its location in 200-300 m water depth, marine deposition on the fan was probably continuous throughout the Late Quaternary. The fan deposits probably contain a record of the environmental changes in the Gulf of Carpentaria associated with eustatic sea level cycles. The Arafura Depression is bordered on the south by submarine valleys and ridges that extend onto the Arafura Shelf as far as the Arafura Sill, which is 55 m deep and separates the shelf from the Gulf of Carpentaria (Figs 1.3 & 1.4). In the northeast, the Arafura Shelf is bordered by the Maerauke Rise (Harris et al., 1991). In the northwest, the shelf margin slopes down into the Timor Trough to a water depth of 2,000 m and joins the volcanic Banda Arc complex, an active convergent plate margin (Smith and Ross, 1986).

Table 2.1. Geomorphic units of the Arafura Shelf region (from Harris et al., 2004a).

Geomorphic Unit Type	Area (km^2)	Percent
Shelf*	88,988	68.77
Bank/shoal	656	0.51
Deep/hole/valley	669	0.52
Basin	790	0.61
Canyon	8,704	6.73
Ridge	999	0.77
Pinnacle	44	0.03
Apron/fan	427	0.33
Terrace	28,120	21.73
Total	129,397	100.00

* Shelf area is less the surface areas of superimposed features.

More than two thirds of the Arafura Shelf region is designated as undifferentiated shelf (Table 2.1; Harris et al., 2004a). Terraces, which cover an area of 28,120 km² or >21% of the seabed, are the next most abundant geomorphic unit, followed by submarine canyons which make up just under 7% of the area. The other geomorphic units each cover less than 1% of the Arafura Shelf region.

Fairbridge (1953) and Jongsma (1974) suggest the shelf break is at 550 m and 120-180 m water depth respectively; there are breaks of slope at both depths forming the upper and lower slope. The upper slope has a gradient of approximately 0.2° down to 500 m, while the lower slope has a gradient of approximately 0.75° (Harris et al., 1991). The shelf and upper continental slope contain a series of terraces at depths between 122 and 250 m. Along the margin, several 'notches, terraces, and scarps', possibly related to Pleistocene sea level fluctuations, occur at water depths of 122, 134, 147, 154, 163, 174, 181, and 225 m (Jongsma 1974).

The Arafura Shelf is separated from the Sahul Shelf in the west by the Van Diemen Rise (Fig. 1.3), which consists of a series of shallow algal banks separated by narrow channels (Fig. 2.2; Harris et al., 2004a). The shelf edge occurs seaward of these banks, at water depths of 120 to 180 m (Jongsma, 1974). The algal banks that make up the Van Diemen Rise are oriented across-shelf and have broad flat tops that locally rise up to 50 m water depth (Jongsma, 1974), and are surrounded by a terrace of regional extent (Harris et al., 2004a). Narrow, deep channels dissect the banks and exhibit orientations that appear to have been controlled by the underlying geology. The channels probably formed from fluvial incision of the algal banks during periods of sea level lowstand when the shelf was subaerially exposed (van Andel and Veevers, 1967; van der Kaars, 1991), although it is likely that tidal currents have also acted to preserve these channels. East of these submerged banks, the shelf break trends towards the north and follows the interfluve of the Arafura Depression, and thus does not extend between Australia and Papua New Guinea. Instead, in the east, the shelf is bounded by the Arafura Sill and Maerauke Rise (Fig. 1.3), which separate it from the Gulf of Carpentaria (Harris et al., 2004a). Relict coral reefs also occur locally on the sides of the drainage channels and on the outer shelf–upper slope (Harris et al., 2004a).

2.3. Oceanography

Relatively few oceanographic data are available for the Arafura Shelf region. The available data indicate that surface currents flow at speeds of up to 0.5 to 1 m s^{-1} towards the west between April to November under the influence of the South Equatorial Current, although the exact nature of this flow is unknown. Upwelling of cooler nutrient-rich water occurs along the outer shelf and upper slope near the Arafura Depression, resulting in elevated productivity on the outer shelf (Rochford, 1966). During the monsoon (December to March), ocean currents are generally weak and have no constant direction (Harris et al., 1991).

Tides in the Arafura Sea region are mesotidal and tidal heights are 2-4 m (Fig. 2.3; Harris et al., 1991). Available tidal height data indicates that the tides are predominantly semidiurnal, with a small diurnal inequality (Easton, 1970). The succession of tides is typically HHW>HLW>LHW>LLW, with the greatest change in height between LLW and HHW.

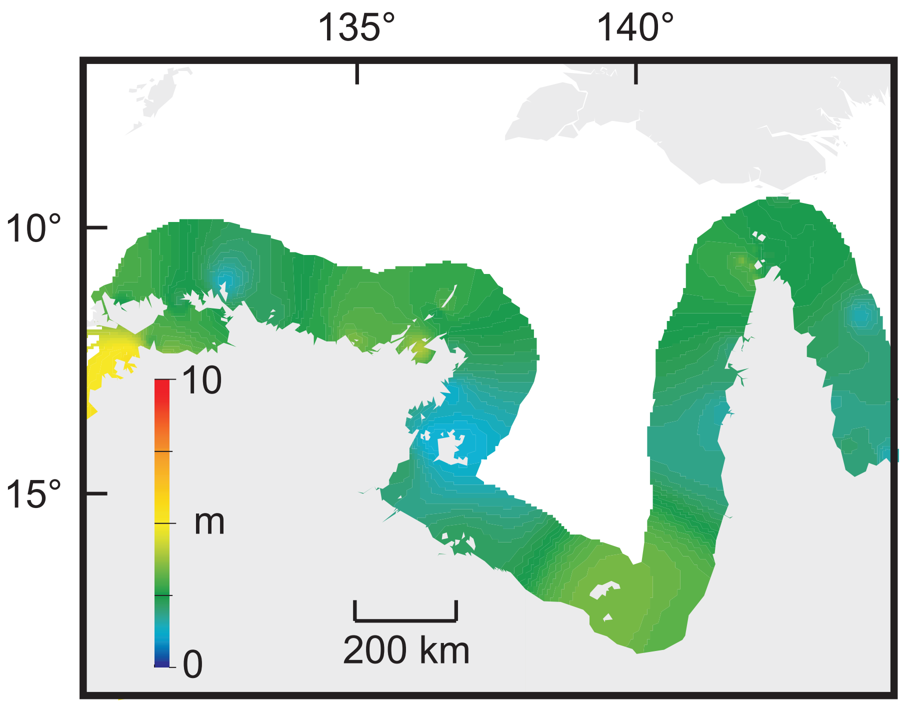

Figure 2.3. Map showing the tidal range at the coast. Tidal heights are between 2-4 m on the Arafura shelf. The tidal signature is predominantly semidiurnal, with a small diurnal inequality.

Modelling of tides and waves on the shelf indicates that near-bed tidal velocities are generally <0.8 m s^{-1} and variable over the shelf (Fig. 2.4). Tidal velocities increase locally around islands and coastal promontories, where they attain >1 m s^{-1}. Maximum annual wave energy at the bed exceeds 5,000 W m^{-2} over nearly the entire shelf, except near the coast (Fig. 2.5). Over most of the shelf, tides are the dominant process for the mobilisation of bed sediment (Fig. 2.6). Along the coast, the distribution is more complicated, with waves having a greater influence, and the pattern of mobilisation reflects local acceleration of tidal currents next to islands. The influence of waves is greatly reduced in deeper water, and tides dominate the mobilisation of bed sediment in the channels of the Arafura Depression. The entire Arafura Shelf region is affected by tropical cyclones that locally generate very strong shelf currents that are capable of creating significant geomorphic change. The frequency of cyclones in the Arafura Sea is high to moderate, relative to other parts of northern Australia. For any 100 km stretch of coastline, a cyclone will cross over it once every 10 to 15 years (Lourensz, 1981).

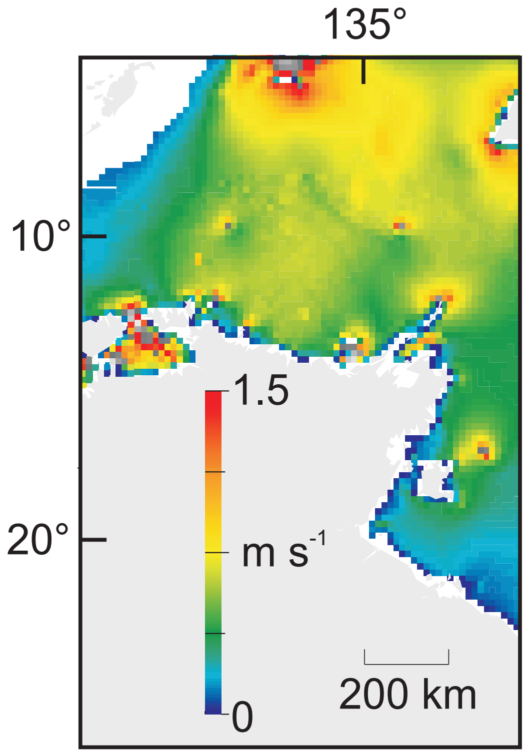

Figure 2.4. Map showing the distribution of tidal velocities. Near-bed tidal velocities are generally <0.8 m s^{-1} and attain >1 m s^{-1} around islands and coastal promontories.

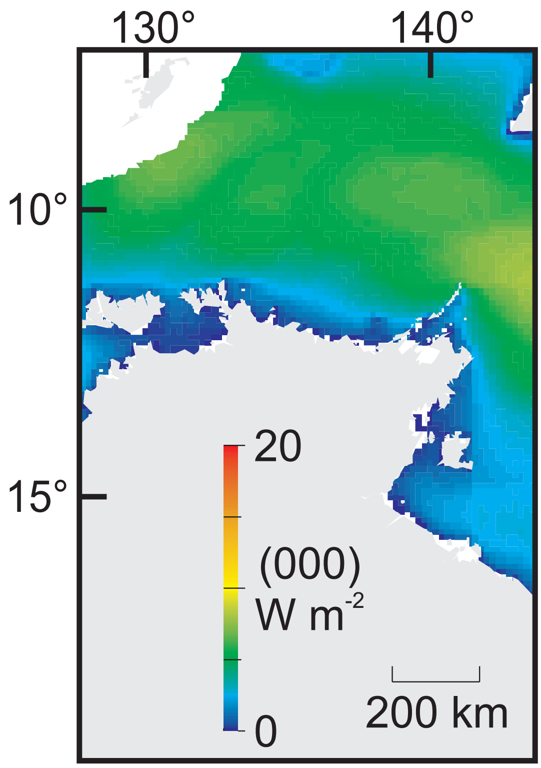

Figure 2.5. Map showing the distribution of wave energy at the bed. Maximum annual wave energy exceeds 5,000 W m^{-2} over most of the shelf, except near the coast where it is significantly reduced. Tropical cyclones can greatly perturb the figures.

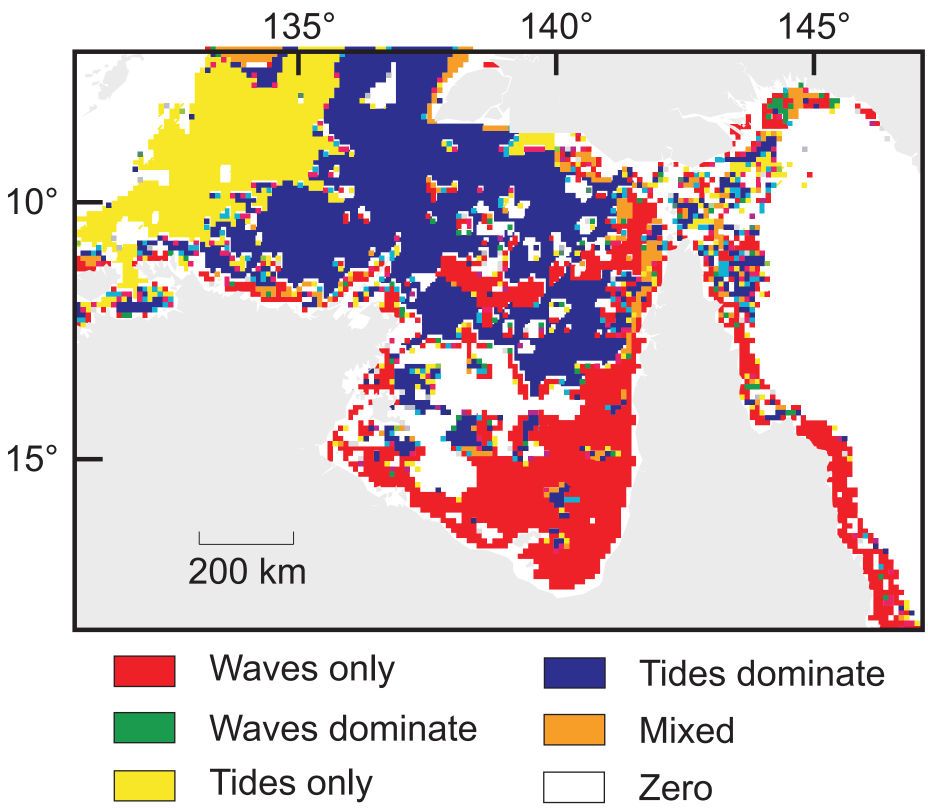

Figure 2.6. Map showing the distribution of sediment mobility on the bed. Tides dominate the mobilisation of bed sediment, although waves exert a greater influence near the coast. The influence of waves is greatly reduced with increasing water depth. Tropical cyclones can mobilise sediment over the entire shelf.

2.4. Surface Sediments

The regional sedimentology of the shelf has been studied by only a few geological surveys. The substantive results of the surveys have been published by Fairbridge (1951; 1953) and Jongsma (1974), which reveal several broad trends that are significant for regional processes. The most comprehensive survey (Jongsma, 1974) collected 399 surface sediment samples and 16 gravity cores from which much of the following summary was derived. While detailed sedimentology was undertaken on the samples and cores, only very general remarks on the biota were provided.

In the east, the Arafura Shelf is covered mostly with mixed siliciclastic-carbonate sand, while the central regions are covered mainly by silty clay (Fig. 2.7). Sediments in the drowned fluvial system in the north are a mixture of sand, silty sand and clayey sand. The sediment texture grades from sand to clayey sand and sandy clay with increasing water depth and distance offshore. Gravel-sized clasts are most abundant in three patches on the inner-shelf, where they consist of terrigenous ferruginous siltstone and sandstone, and in an alongshore-trending band located on the outer shelf between water depths of 100 m and 200 m, where they consist of relict shell.

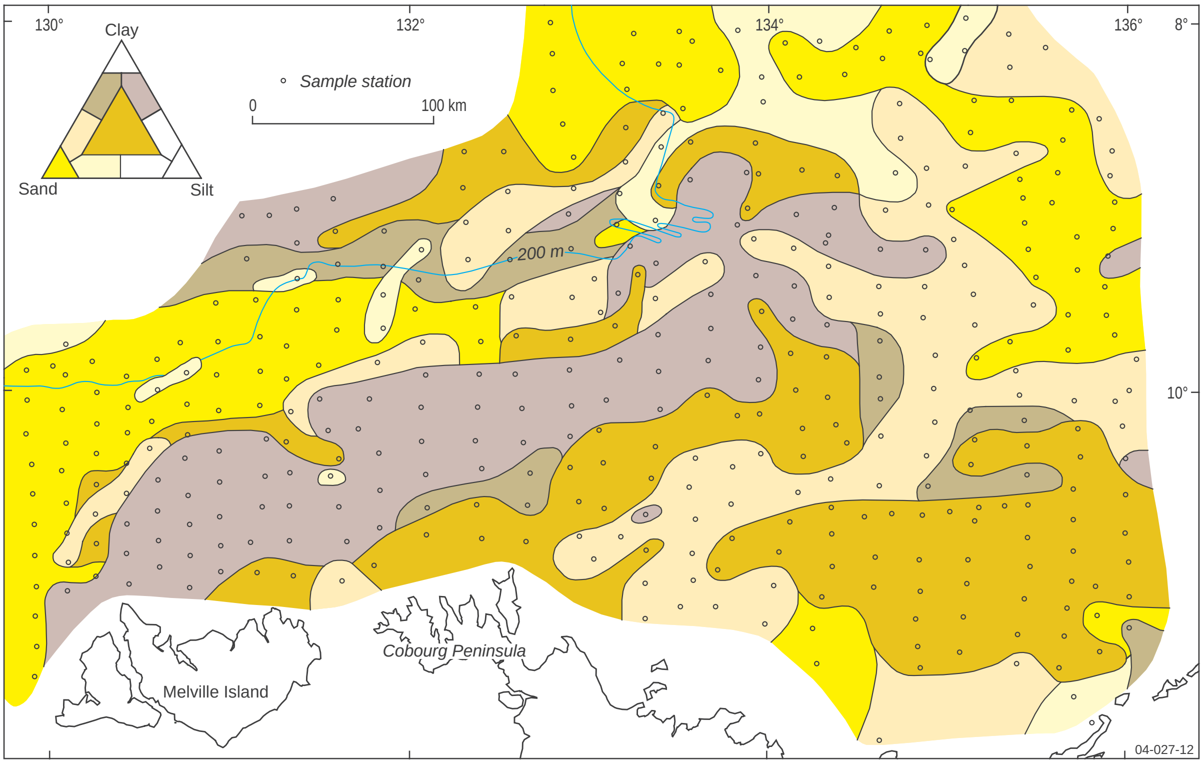

Figure 2.7. Map showing the distribution of surface sediment facies (redrawn from Jongsma, 1974). The shelf is covered mostly with mixed siliciclastic-carbonate sand while the central regions are covered mainly by silty clay. The sediment texture grades from sand to clayey sand and sandy clay with increasing water depth and distance offshore.

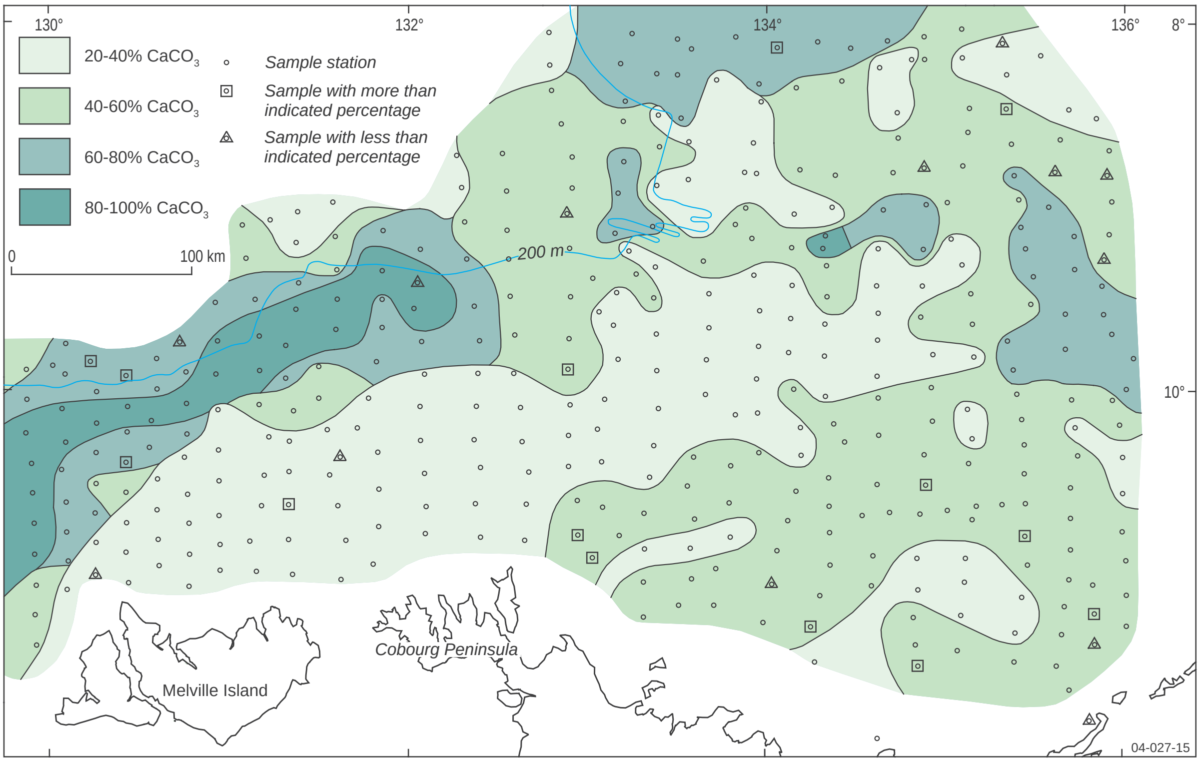

Figure 2.8. Map showing the distribution of calcium carbonate concentrations (redrawn from Jongsma, 1974). The percentage of carbonate in the surface sediments is positively correlated with grain size and negatively correlated to terrigenous inputs.

Across the Arafura Shelf, surface sediments are composed mostly of carbonate grains (Fig. 2.8). Given the high concentrations of carbonate and the overall shelf morphology, the shelf is a 'homoclinal carbonate ramp' (Read, 1982). The percentage of carbonate in the surface sediments is positively correlated with grain size and negatively with proximity to terrigenous inputs (Jongsma, 1974). Highest carbonate concentrations of >80% occur on the outer shelf (i.e., far from fluvial sources). The outer shelf is characterised by coarse-grained shelly sand. On the outer most shelf and upper slope, carbonate concentrations decrease because carbonate is diluted by terrigenous clay shed from Indonesia (Jongsma, 1974).

Other less abundant constituents of the seabed sediment include glauconite, calcareous nodules, and oolites. Glauconite is widespread and concentrated in areas of low relative sediment supply, particularly in the northeast and in association with the Arafura Depression. Glauconite occurs as discrete sand-sized grains of 0.1-0.5 mm diameter and also as crystals that infill foraminifera tests and gastropod shells. Brown calcareous nodules (pisoliths) 2-10 mm in diameter are abundant in surface sediments on the middle and outer shelf in water depths of between 40 and 80 m. These nodules probably formed in the littoral zone during a period of lower sea level and have been stranded on the shelf (Jongsma, 1974).

Foraminiferal distributions in the surface sediments correlate with water depth. Thick-walled tests are abundant in the shallower coastal and inner shelf sediments. Overall, Foraminiferal tests are most abundant at water depths of between 80 and 130 m, where organic remains are also most abundant. Miliodidae and Textularia are common in sandy sediment and *Ammonia* spp. are most abundant in muddy sediments. On the middle and outer shelf, benthic tests become less abundant. On the upper slope they are absent, and the sediment contains only planktonic tests; the most abundant species are *Globigerinoides ruber*, *Neogloboquadrina dutertrei*, *Globorotalia menardii* and *Globigerinita glutinata*.

2.5. Acoustic Facies

In 2003, Geoscience Australia employed Damuth's (1980) scheme to classify shallow seismic profiles collected in the Arafura Sea (see Appendix A) from three surveys of the R/V *Rig Seismic* (Table 2.2). Line spacing between adjacent profiles ranged from 20 to 50 km.

Table 2.2. R/V *Rig Seismic* surveys to the Arafura Sea.

Survey Number	Survey Name	Year	Frequency (kHz)	Reference
94	Central Arafura Sea	1990	3.5	Napier et al. (1991)
106	East Arafura Sea	1991	12	Hill et al. (1993)
118	Malita Graben	1993	3.5	Hill et al. (1993)

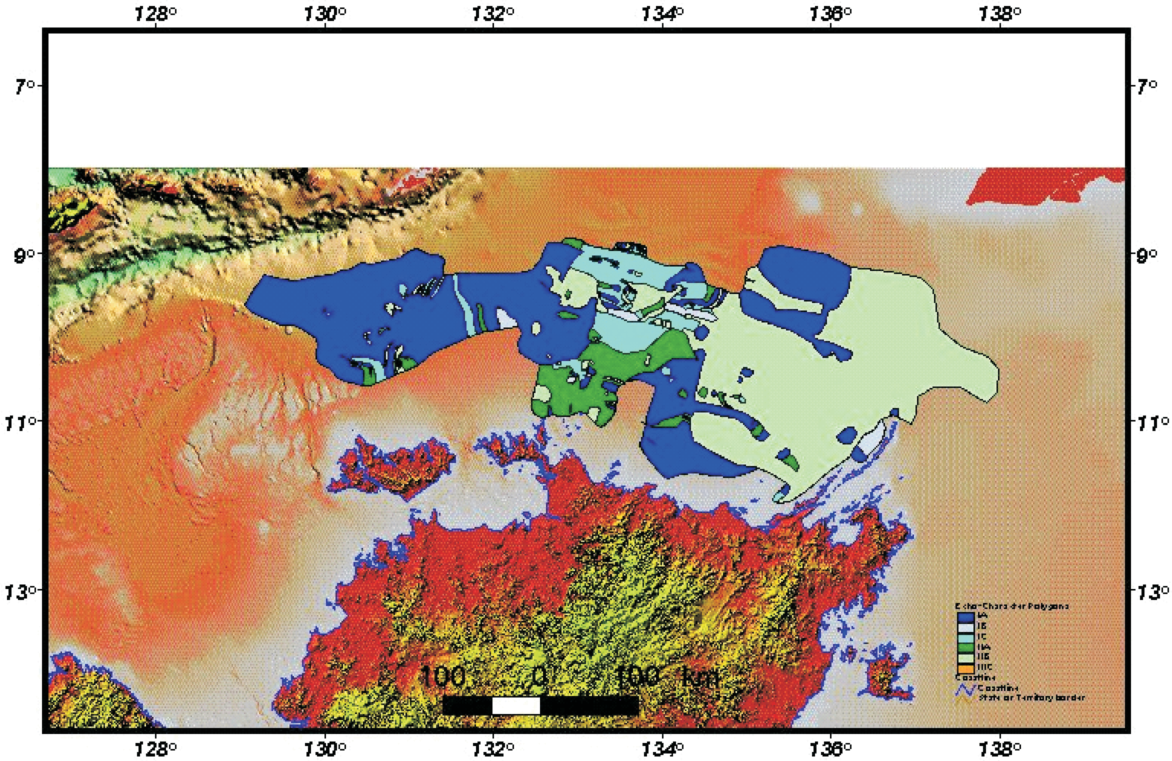

Figure 2.9. Map showing the distribution of acoustic facies. Most of the Arafura Shelf is characterised by echo-types I and II, with only two small areas of type IIIC. This uniform distribution of echo types is related to the fact that the surface of the shelf is relatively smooth.

Most of the Arafura Shelf is characterised by echo-types I and II, with only two small areas of type IIIC (Fig. 2.9). This uniform distribution of echo types indicates that the surface of the shelf is relatively smooth; the shelf is characterised by features with subtle morphology, including channels, scours, small mounds, and sand waves. Type III echoes are not common on the shelf, due to the relative absence of larger topographic features (e.g., submarine canyons, reefs, banks). The echo types were compared with the sediment data and descriptions reported by Jongsma (1974), to provide information on the nature of the seabed (Fig. 2.10). Sediments associated with echo-type I generally were coarser than sediments associated with echo-type II. Samples corresponding to echo-type IA contained combined sand and gravel concentrations of >50%, whereas samples corresponding with echo-type IIB contained combined sand and gravel concentrations of <50%. Of the 112 samples corresponding with echo-type IA, those located in the west, northeast and central south shelf regions were mostly sand. Those located in the central shelf regions were mostly clayey sand and silty sand. Three samples corresponded with echo-type IB. Two of these samples were located in the central shelf region and were silty clay, and the remaining sample was clayey sand. A total of 29 samples corresponded with echo-type IC. These samples corresponded with echo-types IIA and IIIB, respectively. Type IIA was silty clay and type IIIB was clayey sand. No samples have been collected where the shelf was characterised by echo-type IIIC.

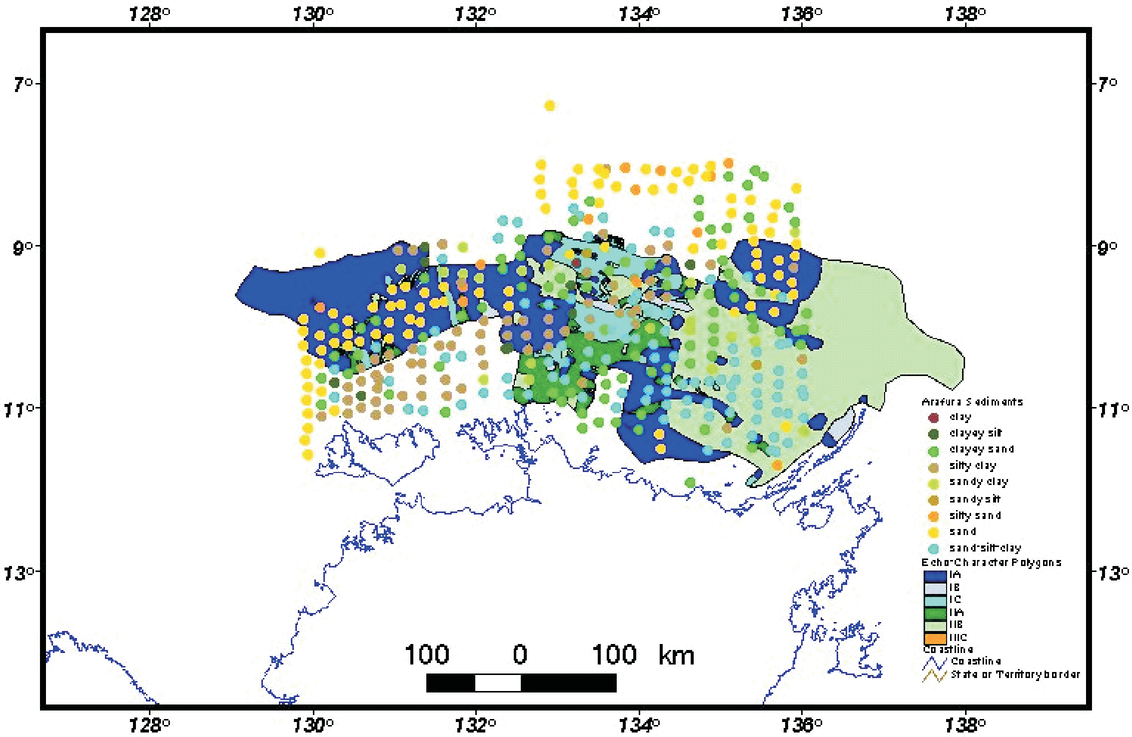

Figure 2.10. Map showing the distribution of acoustic facies with the location of sediment samples shown. Sediments associated with echo-types I generally are coarser than sediments associated with echo-types II. No samples were collected where the shelf was characterised by echo-type IIIC.

2.6. Late Quaternary Evolution

The present morphology of the Arafura Shelf is largely a product of low sea level erosional processes (Jongsma, 1974). High-resolution seismic profiles reveal truncation of underlying shelf strata on the sides of deeply-incised channels along the edge of the shelf (e.g., Nicol, 1970; Brown, 1979). These channels presumably formed from incision of the shelf break by lowstand rivers draining onto the upper slope. However, probably the most significant source of sediment to the Arafura region was from the Carpentaria Basin across the Arafura Sill, which became a major outlet for sediment and water bypassing the basin. During periods of low sea level, rivers eroded channels into the Arafura Sill (Jones and Torgersen, 1988) and sediment from the basin was deposited on the outer shelf and upper slope. Seismic profiles indicate that the primary depocentres for this sediment were the submarine valleys extending from the sill to the Arafura depression, where a Pleistocene (and older) sediment sequence comprising foreset beds of a broad submarine fan has been deposited (Jongsma, 1974). Since it is located in water depths of over 200 m, the floor of the valley would not have been exposed during the Late Quaternary and it is likely that the fan sediments record a relatively complete history of sedimentation in this region. Fluvial input from Irian Jaya also probably fed sediment into this valley.

The Arafura Shelf has also been the site of limited Late Quaternary coral reef growth (Napier et al., 1991). Several relict reefs occur next to the drainage channels on the outer slope. The sparsely distributed reefs probably grew at locations of local upwelling of cooler, nutrient rich water from the Timor Sea. These reefs would have flourished during relative sea level highs and were repeatedly eroded by subaerial processes during sea level lowstands. There is no published information on the age or growth history of these reefs.

The outer shelf and upper slope contain several steps and notches of regional extent. Corals collected from a submarine terrace located in 200 m water depth by submersible returned ages of 170,000 years BP, while a sample of beachrock dredged from a depth of 130-175 m returned an age of 18,700 years BP (Jongsma, 1974). These ages indicate that the terraces are probably remnants from Pleistocene sea level lowstands. Sediments deposited below the depth at which the terraces occur would not have been subaerially exposed during the Pleistocene. Deposits at shallower depths on the shelf would have been subject to extensive periods of subaerial exposure and erosion.

3. Gulf of Carpentaria

The Gulf of Carpentaria is a tropical epicontinental sea that forms a shallow basin extending from Cape Wessel in the west to Torres Strait in the east (Fig. 1.2). Most of the Gulf forms a shallow (<70 m) low-gradient basin that covers an area of >400,000 km² (Fig. 1.4). In the northwest, it is connected to the Arafura Shelf across the 53 m deep Arafura Sill (Harris et al., 1991; Chivas et al., 2001). This sill has greatly influenced sedimentation and the nature of sedimentary environments in the Gulf and Arafura Shelf by regulating the transport of water and sediments between the two regions over several sea level cycles.

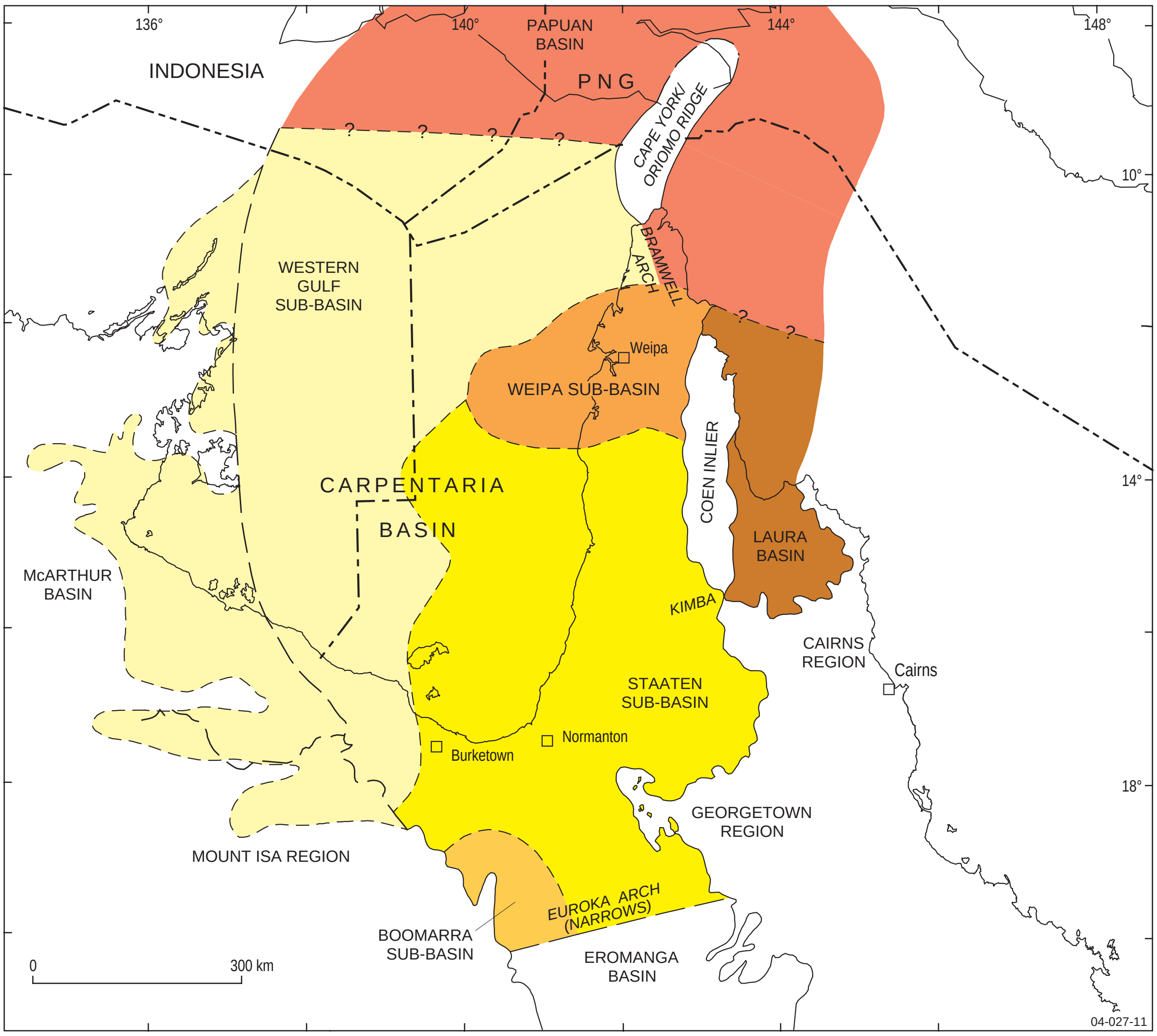

Figure 3.1. Map showing the geologic setting of the Gulf of Carpentaria (redrawn from McConachie et al., 1997). The Gulf is underlain by the Carpentaria Basin, which forms deep sedimentary units consisting of a series of stacked flexural intracratonic basins and depressions.

3.1. Tectonic Setting

The Gulf of Carpentaria is underlain by the Carpentaria Basin (Doutch et al., 1973), which forms deep sedimentary units consisting of a series of stacked flexural intracratonic basins and depressions (Chivas et al., 2001). Much of the Carpentaria Basin is located under the Gulf, but the margins also extend onshore into the Northern Territory and Queensland (Fig. 3.1). Sedimentary units in the basin are Late Jurassic to Early Cretaceous fine-grained, lithic marine rocks that are rarely preserved in outcrop. However, older Middle to Late Jurassic units consisting of mainly quartz sandstones are preserved along the eastern and southern margins (Miyazaki and McNeil, 1998). The upper 300 m are probably Miocene to Pleistocene in age (Chivas et al., 2001). Seismic records reveal that this younger section contains up to 17 reflectors that are marked by incised channels and unconformities (Fig. 3.2; Edgar, 1994; 2003) which are interpreted to delineate major transgressive/regressive cycles (Chivas et al.,

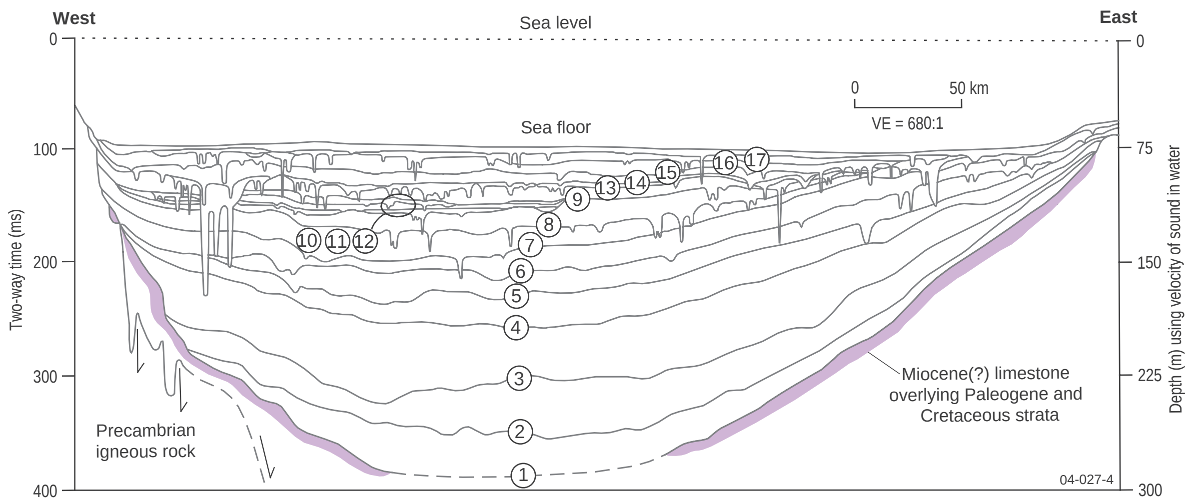

Figure 3.2. Interpreted seismic profile showing Cainozoic sediments underlying the Gulf (redrawn from Chivas et al., 2001). This section is interpreted to contain up to 17 reflectors that are marked by incised channels and unconformities and which are inferred to delineate major transgressive/regressive cycles.

2001). The sedimentary units of the basin overlie granitic basement and consist of Proterozoic, Palaeozoic, and Triassic sediments that are covered by Tertiary sediments of the Karumba Basin. During the Late Cretaceous, the margins of the basin were locally faulted, uplifted and eroded prior to sedimentation in the Karumba basin (Miyazaki and McNeil, 1998).

The Carpentaria Basin can be subdivided into four sub-basins (Fig. 3.1; McConachie et al., 1997):

1) Western Gulf sub-basin, which includes the western flanks, occurs mostly offshore but crops out in the Northern Territory and northernmost Cape York Peninsula. Sediments

in this sub-basin have undergone mild tectonic deformation and differential compaction over an irregular basement surface.

2) Weipa sub-basin, which occurs onshore and offshore around the coastal town of Weipa, and contains the two important depocentres of Carpentaria Depression and Oliver River. The Carpentaria Depression is the major depocentre, with the sediments attaining a total thickness of 1800 m (Miyazaki and McNeil, 1998). The origin of the Carpentaria Depression is unknown, although it may have been a failed tectonic rift that developed into an elongated rift (McConachie et al., 1997). This process controlled the earliest Carpentaria Basin deposition.
3) Staaten sub-basin, which includes a large region of the western Cape York Peninsula and Gulf Country west to Mornington Island.
4) Boomarra sub-basin, which includes the southeast regions of the Gulf, including western Cape York Peninsula south of the Weipa sub-basin. Sediments in the sub-basin are cut by the Boomarra Fault, the most significant structural element, which trends north and has produced a series of horsts and grabens with at least 300 m of vertical displacement (McConahie et al., 1997).

3.2. Geomorphology

The Gulf of Carpentaria resembles a broad shallow basin of >200,000 km^2 or >49% of the region (Fig. 1.4; Table 3.1). The floor of the basin is a low-gradient (<1:18,000) plain (Harris et al., 2004a). The deepest parts are located in the east, where water depths attain 70 m, but over most of the Gulf water depths are between 50 and 60 m, with deviations of <2 m (Chivas et al., 2001). The margins of the Gulf generally have extremely shallow gradients of 1:750-1:1,500 in the east, 1:3,000 in the south, and 1:250-1:125 in the west. The steepest gradients occur along the basin margin from Groote Eylandt to Cape Wessel and in association with a submerged linear feature which trends east-west south of the island Pulau Dolak (see Fig. 1.3 for locations of features; Jones and Torgersen, 1988). In the northeast, a broad, low-relief terrace 40-45 m deep extends from Torres Strait into the Gulf (Harris et al., 2004a). A broad ridge of up to 13 m relief trends ENE-WSW and terminates at the Arafura Sill with a sill depth of 53 m. The Arafura Sill covers an area of >10,000 km^2 of the shelf (Fig. 1.4; Table 3.1) with a relief of <2 m (Torgersen et al., 1983). The sill would have formed the northwest drainage boundary of the gulf during periods of lower sea level (see below).

In the south, the seabed topography is more variable and contains a number of small, rounded pinnacles and several broad, flat-topped platforms (Fig. 3.3). The total area of the pinnacles and platforms (called plateaus by Harris et al., 2004a) is 5,328 km^2 or >1.28% (Table 3.1).

Table 3.1. Geomorphic units of the Gulf of Carpentaria region (from Harris et al., 2004a).

Geomorphic Unit Type	Area (km^2)	Percent
Shelf*	178,113	42.94
Bank/shoal	2,102	0.51
Deep/hole/valley	1,322	0.32
Basin	206,953	49.89
Reef	141	0.03
Canyon	45	0.01
Ridge	599	0.14
Pinnacle	250	0.06
Plateau	5,078	1.22
Saddle	501	0.13
Sill	10,988	2.65
Terrace	7,435	1.79
Sandwave/sand bank	1,233	0.31
Total	414,760	100.00

* Shelf area is less the surface areas of superimposed features.

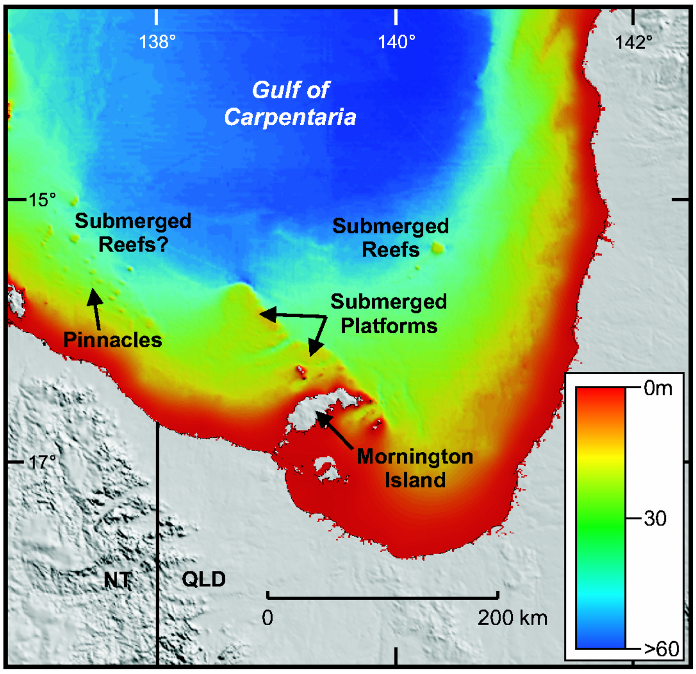

Figure 3.3. False-colour image showing the bathymetry and gross geomorphology of the southern Gulf. Three of the broad, flat-topped platforms are submerged patch coral reefs. Other reefs may also exist in the southern Gulf.

They are probably the high points of submerged continental rocks, protruding through nearshore and pelagic sediments on the seabed. The platforms are bounded to the northeast by steep slopes that strike northwest and form escarpments, and are separated from each other by shallow submarine valleys (Harris et al., 2004a). Platforms northwest of Mornington Island (Fig. 3.3) appear to be the surface expression of submerged continental rocks.

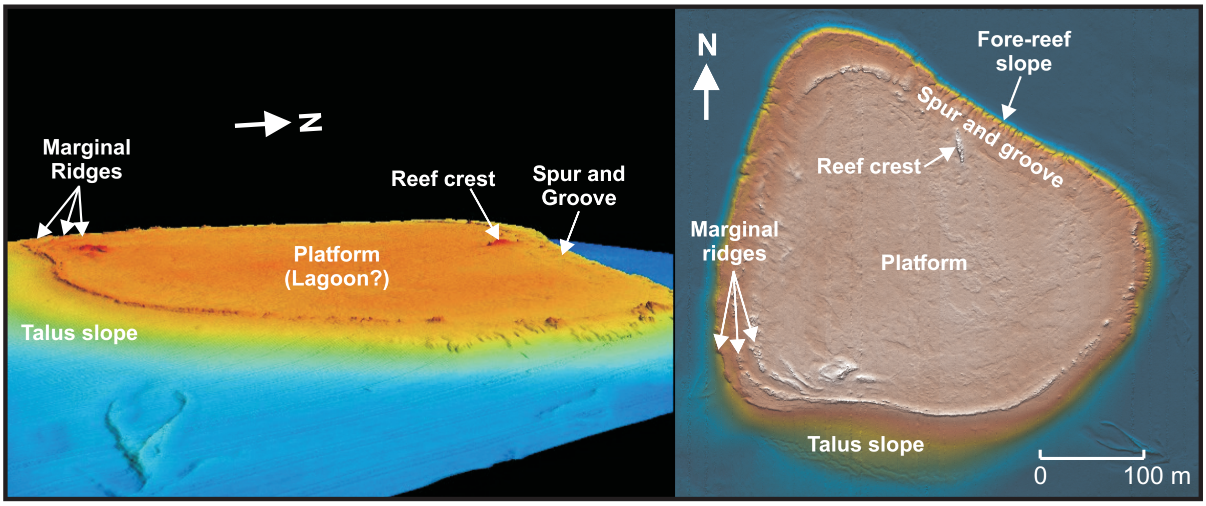

Figure 3.4. False-colour images showing the morphology and bathymetry of the largest patch reef discovered in the southern Gulf. All the reefs mapped exhibit classic patch reef morphology.

The total area of reefs in the Gulf has been reported as 141 km² (Table 3.1; Harris et al., 2004b). In May-June 2003, a Geoscience Australia survey to the southern Gulf (Heap et al., in press) discovered that three of the flat-topped platforms located there were submerged patch coral reefs (Fig. 3.4). These reefs are located in about 30 m water depth and cover a total area of >80 km², with the largest being 72 km². They all exhibit classic patch reef morphology, including steep fore-reef slopes on their northern margins, broad flat-topped platforms (former lagoons), marginal ridges, and a talus slope on their southern margins. The marginal ridges indicate that each reef has undergone several periods of reef growth, with each successive ridge representing a new phase of lateral reef development.

Shallow seismic profiles (Fig. 3.5) reveal that the reefs are all located on basement highs and comprise between 10-15 m of carbonate, which is similar in thickness to the Holocene portion of the coral platforms of the Great Barrier Reef. However, the reefs in the Gulf are mostly older framework limestone and support only a thin veneer of Holocene coral dominated by the plate coral *Turbinaria* spp. Local single-beam bathymetry indicates that the surfaces of other pinnacles and platforms in the southern Gulf are at similar elevations and have similar expression as the known reefs (Fig. 3.3). Submerged coral reefs may be much more extensive in the Gulf of Carpentaria than previously thought (Harris et al., 2004b). They are likely to be absent in the river-influenced coastal waters due to their inability to compete with fleshy algae and seagrasses for habitat.

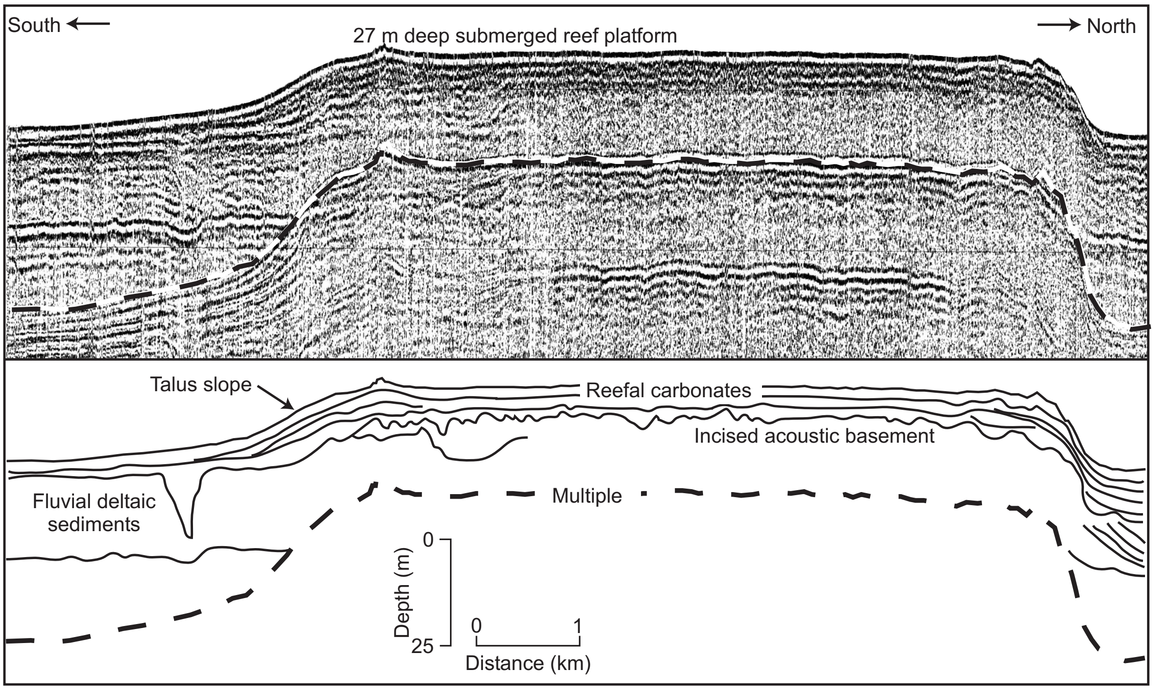

Figure 3.5. Shallow seismic profiles showing the internal stratigraphy of the patch reefs. Distinct internal reflections indicate that the reefs are located on basement highs and comprise between 10-15 m of Holocene carbonate that has accumulated over several sea level cycles.

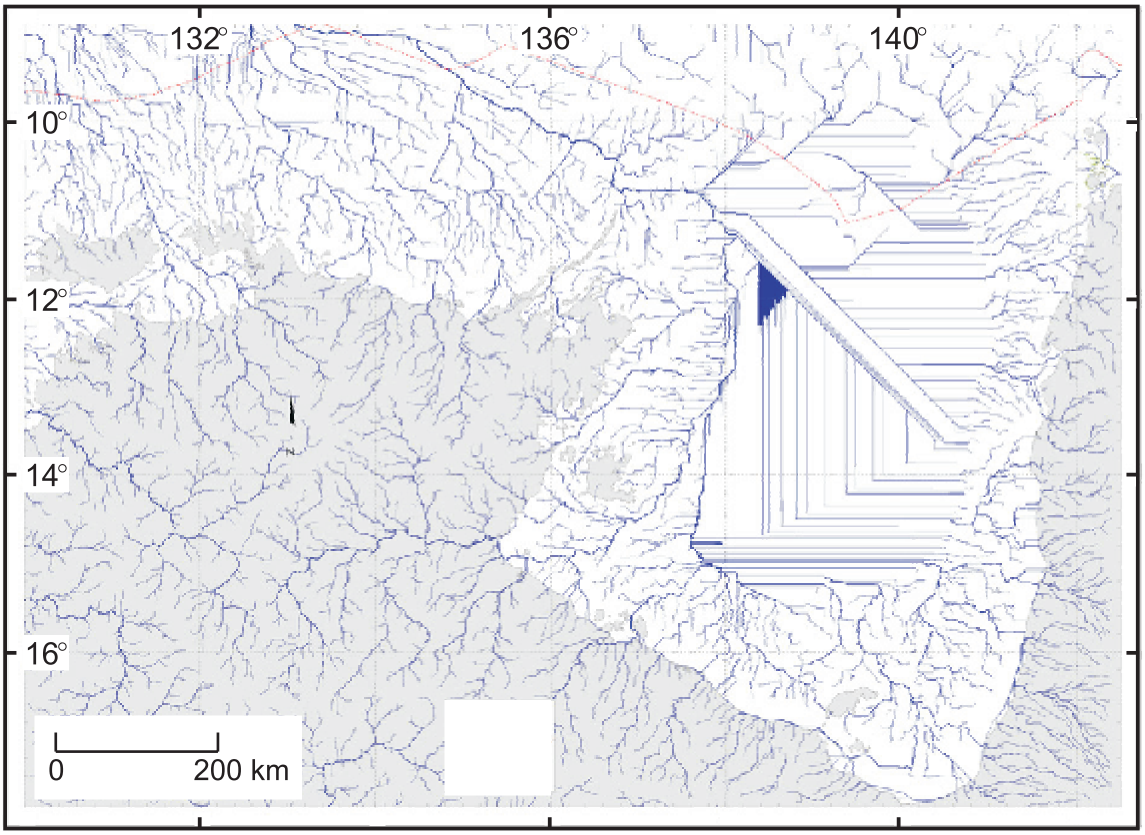

Figure 3.6. Map showing the results of a drainage analysis for the Gulf of Carpentaria. Fluvial channels drain into the basin (delimited by the straight lines) and exit to the northwest to the Arafura Sea via the Arafura Sill. The transport of fluvial sediment through the gulf was probably negligible due to the flat gradient of the exposed plain.

Offshore-trending shelf channels up to several hundred metres wide and several tens of metres deep filled with late-Quaternary sediments occur in water depths of about 30 m in the southeastern Gulf (Jones, 1986). These channels, which regularly have surface expression, appear to be the continuation of onshore drainage features that were presumably more active during periods of lower sea level. Shallow seismic and swath bathymetry profiles (Heap et al., in press) indicate that modern coastal streams from the Albert River to Spring Creek (see Fig. 1.3 for locations) converged into a single channel during the last period of subaerial exposure. A drainage analysis algorithm applied to the most recent bathymetry model for the Gulf (Fig. 3.6; Harris et al., 2004a) shows these channels draining into the basin (delimited by the straight lines) and exiting to the northwest to the Arafura Sea via the Arafura Sill.

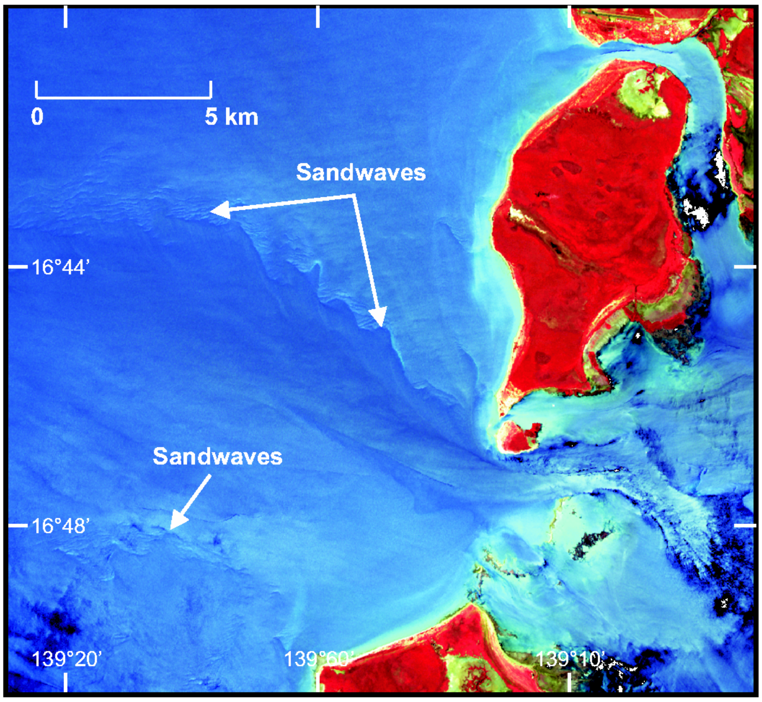

Figure 3.7. Satellite image of well-developed sandbanks west of Mornington Island, southern Gulf of Carpentaria. The sandbanks are fashioned by tidal currents that are locally accelerated between the islands. Vegetation is artificially coloured red in this image.

In the southern Gulf, high-resolution multibeam and shallow seismic surveys have revealed the widespread existence of more subtle features such as fields of subaqueous dunes, palaeo-shorelines, hard-grounds, comet marks, and possible palaeo-beach ridges. Tidal sand banks and subaqueous dunes with wavelengths of between 80 and 200 m occur in water depths of 15 to 20 m over a wide area north of Groote Eylandt (Harris et al., 1991). Well-developed sand banks are also present west of Mornington Island (Fig. 3.7), and at the entrances of harbours, estuaries and rivers. They are relatively abundant in the Gulf and cover a total area of 1,233 km^2 (Table 3.1; Harris et al., 2004a). East of Mornington Island are widespread hard grounds characterised by eroded tidal channels, a bryomol (bryozoan/molluscs) reef, and numerous comet marks, which are indicative of high-energy sediment transport around bathymetric highs (Heap et al., in press). Multibeam sonar mapping of the area indicates that the surface of the bryomol platform is located at 30 m water depth. It is heavily pock-marked with bowl-shaped depressions up to 500 m in diameter that are probably relict "blue-holes" (sink holes) (Fig. 3.8). The comet marks form unusual crescent-shaped patterns and indicate that the sediment on the seabed in this region moves northwards. Their curved forms imply that they probably formed from fluvial erosion when the region was subaerially exposed rather than by tidal scour or sediment deposition after the basin was submerged. Palaeo-shoreline features have been reported from around the margins of the basin, recognised from erosional unconformities of regional extent in shallow seismic profiles (Edgar et al., 1994; 2003). Prominent shorelines are located at 19, 29, and 65 m water depth (Torgersen et al., 1983).

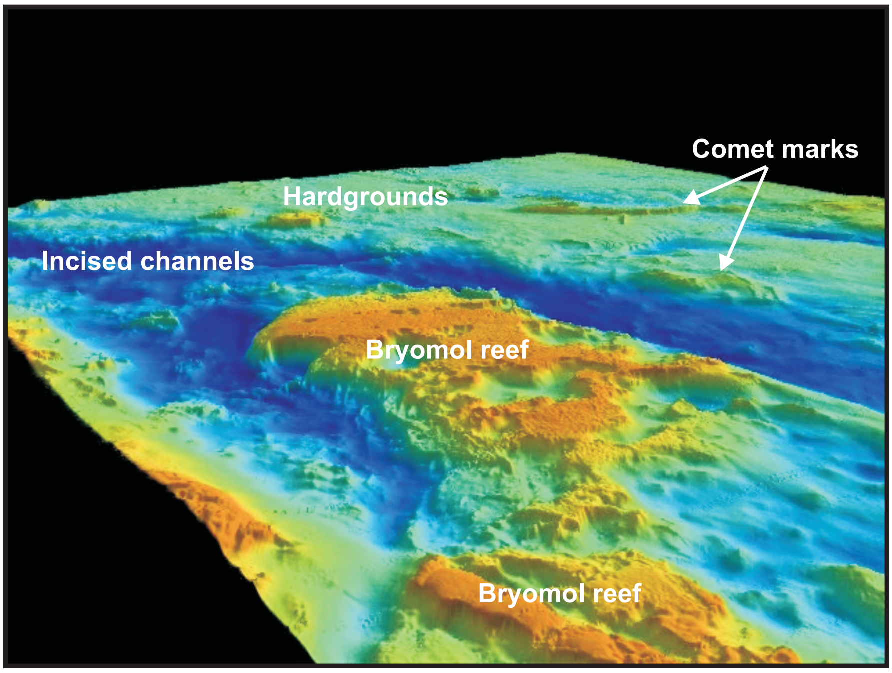

Figure 3.8. False-colour image showing the gross geomorphology and bathymetry of the seabed east of Mornington Island. The seabed is characterised by widespread hard grounds containing eroded tidal channels, a bryomol reef (centre-ground), and numerous comet marks, which are indicative of high-energy sediment transport around bathymetric highs on the seabed.

3.3. Oceanography

In summer, during the monsoon, differences between bottom and surface water temperatures can be as much as 5°C (Rochford, 1966). A numerical model indicates that during this time wind-driven circulation results in a clockwise gyre in the Gulf, and tracking of drogue-buoys confirms that current speeds of up to 0.08 m s^{-1} occur in the gyre (Church and Forbes, 1981; 1983). Evaporation, runoff, precipitation, wind and tidal mixing are considered important as water exchanges with the Arafura Sea in explaining the broad scale physical properties of water masses in the Gulf of Carpentaria (Forbes and Church, 1983; Forbes, 1984). Water flows through Torres Strait are negligible (Wolanski et al. 1988) and mixing with Coral Sea waters located in the east is probably not a significant factor in determining the overall physical characteristics of Gulf water.

In winter, during the trade winds, tidal and wind mixing result in homogeneous, non-stratified conditions in much of the Gulf shallower than about 20 m. Furthermore, water masses in regions where the ratio of water depth to tidal current speed cubed is greater than 100 will be well mixed (Wolanski et al., 1988). Coastal waters are confined to the southeast corner by a strong clockwise residual current (Wolanski, 1993). This current also brings in central Gulf surface water, which may be responsible for transporting coral larvae from Torres Strait (Veron, 1993) to seed the modern coral communities recently discovered in the south.

A numerical tidal model indicates that the M_2 amphidromic points are located near Groote Eylandt and Mornington Island (Church and Forbes, 1981). This is contrary to the original prediction of Easton (1970), who located them in the north. The model predicts also that the amplitude of the M_2, K_1 and O_1 tidal constituents are similar in magnitude, so that tides in the Gulf vary from mixed-semidiurnal in the north to mainly diurnal in the south. Tidal ranges throughout the whole Gulf are mesotidal (2-4 m; Davies 1964). Current meter observations near Groote Eylandt indicate that tidal currents attain 0.75 m s^{-1} (Church and Forbes, 1981). Evidence for strong tidal currents in the southern Gulf of Carpentaria consists of large areas covered by subaqueous sand dunes and sand banks, and widespread hard-grounds.

Modelling of tides and waves indicates that tidal velocities at the bed attain 0.6 m s^{-1} in the central and southeast regions and are less in the central south (Fig. 3.9). The pattern of maximum annual wave energy in Figure 3.9 was distorted due to the strong influence of tropical cyclones. For example, Cyclone Steve, produced wave powers of >10,000 W m^{-2}, but away from the cyclone maximum annual wave energies are <3,000 W m^{-2} (Fig. 3.10). Tides and waves cause mobilisation of bed sediment in approximately equal areas in the Gulf, with tides more dominant in the deeper regions and waves more dominant in the shallower coastal regions (Fig. 3.11). The distribution is complicated around islands, where tidal currents are locally accelerated. A large zone of zero mobility occurs in the west.

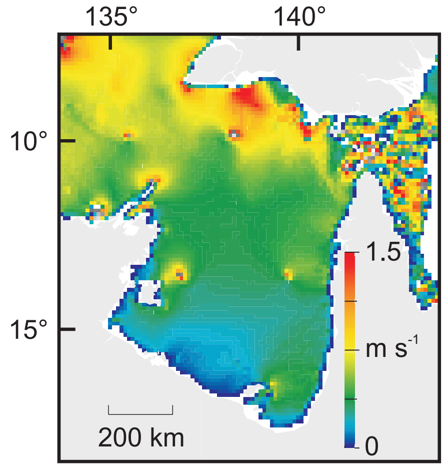

Figure 3.9. Map showing the distribution of tidal velocities. Tidal velocities at the bed attain 0.6 m s^{-1} in the central and southeast regions and are reduced in the central south.

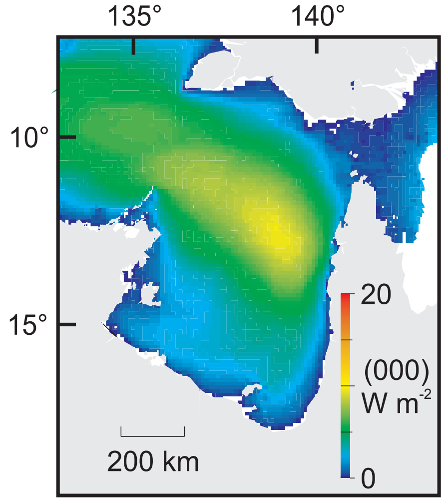

Figure 3.10. Map showing the distribution of wave energy at the bed. Maximum annual wave energy in the gulf is distorted here due to the influence of tropical cyclone Steve. Wave energy away from the influence of cyclone Steve is <3,000 W m^{-2}.

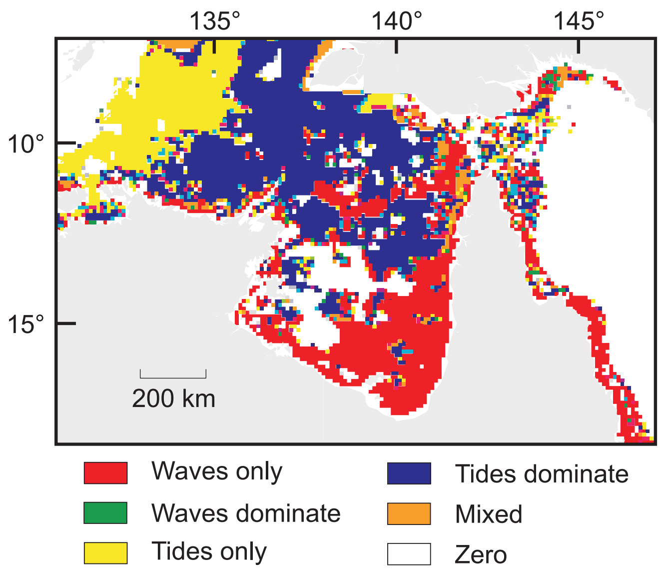

Figure 3.11. Map showing the distribution of sediment mobility on the bed. The overall distribution is characterised by roughly equal areas for tides and waves. The pattern is complicated around islands and a large area of the Gulf is characterised by zero mobility.

The entire Gulf of Carpentaria region is affected by tropical cyclones that, as shown in the models above, locally generate very strong shelf currents that are capable of significant geomorphic alteration. The frequency of cyclones in the Gulf of Carpentaria is high to moderate, relative to other parts of northern Australia. Cyclones are most common near Karumba in the southeast (Fig. 1.3), where one cyclone will cross a 100 km section of the coastline every 10 years (Lourensz, 1981). In February 1979, during the passage of tropical cyclone Rosa, wind speeds of up to 130 km hr^{-1} were recorded up to 100 km from the centre (Church and Forbes, 1983). Current meter observations in the southern Gulf gave 1-hr averages of wind-driven currents measured 5 m above the bed of up to 0.25 m s^{-1}. Instantaneous velocities would have been much greater. Sand sized and finer grains would have been resuspended across the entire sea bed over a distance of 50 to 100 km from the centre of the cyclone. Associated with tropical cyclones, storm surges up to 10 m in height have been reported (Easton, 1970). Although no published data exist on the effects of these storm surges, they certainly would generate very strong near-bed currents capable of eroding and transporting vast amounts of bed sediment possibly to a depth of several tens of centimetres (cf., Gagan et al., 1988; Larcombe and Carter, in press).

3.4. Surface Sediments

The surface sediments of the Gulf of Carpentaria have been studied in detail by a number of workers (e.g., Phipps, 1970; 1980; Jones, 1986; 1987; Jones and Torgersen, 1988; Harris, 1994a) and the distribution of sediment facies is reasonably well established (Fig. 3.12). Over much of the central Gulf of Carpentaria the marine sediments are <1 m thick and overlie weathered lacustrine deposits (Torgersen et al., 1985).

The surface sediments can be broadly divided into two distinct zones that trend generally parallel with the coast: 1) a nearshore zone (<20 m) of active sedimentation; and 2) an offshore zone of comparatively low sedimentation comprising the remainder of the flat floor. At a finer scale, the nearshore zone consists of two sandy nearshore facies characterised by relatively high to moderate sedimentation rates, and the deeper water zone consists of several muddy sand and sandy mud facies characterised by relatively low sedimentation rates (Fig. 3.13; Jones, 1987). Large areas of the nearshore zone are also characterised by relict sediments of diverse origins with one or more of the following: 1) poorly sorted, stained and fractured quartz; 2) ferruginous or calcareous pisoliths; 3) ooids; and 4) abraded, yellow-brown stained foraminifera (Jones, 1987). The deep water facies are largely made up of poorly-sorted mixtures of relict greenish terrigenous mud and locally derived carbonate sand.

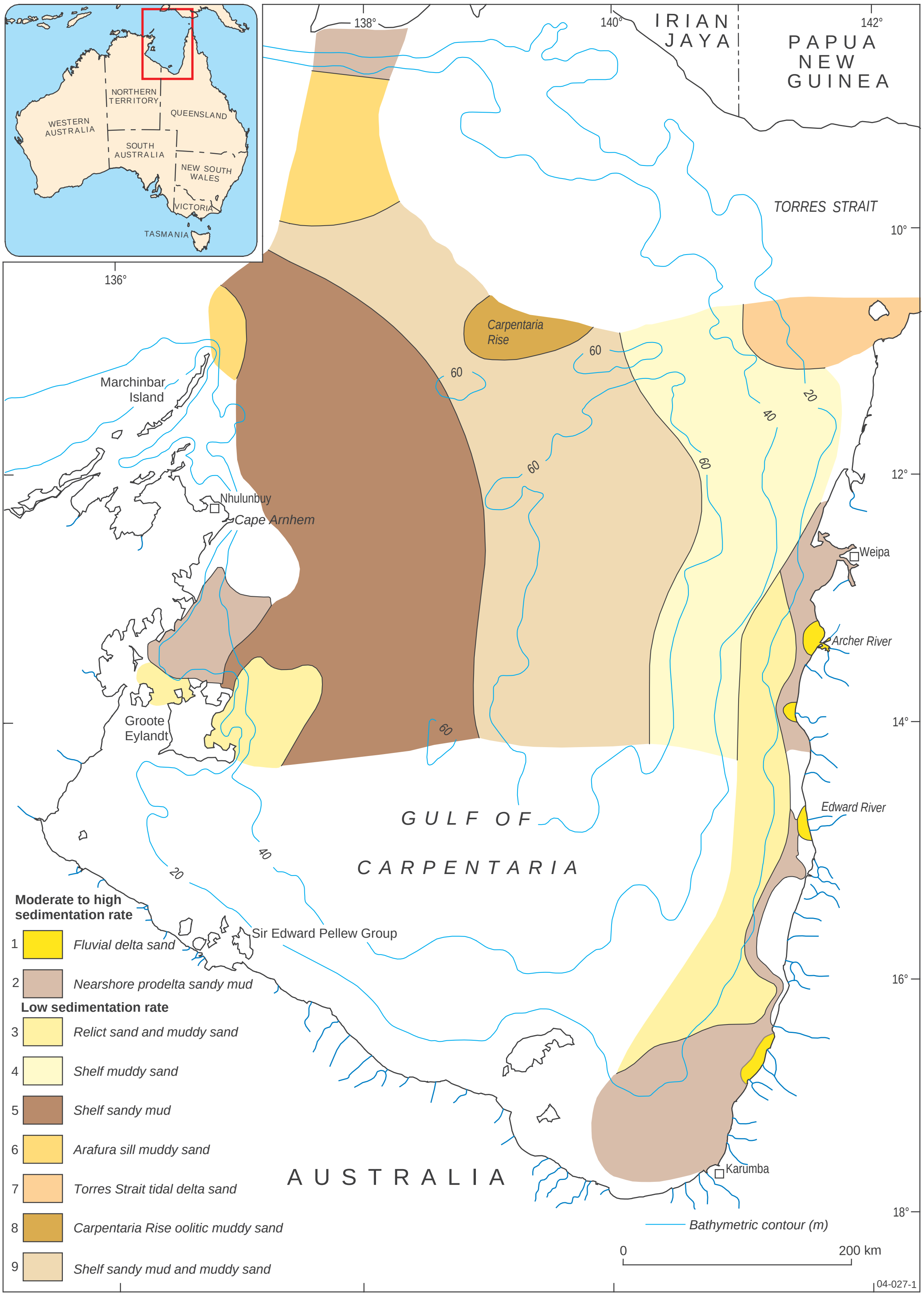

Figure 3.12. Map showing the distribution of surface sediment facies (redrawn from Jones, 1987). The sediment can be divided into facies that characterise a nearshore zone (<20 m) of active sedimentation and an offshore zone of comparatively low sedimentation.

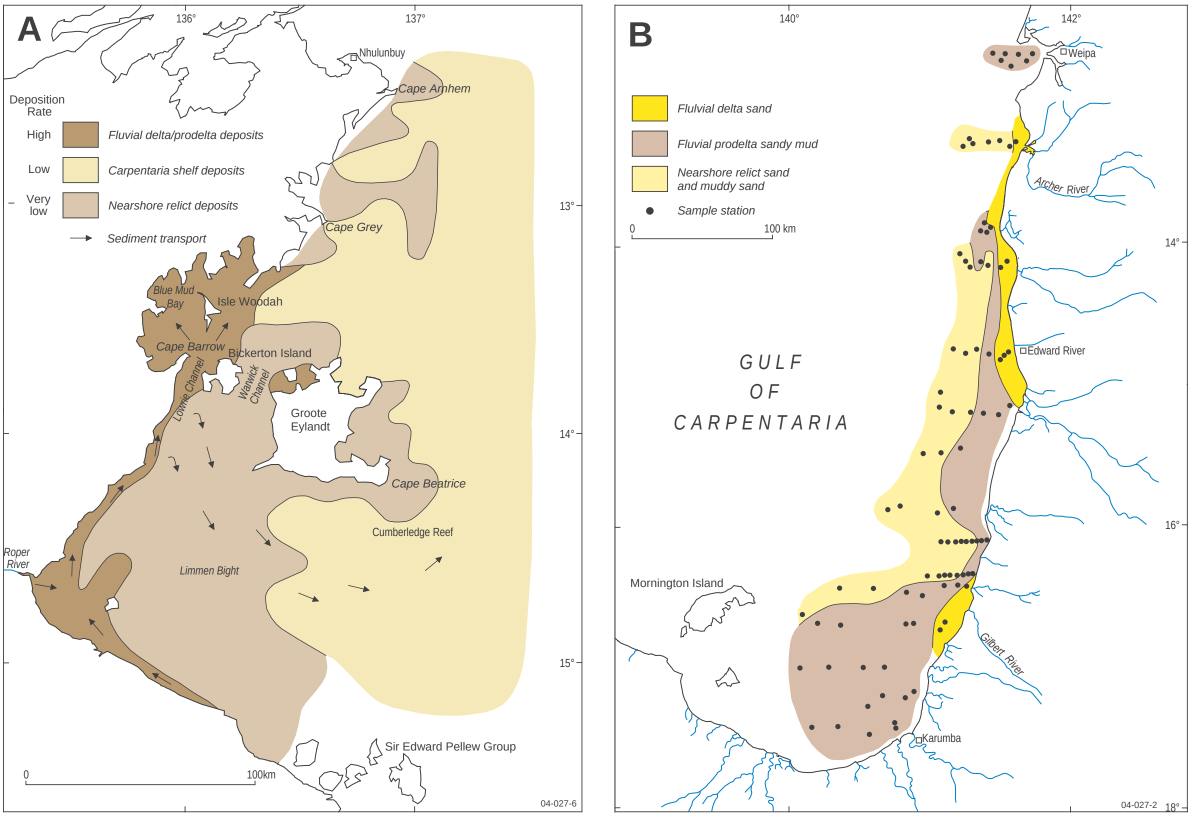

Figure 3.13. A) & B) Maps showing the nature of surface sediment in the nearshore zone (redrawn from Jones, 1986, 1987). Two sandy nearshore facies with relatively high to moderate sedimentation rates occur in shallow water and muddy sand and sandy mud facies with relatively low sedimentation rates occur in deeper water.

Ooids are widespread on the Gulf floor (Fig. 3.14). For example, a large belt of oolitic sand occurs on the Carpentaria Rise in the west (see Fig. 1.3 for location; Jones and Torgersen, 1988). Away from the Carpentaria Rise, ooids are less common and their distribution has not been fully ascertained. Where sampled, they usually occur as individual grains but sometimes as aggregates (Jones and Torgersen, 1988). The distribution of ooids provides clues to the location of previous shorelines, and although they are widespread in the sediments they are not known to be forming at present. Ooids form in relatively shallow water (typically <5 m; Ginsberg and James 1974). In the Gulf of Carpentaria, they have been sampled in sediments from water depths of between 25 and 60 m, indicating that they formed probably during periods of lower sea level. Radiocarbon ages of between 15,500 and 8,600 years BP from the ooids place their formation during the last post-glacial transgression (Jones, 1987). Pisoliths (Jones, 1987), formed by the erosion and reworking of pedogenic limestone concretions, are also common and formed during lowstand and transgression. Less abundant components of the offshore facies include kaolinite and illite clays, fine-grained quartz grains, and a variety of benthic foraminifera tests.

The nearshore facies are mainly deltaic sands and muds (Fig. 3.15). The distribution of these sediments is linked mainly to present-day processes, and they are modern terrigenous

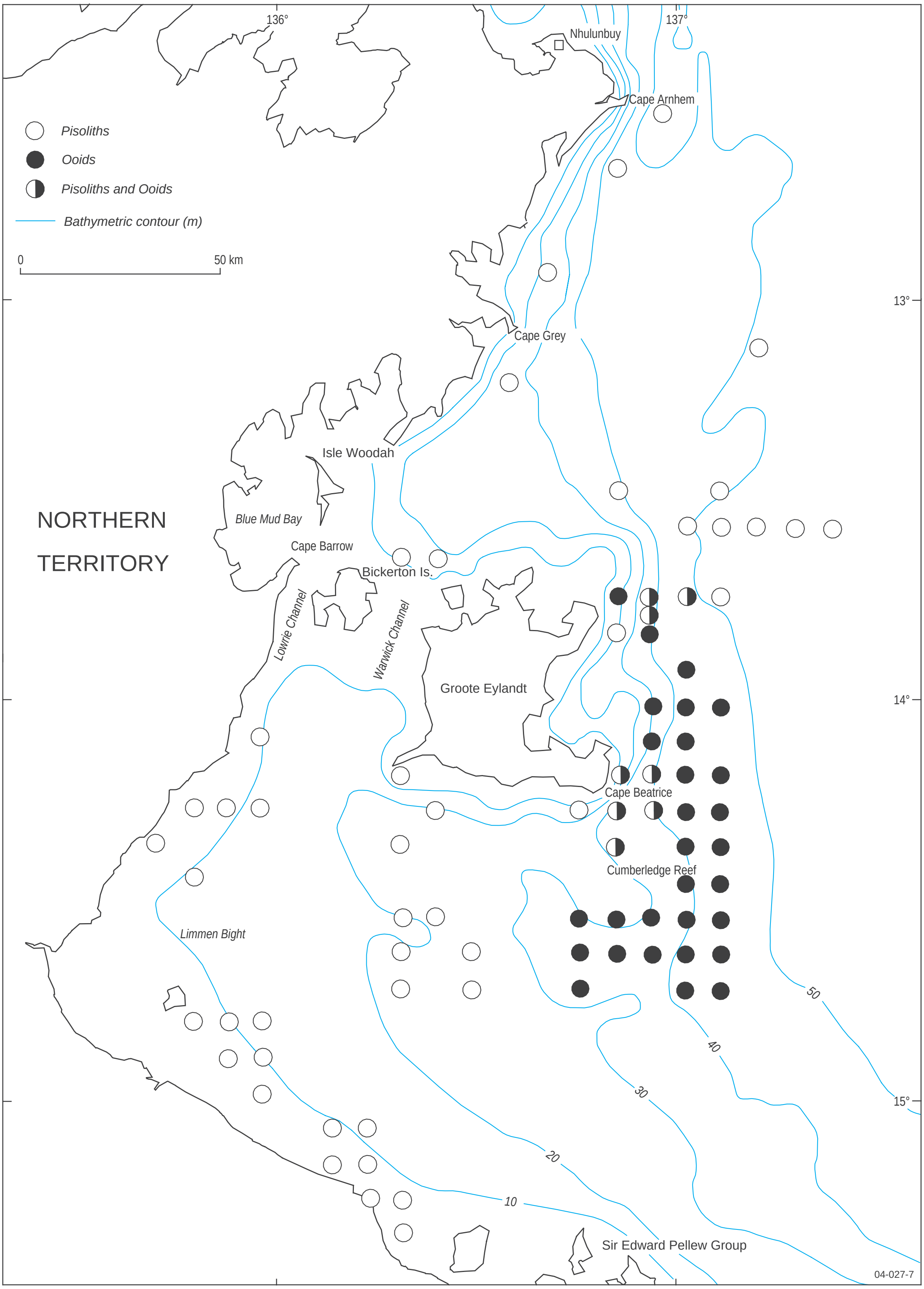

Figure 3.14. Map showing the distribution of ooids and pisoliths (redrawn from Jones, 1987). Ooids are abundant in the west and are less prominent in the central Gulf of Carpentaria. Their distribution has not been fully ascertained.

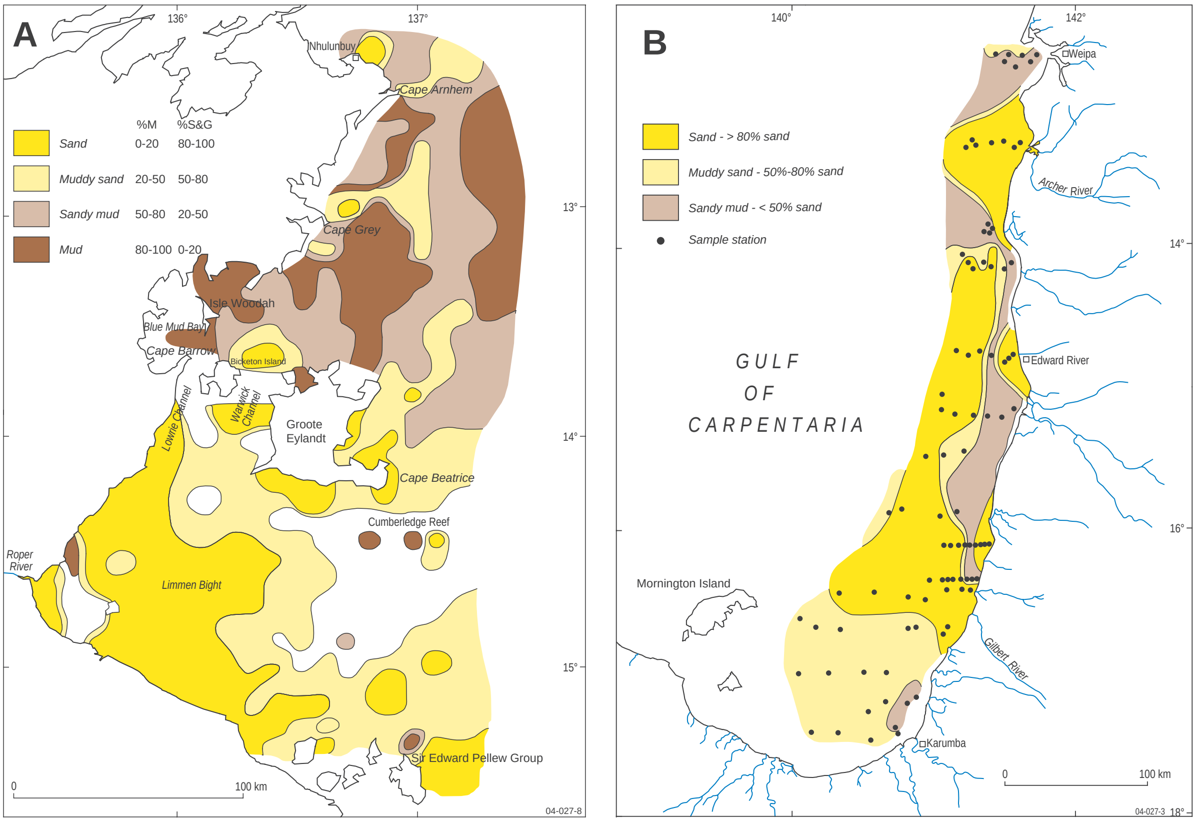

Figure 3.15. A) & B) Maps showing the concentration of mud in surface sediments (redrawn from Jones, 1986, 1987). High concentrations are indicative of terrigenous input. The overall distribution of mud is linked mainly to present-day processes.

sediments mixed in varying degrees with the relict siliciclastic and modern carbonate sediments on the seabed. However, on the inner shelf the sandy nearshore facies have not been supplied by modern-day rivers during the present sea level highstand (cf., Jones et al., 2003) and were most likely deposited during lower sea level periods. Jones (1987) postulated that the sands represented extensions of the large onshore alluvial fans, which have been concealed by prodelta sediments in very shallow waters. Around most of the west coast of the Gulf, the concentration of mud increases from <20% to >80% with increasing water depth and distance from the shore (Fig. 3.15).

Around the islands, including Groote Eylandt and Sir Edward Pellow Group (Fig. 1.3), the surface sediments are 80-100% sand. These sands have been locally fashioned by strong tidal currents into fields of large subaqueous sinuous-crested dunes (Fig. 3.7). Prominent examples are located in Endeavour Strait (west of Torres Strait) and south of Mornington Island (the "Mornington Island tidal delta" of Phipps, 1980). In the Limmen Bight region, the sediments are typically fine to very-fine sand gains. Further west, coastal sediments contain higher mud concentrations and large regions of the seabed, such as north of Groote Eylandt and Blue Mud Bay, are silty clay and sandy clay (Sommers, 1987).

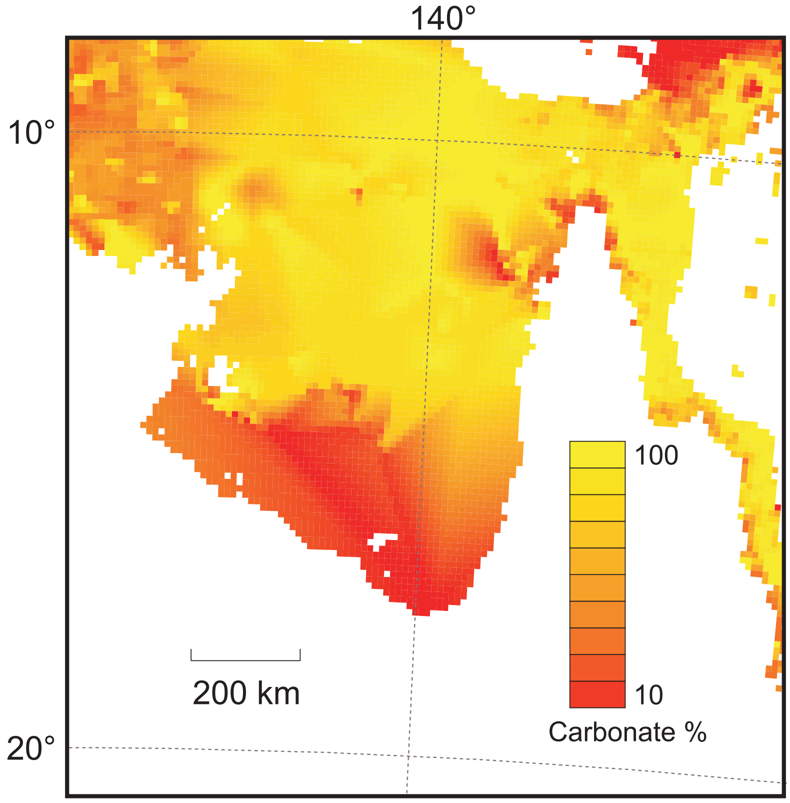

Figure 3.16. Map showing concentrations of calcium carbonate in surface sediments. The southern Gulf of Carpentaria is Australia's largest shelf province of terrigenous-dominated sediment and covers an area of >100,000 km^2.

The high concentration of terrigenous mud in the inner-shelf sediments means that the southern Gulf of Carpentaria is Australia's largest shelf province of terrigenous-dominated sediment (Fig. 3.16). This region covers an area of >100,000 km^2 where surface sediments have an average terrigenous content exceeding 50% (Harris et al., 2004a). The adjacent coastline is characterised by prograding deltas and chenier plains, indicative of considerable sediment discharge to the coast throughout the Holocene (Jones et al., 2003). Accordingly, the texture of the nearshore sediments varies greatly depending on local catchment influences. A substantial amount of terrigenous sediment accumulates in the coastal zone, principally in large prograding deltas at the mouths of the major rivers: including the McArthur, Leichhardt, Flinders, Norman and Gilbert Rivers (see Fig. 1.3 for locations; Jones et al., 2003). Because the discharge of these rivers is very great during the summer monsoon, fluvially-derived sediments contribute a major part of the modern sediment budget.

The distribution of foraminifers has had little systematic study, and our understanding of the mechanisms contributing to the observed distributions is far from satisfactory. Foraminiferal studies are limited to central and northern regions above 14ºS and, in most cases, have focused on the temporal variability of the fauna rather than its spatial distribution (e.g., Torgersen et al., 1985; 1988; Chivas et al., 2001). Interestingly, many foraminifera tests (particularly *Ammonia beccarii*) contain glauconite and might be connected with the glauconite sands common in the eastern Arafura Sea (Phipps, 1980).

Shallow cores recovered from the central and deepest regions of the Gulf (Chivas et al., 2001) indicate that the sediments contain (in decreasing abundance): reworked marine (euryhaline) benthnic foraminifera, molluscs, bryozoans and ostracods. Most abundant are the benthic foraminifera *Pseudorotalia inflata*, *Heterolepa subhaidingeri*, *Neoeponides schreibersi*, *Ammonia beccarii*, *A. convexa*, *Quinqueloculina philippinensis* and *Textularia agglutinans* (Chivas et al., 2001). Sediments in core tops are indicative of an open marine, shallow-water environment and contained the planktonic foraminifera *Gallitellia vivans*. This foraminifera is a small (<125 μm) triserial Neogene form well-represented in tropical environments, and is particularly abundant in high-nutrient waters and marginal basins (Kroon and Nederbragt, 1990). Interestingly, the modern sediments and overlying waters contain a very specific group of foraminifers dominated by *Elphidium striatopunctatum*, *Parrellina hispidula* and *E. carpentariensis* (Abani and Yassini, 1993), but their distribution is based on only four samples taken in water depths of <11 m.

Classification of echo-types could not be undertaken in the Gulf of Carpentaria because shallow seismic survey profiles were not available for interpretation. It is likely, given the extremely flat floor and relatively uniform sediment distribution, that the echo-types would be relatively consistent. Geoscience Australia has recently collected over 3,000 line-km of shallow Chirp seismic profiles in the southern Gulf and is in the process of classifying the sediment facies (Heap et al., in press).

Seagrass beds are well developed in depths of <20 m (Fig. 3.17). While their overall distribution remains uncertain, seagrasses cover >900 km^2 and border more than 670 km of open coastline (Poiner et al., 1987). The largest patches occur along the western and southern margins, with few beds found on the southeast and eastern margins apart from very small stands at the mouths of estuaries. Intertidal and subtidal species occur in all of the areas mapped and their abundance is strongly depth-related. The seagrass community is relatively diverse compared with Torres Strait and Arafura Sea; the most abundant species are *Syringodium isoetifolium*, *Cymodocea serrulata*, *Halodule uninervis*, *Halophila ovalis* and *Halophila spinulosa* (Poiner et al., 1987). It is speculated that the seagrass beds flourish in the Gulf of Carpentaria because they are regularly nourished by outwelling of nutrients and saline waters from the large coastal salt flats during the wet-season (Ridd et al., 1988).

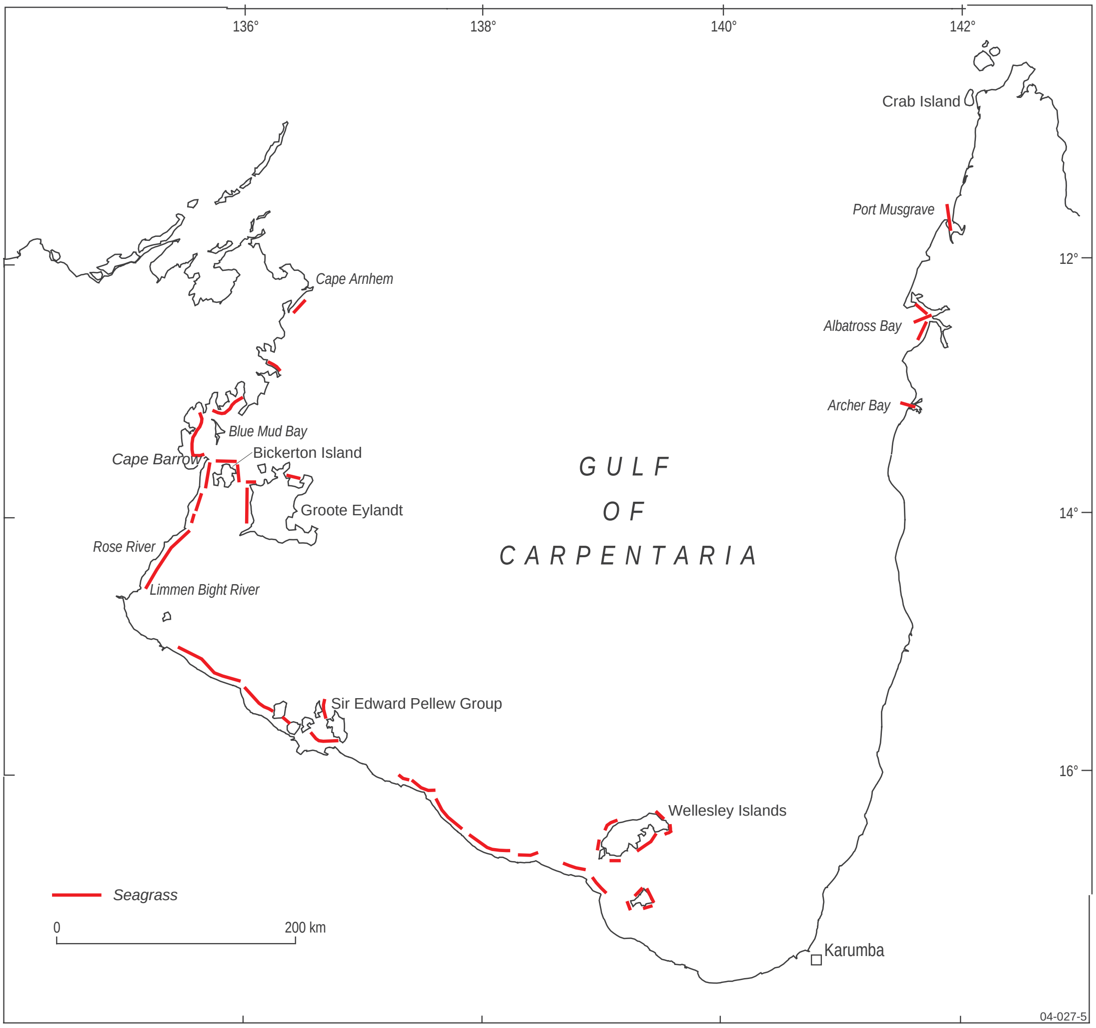

Figure 3.17. Map showing the distribution of seagrass (redrawn from Poiner et al., 1987). The seagrasses cover an area of >900 km^2 and border >670 km of open coastline and are dominated by intertidal and subtidal species whose abundance shows a direct relationship with water depth.

3.5. Late Quaternary Evolution

The available geologic and geophysical evidence indicates that the Gulf of Carpentaria has been subjected to erosional and depositional processes in fluvial, lacustrine and marine environments at various temporal/spatial scales throughout the late Quaternary.

Inter-bedded marine, coastal and lacustrine deposits have been recovered to a depth of 14 mbsf in shallow cores from the central Gulf floor (e.g., Phipps, 1980; Jones and Torgersen, 1988; Torgersen et al., 1985; 1988; Chivas et al., 2001). The sediments cover a time period of about 125,000 years and show that during times of low sea level the basin contained a brackish to freshwater lake (Lake Carpentaria) that was perched above contemporaneous sea level and had an outlet channel over the Arafura Sill (Chivas et al., 2001). At its greatest extent, with a shoreline equating to the -55 m isobath (i.e., the elevation of the sill), Lake Carpentaria would have covered an area of 165,000 km^2 (Fig. 3.18) and attained a maximum

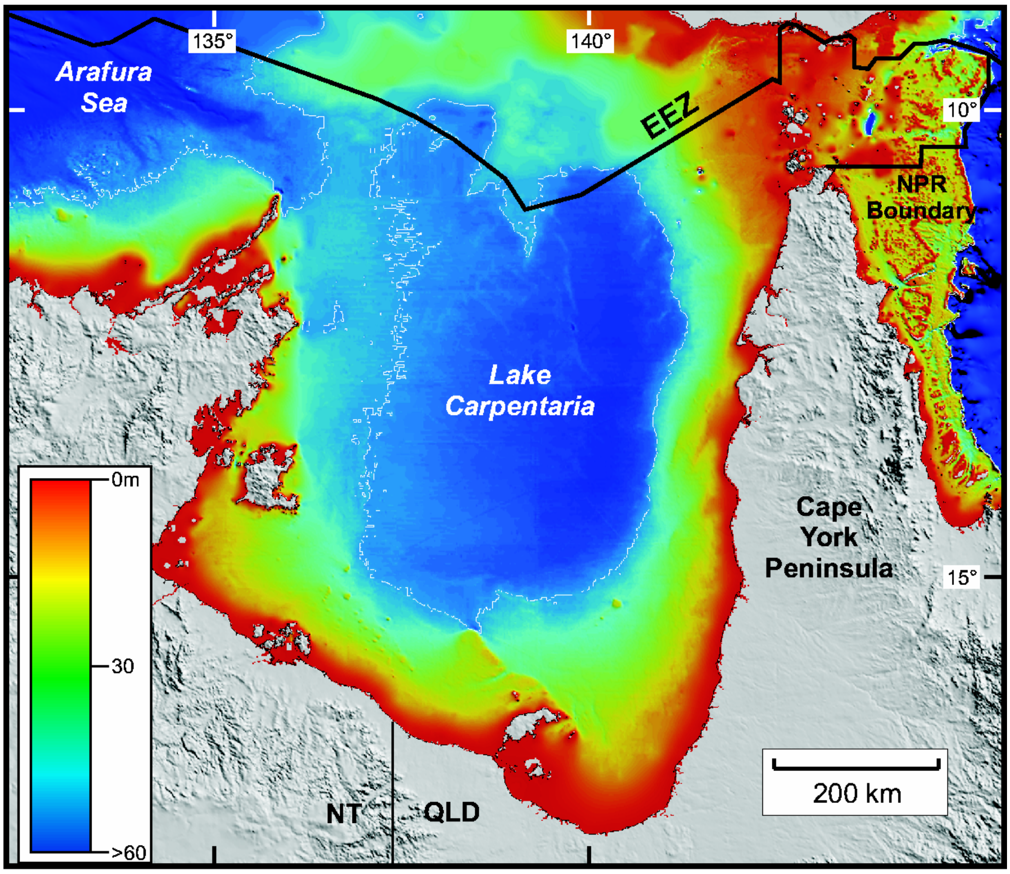

Figure 3.18. False-colour image showing the maximum extent of Lake Carpentaria. At its maximum level the lake would have covered an area of 165,000 km^2 and attained a maximum water depth of >15 m.

water depth of >15 m (Jones and Torgersen, 1988). Laminated lacustrine muds about 1 m thick occur in cores recovered from within the inferred confines of the lake. The lacustrine muds are overlain by a unit of marine sandy mud up to 1 m thick and unconformably overlie subaerially weathered cohesive clay of marine/estuarine origin. Analysis of pollen, assemblages of foraminifers and ostracods, $\delta^{13}C$ values, and C/N ratios of organic matter corroborate the boundaries of the marine/non-marine environments (Chivas et al., 2001). Curiously, the $\delta^{13}C$ and C/N data indicate that the lowstand Gulf plain was covered by C_4 savannah grasslands and not C_3 woodland, mangrove and tropical rainforest vegetation.

The morphology of the newly discovered coral reefs in the south provides insights to the Late Quaternary evolution of the region and the probable development of other reefs in the region. The reefs are distinguished by six prominent reflecting surfaces, two of which (A and B, Fig. 3.19) are recognised as palaeo sea-level indicators (Harris et al., 2004b). These submerged surfaces correspond in depth to regionally significant phases of carbonate deposition during prolonged sea level still-stands at -27 and -30 m (cf., Searle and Harvey, 1982). Several marginal ridges on the reefs indicate multiple phases of lateral reef growth (Fig. 3.4). Corresponding prominent horizontal reflections in shallow seismic

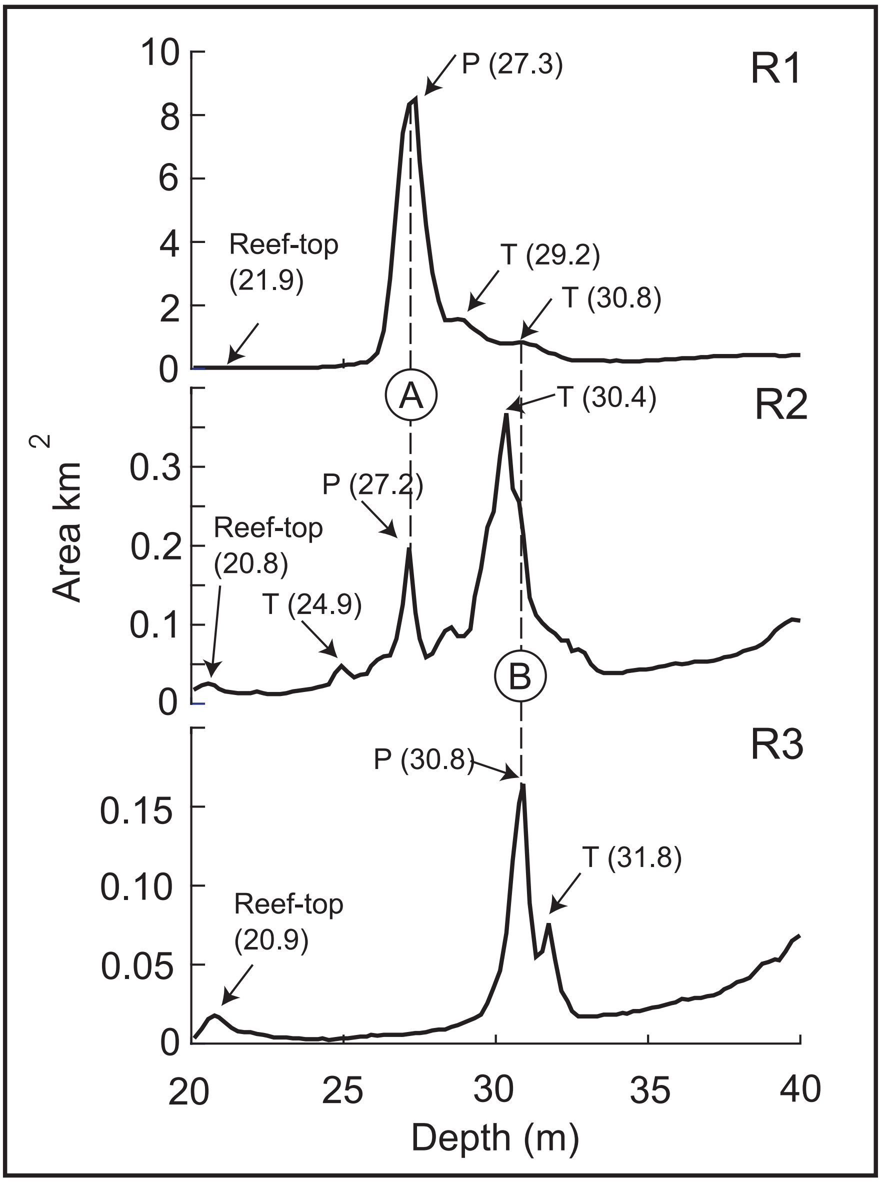

Figure 3.19. Hypsometric curves showing the morphology of the three patch reefs as a function of depth and area (redrawn from Harris et al., 2004b). Two prominent surfaces, A and B, are palaeo sea-level indicators that correspond to regionally significant phases of carbonate deposition in the southern gulf.

profiles suggest that this growth occurred over several sea level cycles (Fig. 3.5). The morphology and depth of the reef surfaces indicate that they formed mainly when sea level was 25-27 m below its present position. In the Late Quaternary, these low sea level periods, turned the Gulf of Carpentaria in to a large marine embayment with only one entrance to the Arafura Sea (Torres Strait was a land bridge) and experienced cooler and drier climatic conditions than at present (Chivas et al., 2001; Kershaw et al., 2001). These conditions were more conducive to reef development. A comparison of the morphology and elevation of the reef surfaces with the regional eustatic sea level curve (Fig. 3.20; Chappell et al., 1996) indicates that they probably developed mostly before the Holocene. The reefs apparently have a similar growth history to corals of the GBR province (e.g., Searle and Harvey, 1982).

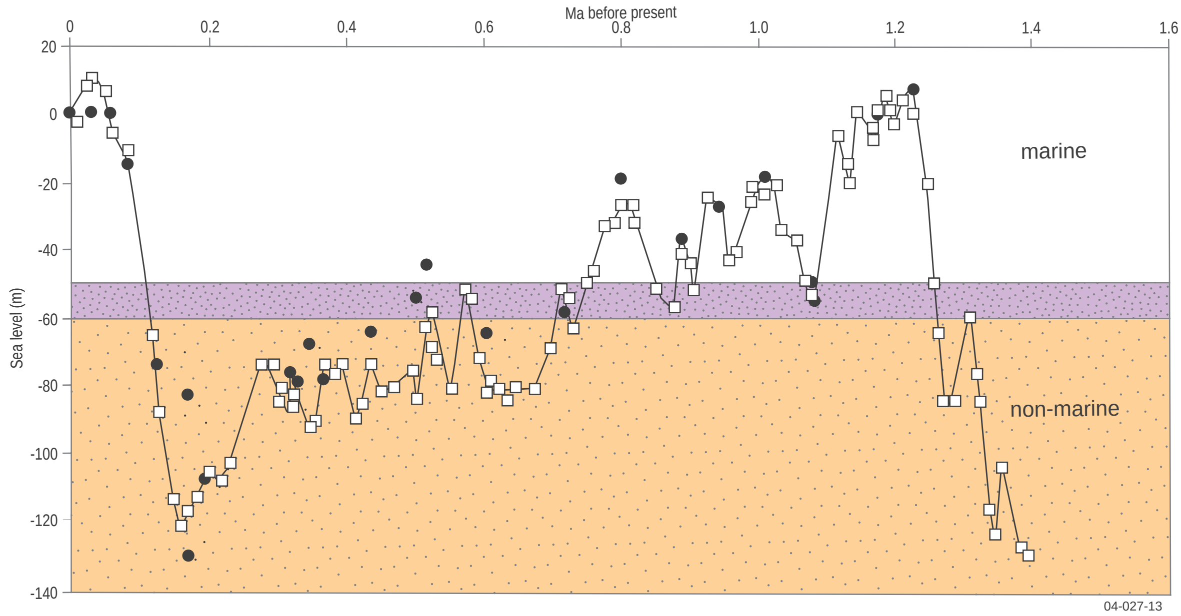

Figure 3.20. Graph showing the late-Quaternary eustatic sea level curve for the region (redrawn from Shackleton, 1987 and Chappell et al., 1996). Comparing the curve with the morphology and elevation of the reefs indicates that conditions were most favourable for reef growth before the Holocene.

Numerous channels that cut into the uppermost 150 m of sediment can be seen in shallow seismic profiles (Chivas et al., 2001; Heap et al., in press[a]). The largest of these channels are >70 m deep and >10 km wide. The channels are widely distributed and point to Late Quaternary periods when large river systems crossed the lowstand plain. However, no major river incision would have occurred around the margins because the onshore and offshore gradients are equivalent (Jones et al., 2003). In the Arafura Sill, incised channels up to 10-15 m deep extend to a maximum of 75 m below present sea level. They were probably formed by fluvial incision during lows in sea level (Jones and Torgersen, 1988). Smaller, deeply-incised channels elsewhere in gulf probably represent tidal channels.

Regional erosional unconformities have been interpreted as palaeo-lake shorelines (Edgar et al., 1994). Some of the unconformities coincide with sequence boundaries that separate the sedimentary units. The seismic evidence (>7,000 line-km in total) indicates that the Late Neogene and Quaternary geologic evolution of the gulf is recorded in a basin-wide sedimentary sequence containing marine/non marine cycles, punctuated by numerous inferred exposure surfaces containing deeply incised channels (Chivas et al., 2001).

The Late Quaternary evolution of the Gulf of Carpentaria can be summarised as follows:

c.125 to c.70 ka BP:—The gulf was submerged and consisted of a shallow epicontinental sea, similar to the present one.

c.70 to c.18 ka BP:—Lowering of eustatic sea level saw part of the gulf become a broad subaerial plain dissected by incising rivers and covered by savannah grasslands. A brackish to freshwater lake varied in extent. Basin sediments were eroded and subaerially weathered with fluctuations in the size of the lake, with implications for the formation of the Arafura Fan. The Carpentaria Basin contained a fully freshwater lake of close to its maximum extent, immediately prior to submergence by the latest marine transgression approximately 9-10 ka BP.

c.9-10 ka BP to present:—Sea level had risen from a lowstand of c.120 m to the level of the Arafura Sill (i.e., -55 m) and sea water began to flood the Gulf, depositing marine sediment and causing extensive environmental changes. The size of the freshwater lake quickly reduced because of the low gradient; small rises in sea level corresponded to large horizontal shoreface excursions into the basin. These environmental changes are confirmed by downcore sediment facies, and foraminifera and ostrocod assemblages, which indicate a rapid transition from fresh to saline conditions approximately 9-10,000 years ago (by contrast the sedimentary evidence indicates a prolonged and gradual transition from saline to fresh conditions associated with the preceding sea level regression) (Chivas et al., 2001). Incised channels were infilled to varying degrees with transgressive and highstand coastal and marine sediments. In the south, submerged reefs were recolonised by corals. Present-day, fully open-marine conditions were established 9-10,000 years ago.

4. Torres Strait

Torres Strait is a shallow seaway located at the northern end of the Great Barrier Reef (GBR) and separates the northern part of Cape York Peninsula (Australia) from Papua New Guinea (Fig. 1.2). Torres Strait contains a discontinuous chain of largely granitic islands in the west, isolated volcanic islands in the east, and scattered coral and higher islands in the centre (Woodroffe et al., 2000). During most of the Late Quaternary Torres Strait was a land bridge that connected the Australian continent with Papua New Guinea.

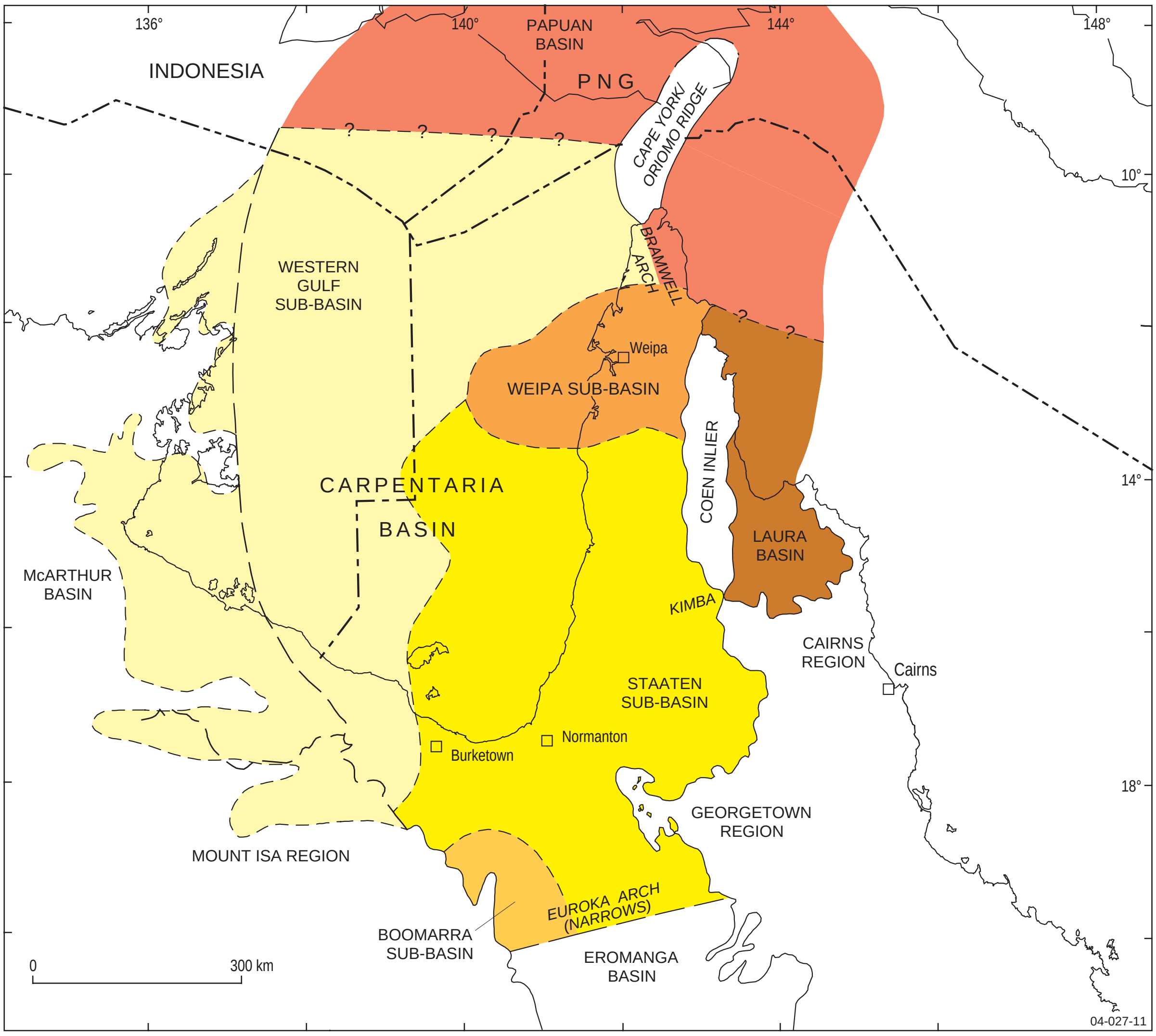

Figure 4.1. Map showing the geologic setting of Torres Strait (redrawn from McConachie et al., 1997). Torres Strait is centred on the edge of an elevated basement ridge, which makes up the Cape York and Oriomo Ridge.

4.1. Tectonic Setting

Torres Strait occupies an extensive area of relatively flat lying rocks which are part of the Carpentaria Basin (Fig. 4.1; McConachie et al., 1997). It is centred on an elevated basement ridge, which makes up the Cape York and Oriomo Ridge. Very little of the underlying structure is evident, and the basement rocks discontinuously crop out across the region. The basement rocks, which are mostly submerged, are made up of Late Carboniferous to Early Permian volcanics and granite intrusions (McConachie et al., 1997). These rocks are capped by a thin veneer of mixed terrigenous/carbonate shelf sediments. The dominant structural features through the Torres Strait region are faults that trend towards the northwest. Younger generation faults also trend NNE (Von Gnielinski et al., 1997).

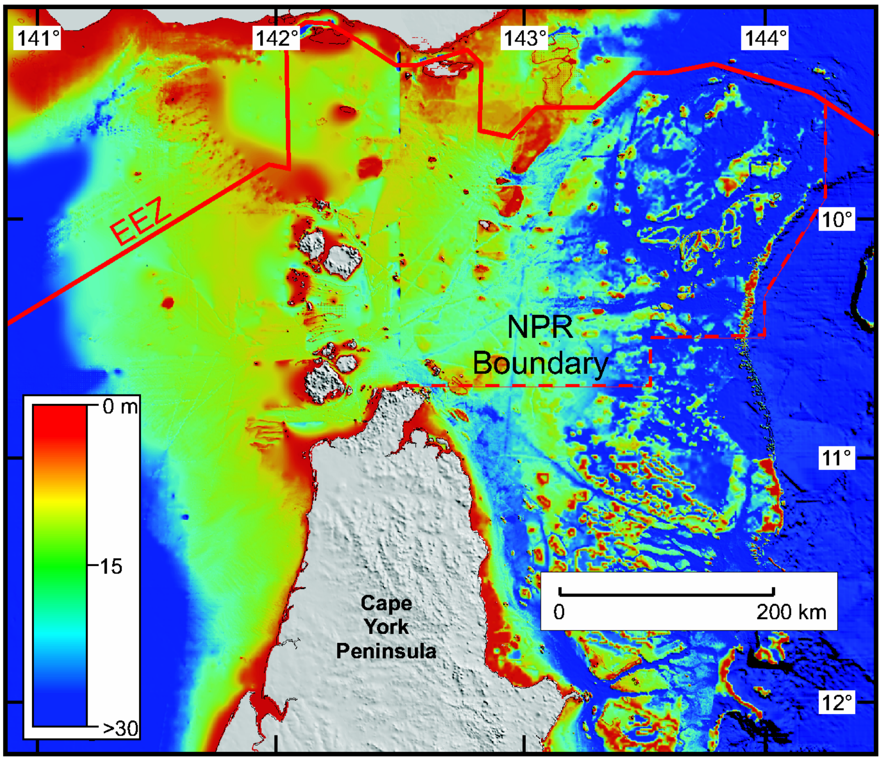

Figure 4.2. Geomorphic map of Torres Strait showing a discontinuous chain of largely granitic islands in the west, isolated volcanic islands in the east, and scattered coral and higher islands in the centre. Approximately 600 individual fringing and patch coral reefs and *Halimeda* banks occur in Torres Strait.

4.2. Geomorphology

Throughout much of Torres Strait water depths are 15-25 m and the seabed forms a low-relief plain (Harris et al., 2004a). Coral reefs dominate Torres Strait, with prolific reef growth occurring throughout the region (Fig. 4.2). Approximately 600 individual fringing and patch coral reefs occur (Woodroffe et al., 2000). The reefs are the most abundant geomorphic unit in the region, covering >2,103 km^2 or ~5 % of the area (Table 4.1). Almost all of the islands contain well-developed reef flats, some up to several kilometres wide (Fig. 4.3). Morphologically, the reefs are similar to those of the northern GBR province, although they are elongated east-west due to local hydrodynamic conditions. Large banks of the coralline algae *Halimeda* occur, particularly in the east (Fig. 4.2).

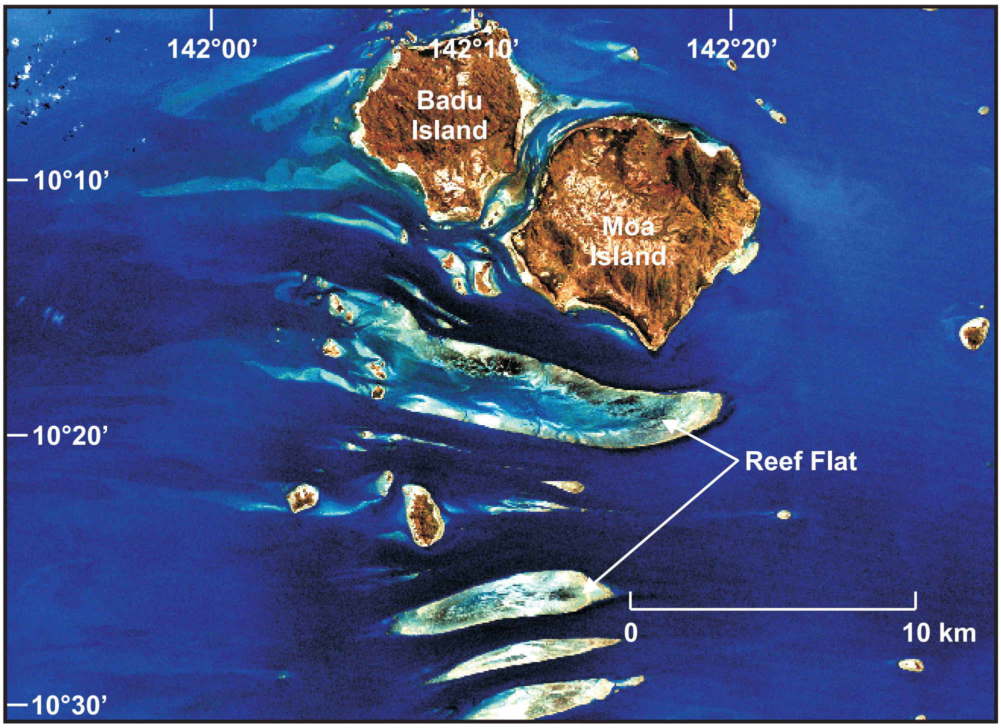

Figure 4.3. Satellite image of select reef flats around two islands in Torres Strait. Reef growth is profilic with almost all the islands and patch reefs having well-developed coral habitats.

Table 4.1. Geomorphic units of the Torres Strait region (from Harris et al., 2004a).

Geomorphic Unit Type	Area (km^2)	Percent
Shelf*	30,651	74.04
Slope*	3,195	7.72
Bank/shoal	1,628	3.93
Reef	2,103	5.08
Terrace	76	0.18
Sandwave/sand bank	3,746	9.05
Total	41,399	100.00

* Shelf and slope areas are less the surface areas of superimposed features.

Sandwaves/sand banks are also relatively abundant in Torres Strait. They cover a total area of 3,746 km^2 or >9% of the seabed (Table 4.1). These mobile sandy bedforms are principally located in the west, between the islands (Fig. 4.4), and their form varies depending on the availability of bed sediment and tidal current velocities. Four main types have been identified (Harris, 1988a): (1) linear sand banks; (2) elongate sand wave trains; (3) sand wave fields; and (4) sand ribbons. Linear banks occur in regions with most sand available for transport, and sand ribbons where sand is least abundant. Some bedforms attain 4-6 m in height and have wave lengths of several hundred metres (Harris, 1988b). The

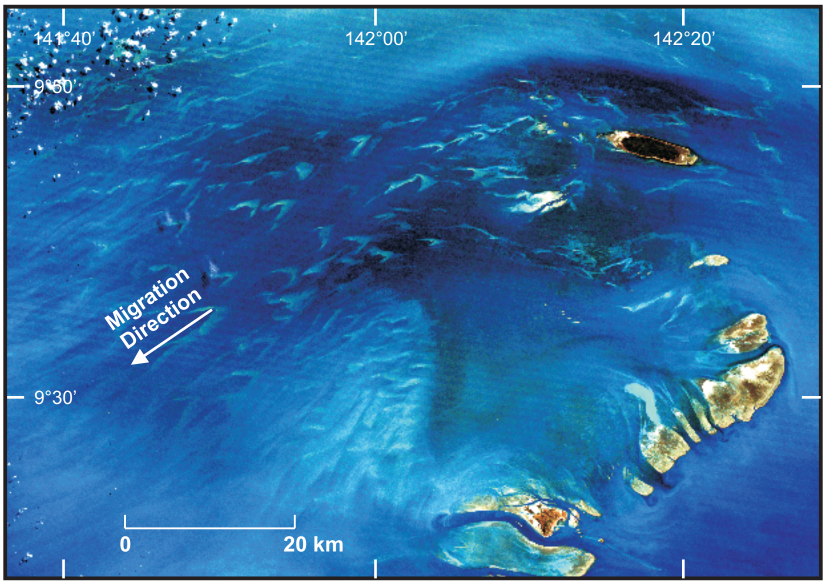

Figure 4.4. Landsat TM satellite image showing the distribution of sandwaves in western Torres Strait. The sandwaves are actively migrating towards the west and southwest, and have amplitudes of 4-6 m and wavelengths of several hundred meters.

larger bedforms, in the western regions, can reach heights of more than half the water depth. The bedforms have actively moved through Torres Strait by the strong tidal currents, sometimes in opposite migration directions in winter and summer (Harris, 1991). Smaller, rapidly migrating bedforms are typically superimposed on the larger less mobile sand banks.

On the northern and northeast margins, the steep prodelta of the Fly River extends onto the adjacent continental shelf. Submarine channels dissect the shelf to depths of up to 120 m (Harris et al., 1996). The channels continue west for over 100 km, particularly along the Papua New Guinea coast, and contain localised "deeps" up to 60 m below the general level of their channels. Harris (1994b), mapped them and interpreted them to be mainly relict and of fluvial origin. The local overdeepening in many of the channels is caused by tidal current scour.

4.3. Oceanography

In Torres Strait, tides are mixed, with one high-high water (HHW) and low-high water (LHW) per day (Harris, 1989). Semidiurnal tides originate from the Coral Sea to the east, and diurnal tides originate from the Gulf of Carpentaria to the west. The numerous reefs and islands form a relatively impermeable barrier to the two tides, so that only about 30% of the tidal wave approaching from the east or west to propagates to the other side (Wolanski, 1986). However, because the tides may be out of phase, sea level can vary by up to 6 m from one side of Torres Strait to the other (Wolanski et al., 1988). Even so, the amplitude of the tide is greatly reduced by the frictional effects of the coral reefs. Mean spring tidal range is 3.8 m (Fig. 4.5) near Adolphus Channel in the south (Harris, 1988a). Tidal currents are directed

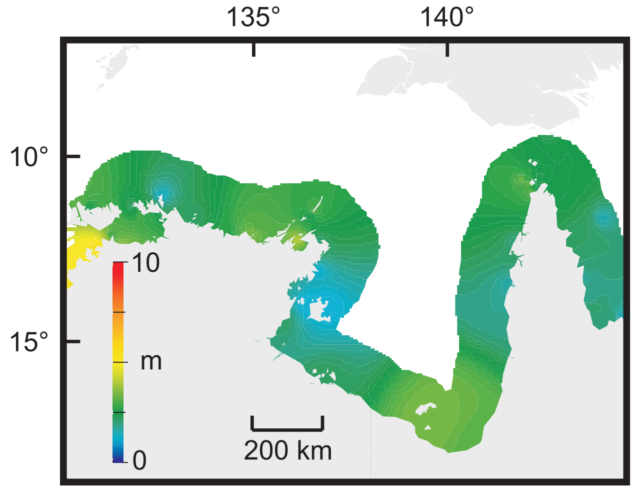

Figure 4.5. Map showing the distribution of tidal ranges. The amplitude of the tides in Torres Strait is greatly reduced by the frictional effects of the coral reefs and islands. Maximum spring tidal range is 3.8 m in Aldophus Channel in the south.

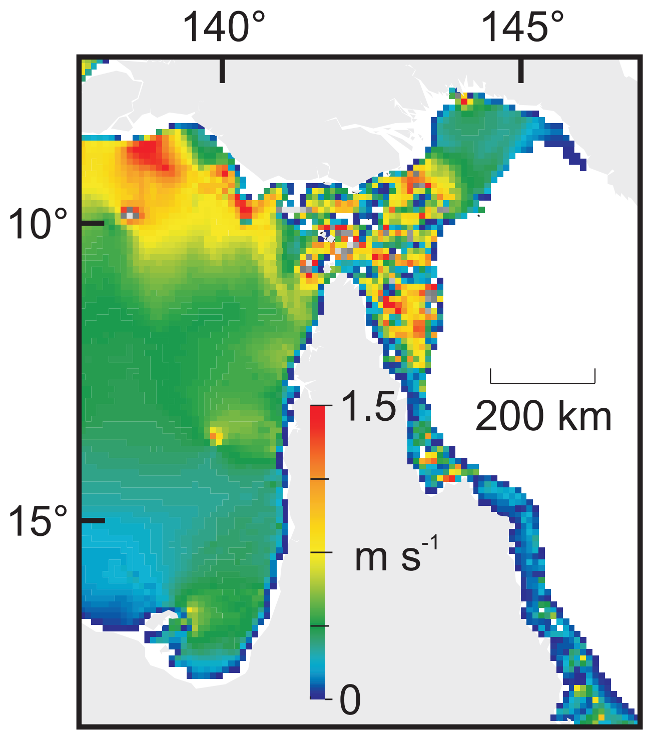

Figure 4.6. Map showing the distribution of tidal velocities in Torres Strait. Tidal currents are directed east-west and are strong due to the difference in tidal height and constricted coastal geometry.

east-west and are strong due to the difference in tidal height and constricted coastal geometry. Surface current speeds attain 2.5 m s^{-1} during spring tides in the narrow passages (Wolanski et al., 1988). Tidal currents are locally accelerated between the reefs and islands, and the western and eastern margins of Torres Strait are characterised by relatively strong (0.8->1.5 m s^{-1}) near-bed currents (Fig. 4.6). Such strong currents extend from Cape York, over Warrior Reefs (see Fig. 1.3 for location) to the southern coast of Papua New Guinea (Fig. 4.7; Bode and Mason, 1995). In contrast, weak near-bed currents occur in central Torres Strait.

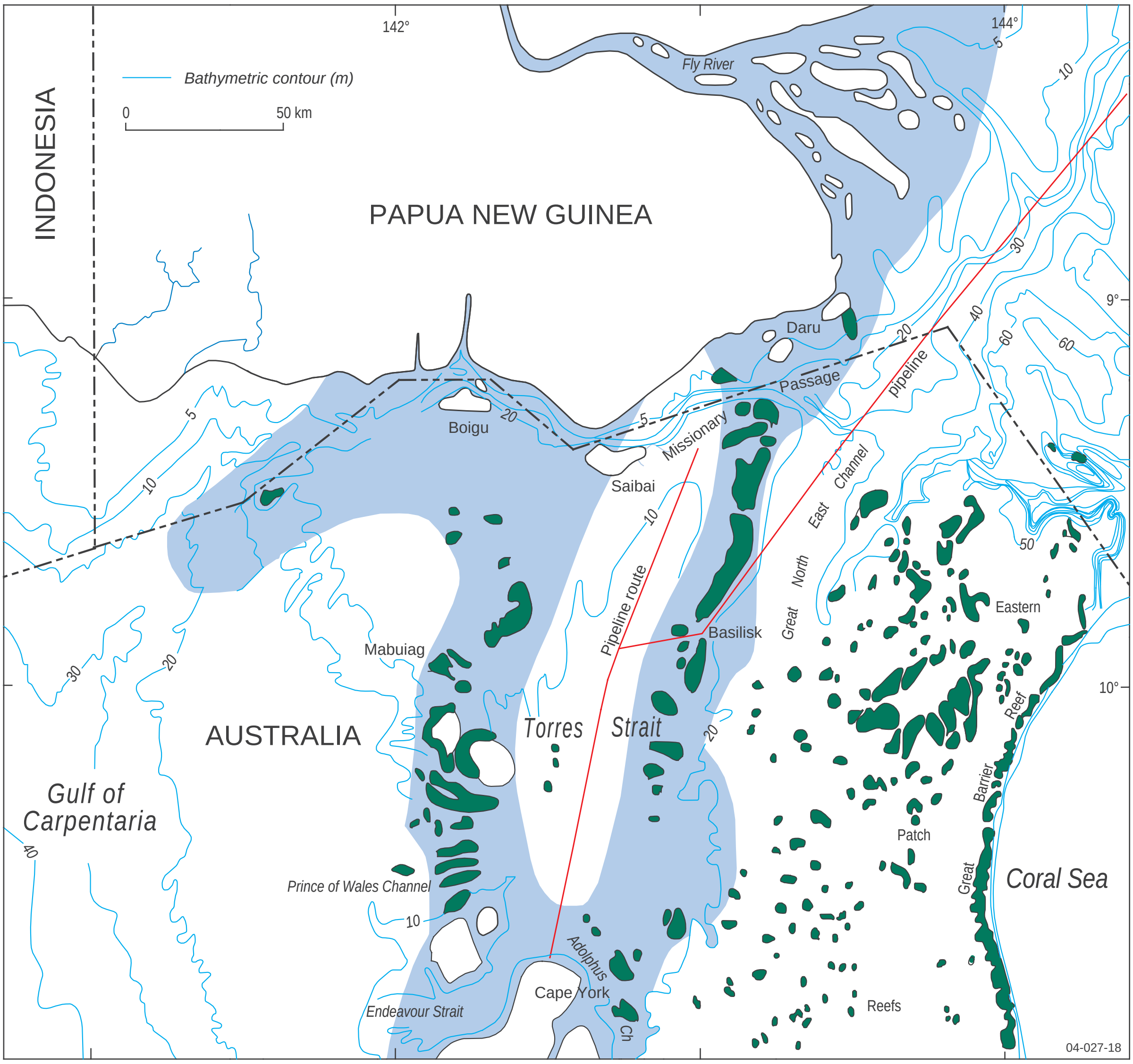

Figure 4.7. Map showing the location of strong (>0.8 m s^{-1}) tidal currents (redrawn from Harris, 2001). This zone (shaded blue) extends from Cape York, over Warrior Reefs to the southern coast of Papua New Guinea.

A simple one-dimensional tidal model, which estimates the variation in tidal current strength, has been constructed for Torres Strait from available tidal current observations and tide gauge data (Wolanski et al., 1988).

Superimposed on the tidal regime are wave-induced currents, wind-driven circulation, ocean currents and storm surges. Maximum annual wave power at the bed is <1,000 W m^{-2} throughout Torres Strait, increasing to 2-3,000 W m^{-2} on the outer shelf (Fig. 4.8). The combined effect of tidal and wind-generated currents produces turbid water in central Torres Strait (Harris and Baker, 1991). The highest suspended sediment concentrations of >20 mg L^{-1} (Harris, 1995) occur in the narrow passages between the reefs, where bed sediment is resuspended by tidal currents. Time-series data indicate that the concentrations rise and fall over the tidal cycle, and are greater on spring tides than neap tides. The highs

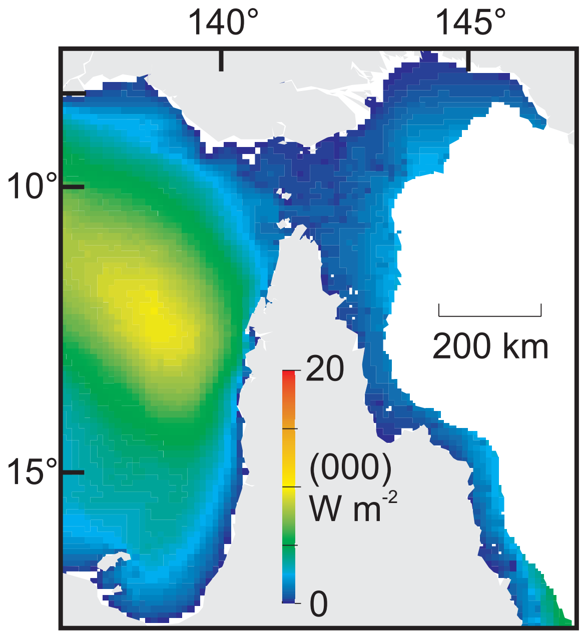

Figure 4.8. Map showing the distribution of wave energy in Torres Strait. Maximum annual wave power at the bed is <1,000 W m^{-2} increasing to 2-3,000 W m^{-2} on the outer shelf.

and lows in the suspended sediment concentrations coincide with the peaks and troughs in current speed (Harris, 1995).

While tides produce the strongest near-bed currents (Wolanski and Thompson, 1984; Wolanski, 1986), current meter records collected in October to March 1986-87 show that the direction of the residual current, and thus advection of suspended sediments changes during the year. During the northwest monsoon season, the residual flow is towards the east, and during the southeast trade wind season it is towards the west. Although the magnitude of these wind-driven currents is typically low at <0.2 m s^{-1}, it is sufficient to induce a seasonal reversal in bedload, and thus a reversal in the orientation and migration direction of bedforms (Harris, 1989; 1991). The overall pattern of sediment mobilisation in Torres Strait is complex, and reflects the effects of the complex bathymetry and constricted geometry of the region on waves and tides (Fig. 4.9). Bed sediment mobility is greater in the constricted channels around the islands and reefs.

One tropical cyclone will cross a 100 km section of the coastline every 10 years (Lourensz, 1981). Shallow water depths mean that tropical cyclones and their associated storm surges generate very strong near-bed currents capable of eroding and transporting vast amounts of bed sediment to a depth of several tens of centimetres (cf., Gagan et al., 1988; Larcombe and Carter, in press). It is estimated that a "typical" storm surge with a return frequency of 100 years would raise water levels by 2.5 m along the coasts of the southern islands (Hopley, 1982).

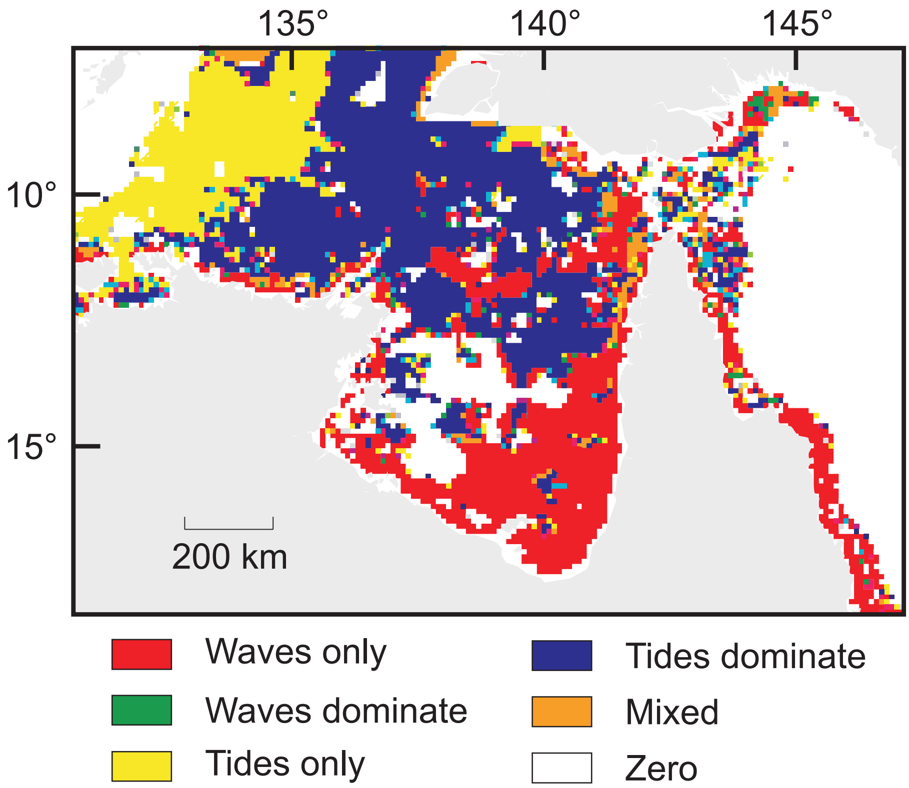

Figure 4.9. Map showing the complex distribution of estimated sediment mobility on the seabed in Torres Strait. Tides are the dominant process causing sediment mobility. Tropical cyclones can mobilise sediment over the entire shelf and occasionally dominate mobility.

4.4. Surface Sediments

Surface sediments in Torres Strait are a mixture of locally-derived carbonate and terrigenous material. Sands and gravels dominate the carbonate fraction and reflect the high-energy conditions found throughout most of Torres Strait. The carbonate fraction is the skeletal remains of benthic foraminifers, molluscs, ostracods, *Halimeda*, and corals. The terrigenous fraction consists largely of relict quartz sands and silts and clays advected to the region from rivers in southern Papua New Guinea, with a small input from underlying Pleistocene silts and clays (Harris, 1995). Interestingly, the terrigenous fraction contains kaolinite and illite, with small amounts of chlorite and mica, and has a similar composition to Fly River sediments (Harris and Baker, 1991). The surface sediments are distinct from the underlying Pleistocene soils, which are dominated by montmorillinite. The texture and composition of bed sediment depends on the proximity of coastal rivers and tidal current regime.

Four main sedimentary facies have been defined in Torres Strait (Harris, 1995): (1) terrigenous mud; (2) high-energy transitional mud and sand; (3) high-energy carbonate; and (4) carbonate mud (Fig. 4.10). Descriptions of the facies are listed in Table 4.2.

Most of the seabed in Torres Strait is characterised by high (>80%) concentrations of carbonate (Harris, 2001), broadly corresponding to the concentration of mud (Fig. 4.11). Three zones of relatively high mud content occur: a belt of >80% mud trends across the front

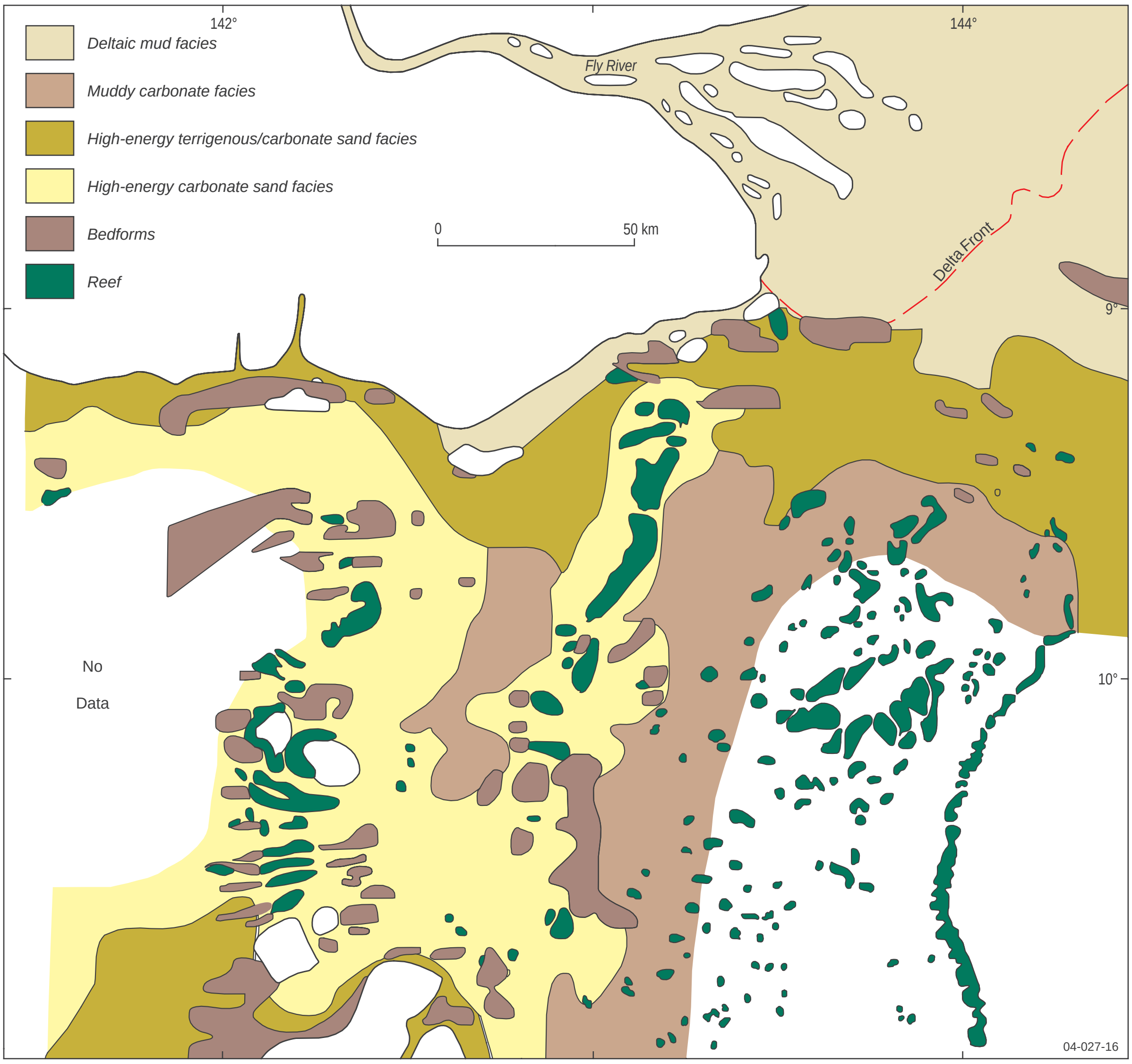

Figure 4.10. Map showing the distribution of surface sediment facies in Torres Strait (redrawn from Harris, 2001). The distribution of the facies is strongly influenced by the concentration of mud.

Table 4.2. Surface sediment facies in Torres Strait (after Harris, 1995).

Facies	Description
Deltaic Terrigenous Mud	Comprises deltaic sediments containing annual laminations formed from variations in surface wave energy. During the southeast trade winds large waves winnow out the finest sediment to leave sand beds; during the northwest monsoon small waves allow mud to drape over sand.
High-Energy Transitional Mud and Sand	Sediment grades from terrigenous mud to carbonate-rich reefal muddy-gravelly sand and well-sorted sand. Contains 20-80% carbonate and <20% mud. Coarse-grained sands and gravels locally form mobile dunes and sand ribbons.
High-Energy Carbonate Sand and Gravel	Contains >80% carbonate and <20% mud. Forms gravel lags and sand/gravel ribbons where tidal currents are locally accelerated and scour the seabed. Finer sediment is deposited further from the scour zones.
Carbonate Mud	Contains >80% carbonate and >20% mud. Carbonate grains are derived from the breakdown of sand and gravel sized clasts from the High-Energy Carbonate Sand and Gravel facies.

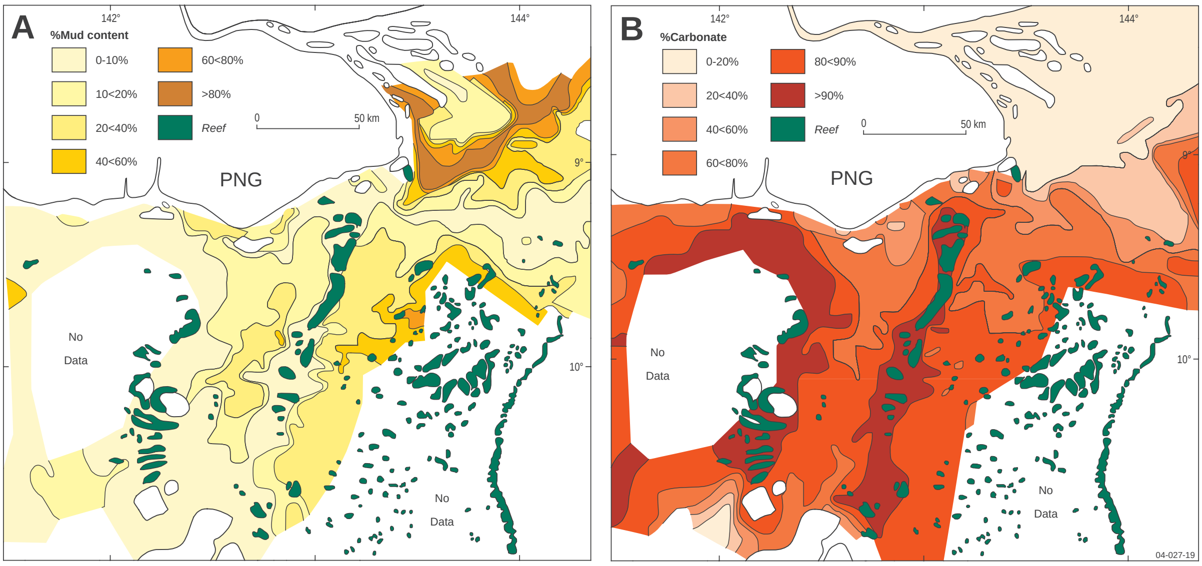

Figure 4.11. Map showing the concentrations of (a) mud and (b) carbonate in the surface sediments in Torres Strait (redrawn from Harris, 2001). Silt and clay sized particles are preferentially deposited in two low-energy depocentres.

of the Fly River Delta (see Fig. 1.3 for location); another belt (>60% mud) occurs in the east next to the reefs; and a third belt of carbonate mud occurs in the centre of the Torres Strait. These belts are low-energy depocentres where silt and clay sized particles are preferentially deposited. The concentration of clay-sized grains in the mud fraction is 10% and 40% (Harris et al., 1990). The mud belts across the front of the Fly River Delta and in the centre of Torres Strait are derived from reworked and degraded bioclastic sediments. The mud belt next to the eastern patch reefs is derived from the Fly River and is wholly of terrestrial origin (Harris and Baker, 1991). On the Fly River Delta, the mean grain size of the mud fraction is 7 μm. Between the eastern patch reefs the mean grain size of the mud fraction is 20 μm. The carbonate mud facies next to the eastern patch reefs is a northern analogue to mud facies found in the Capricorn Channel of the southern GBR.

Areas of low mud content (<20%) contain sand and gravel, and the better sorted areas (<10%) are associated with bedforms (Harris, 1988a). A large field of subaqueous quartzose dunes occurs in the west (Fig. 4.4). The dunes are probably formed of sediment derived from Pleistocene subaerial dunes and riverine and coastal deposits that were submerged during the Holocene (Harris, 1988a).

High-resolution shallow seismic profiles and cores reveal that, over most of Torres Strait, the surface sediments form only a 1-2 m thick layer that overlies coastal, shelf and reef sediments comprised of cohesive Pleistocene clay and cemented limestone (Harris, 1994b; Harris et al., 1991; 1996). Holocene deposits attain a thickness of 2.5 m in the Great North East Channel (see Fig. 1.3 for location) but are patchy and absent from a large section of central Torres Strait (Fig. 4.12). The seismic records also reveal that the mobile dunes rest

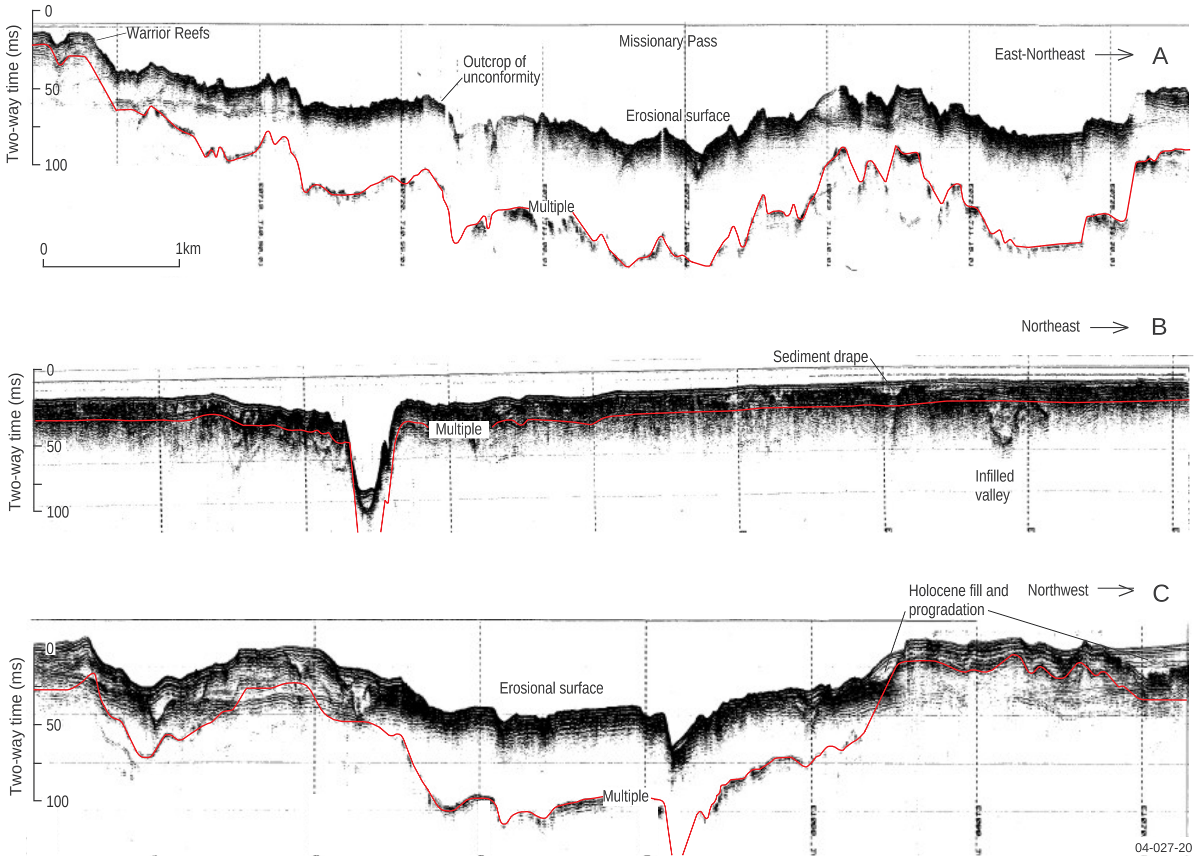

Figure 4.12. Shallow seismic (boomer) profiles showing thickness of Holocene sediments in Torres Strait (redrawn from Harris, 2001). The profiles show that Holocene sediments mostly form a thin veneer over a heavily incised Pleistocene surface, but where they fill channels can reach up to 10 m thick.

unconformably on, and are migrating over, the cohesive Pleistocene clay and weathered limestone. River channels, incised into the shelf, have been partially or completely infilled with younger Holocene sediments (Harris, 1994b). These channels, which may have been overdeepened and exhumed by tidal currents, occur mainly within 20 km of the south coast of Papua New Guinea.

Previous studies (e.g., Cole 1992; 1995; Cole et al., 1995; Collins, 2002; King, 2003) have demonstrated that benthic foraminifers in the surface sediments exhibit a well-defined spatial zonation. The principal causes for the zonation were found to be water depth, substrate type, and energy level. The order Rotaliida (in particular *Amphistegina* spp. and *Ammonia* spp.) is dominant throughout Torres Strait, followed by Miliolida (*Alveolinella* spp. and *Quinqueloculina* spp.). There is a general decrease in the abundance of larger benthic foraminifera with water depth (e.g., *Assilina ammonoides*, *Amphistegina* spp. and *Nummulites venosus*).

4.5. Acoustic Facies

In 2003, seabed echo-types were determined from the echograms of shallow seismic profiles collected in Torres Strait (see Appendix A) during Geoscience Australia Survey 234 (Jan.-Feb. 2002) on the R/V *Franklin* (Harris et al., in press[a]). The data were collected in conjunction with a detailed multibeam survey of the inner and middle shelf areas (Figs. 4.13 & 4.14; Harris et al., in press[a]). The most common echo-types were IA and IIB, with small areas of IB, IC, IIA and IIIC. These echo-types correspond to an area of the shelf that is relatively smooth. Morphological features include: low-amplitude ridges and swales, shallow channels and gullies, rock outcrops, sand waves, and pockmarks. The area contained no large-scale features commonly associated with type III echo-types. Where possible, the classifications were verified against surface sediment samples. Of the six echo-types, only four were associated with surface sediment samples (Table 4.3). The surface sediments are muddy sand, with a single sample of muddy-gravelly sand. The echo-types can be only poorly discriminated by the texture and composition of the bed sediment due to the uniformity of facies types.

Table 4.3. Surface sediment characteristics with associated echo-types.

Echo Type	No. of samples	Gravel (avg. %)	Sand (avg. %)	Mud (avg. %)	Carbonate (avg. %)	Sediment Type
IA	1	13.5	71.0	15.5	61.0	Muddy-gravelly sand
IA	6	4.2	78.4	17.4	55.9	Muddy sand
IC	2	2.3	68.1	29.6	51.2	Muddy sand
IIA	1	9.8	72.3	18.0	52.5	Muddy sand
IIB	11	7.0	67.0	26.0	54.4	Muddy sand

In Torres Strait, a total of 12 species of seagrass representing 22% of all known species occurs, mostly in the inter-tidal areas landwards of the coral reef crests (Bridges et al., 1982). Seagrass beds are sparsely distributed in other environments because of the erosive effects of strong tidal currents and high levels of turbidity. Overall, the distribution of seagrass is complex, and does not necessarily coincide with substrate type. The variation in seagrass abundance is more closely related to local changes in turbidity and sedimentation (Bridges et al., 1982).

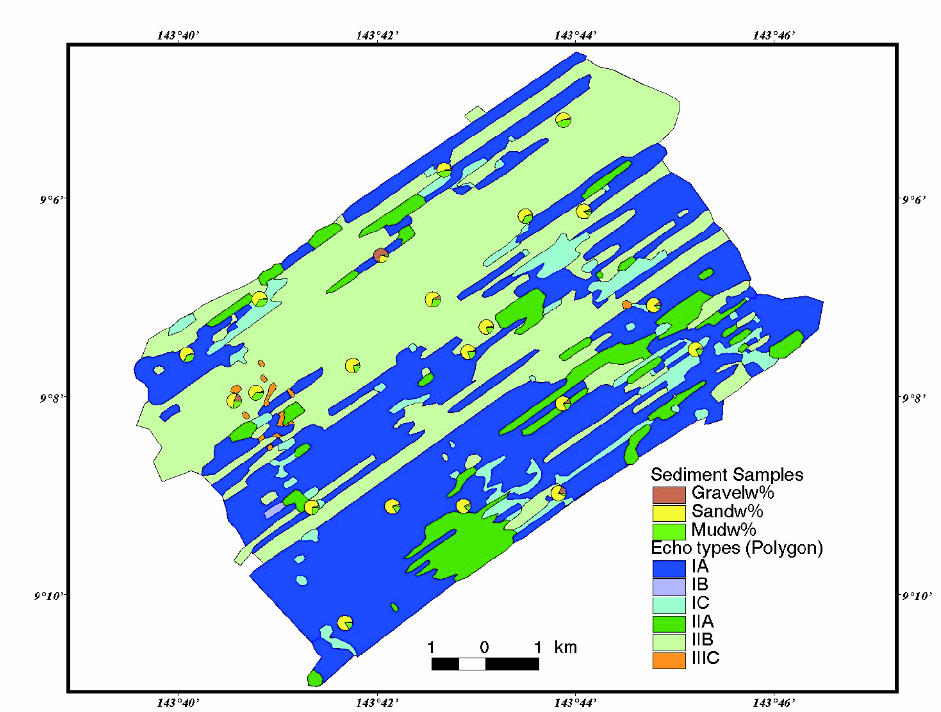

Figure 4.13. Map showing the distribution of acoustic facies for the inner shelf. Locations of surface sediment samples are shown with the concentrations of gravel, sand and mud.

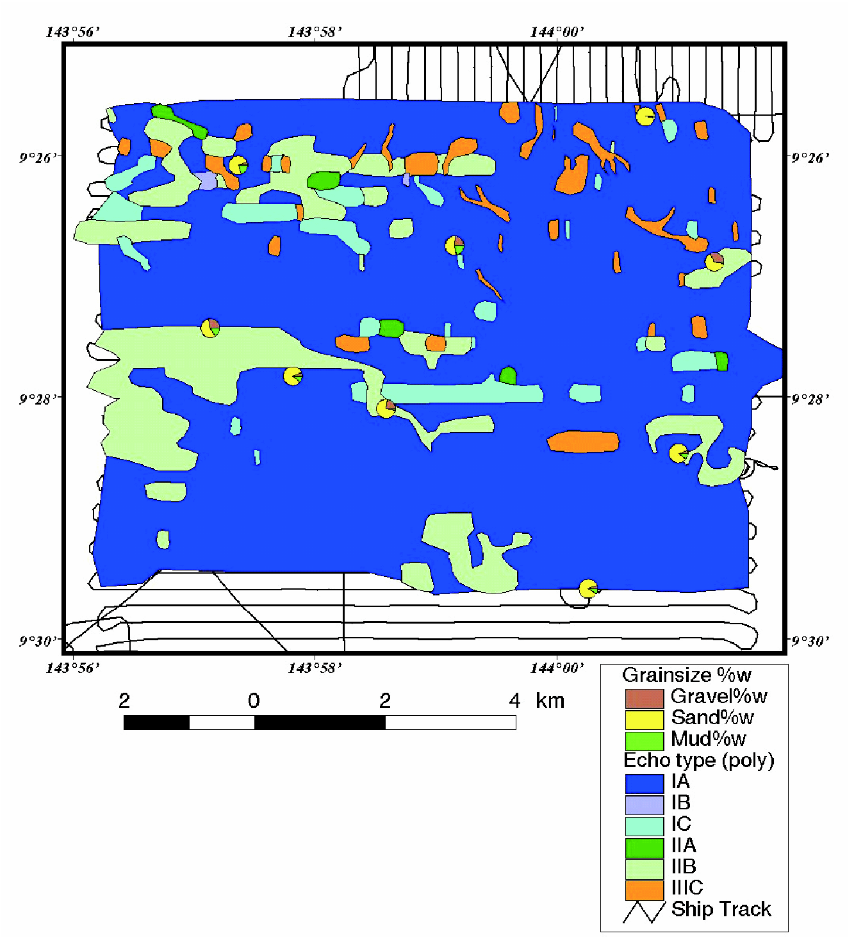

Figure 4.14. Map showing the distribution of acoustic facies for the middle shelf. Locations of surface sediment sample are shown with the concentrations of gravel, sand and mud.

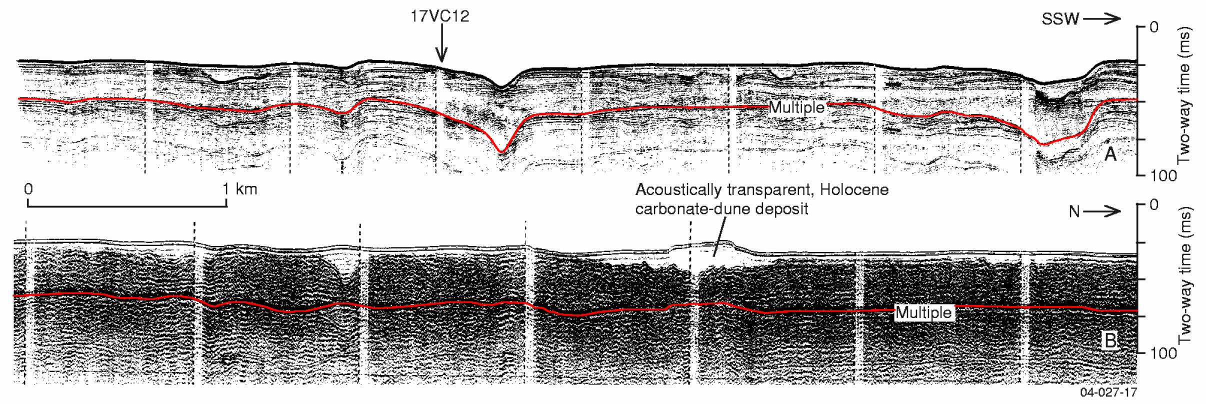

Figure 4.15. Shallow seismic (boomer) profiles showing a thin veneer of Holocene carbonate muddy gravely sand over: (a) Pleistocene fluvial deltaic cut and fill deposits, and (b) Pleistocene cemented limestone and consolidated coastal and fluvial sediments (redrawn from Harris, 2001).

4.6. Late Quaternary Evolution

Torres Strait was a land bridge connecting Papua New Guinea with Australia until it was submerged approximately 9,000 years ago by the last post-glacial sea-level rise. The present complex distributions of hydrodynamic processes and sedimentary environments probably have developed since the onset of sea-level highstand approximately 6,000 years ago.

Seismic data and sediments contained in shallow cores indicate that the Late Quaternary sedimentation in Torres Strait was characterised by widespread erosion in the channels and limited deposition in open shelf regions. Throughout most of Torres Strait, the Pleistocene surface is draped by a veneer (1-2 m) of Holocene sediments that have also partially filled some of the incised channels, although most of the channels remained unfilled (Fig. 4.15; Harris, 1994b). The Holocene sediments were probably first deposited on the shelf and in the channels during the post-glacial transgression, when the shelf was initially flooded. Erosion of terrigenous sediments deposited during lowstand, from the constricted reef passes and the channel flanks, has also provided material for deposition around the reefs and on the open shelf areas.

The Late Quaternary history of corals in Torres Strait is almost identical to that for the reefs in the GBR. Surface and subsurface geologic investigations and radiocarbon dating (Woodroffe et al., 2000) indicate that the modern coral reefs in Torres Strait were established at a depth of ~6 m around 7,000 years ago (Fig. 4.16). Since then the corals grew upwards to reach present sea level around 5,000 years ago and then grew laterally, elongated in an east-west direction by the dominant tidal currents. The reefs mostly occur on antecedent highs of remnant Pleistocene coral reefs that grew during the last interglacial. Because of this close relationship, the area of Holocene reefs is probably similar to that of reefs in Torres Strait

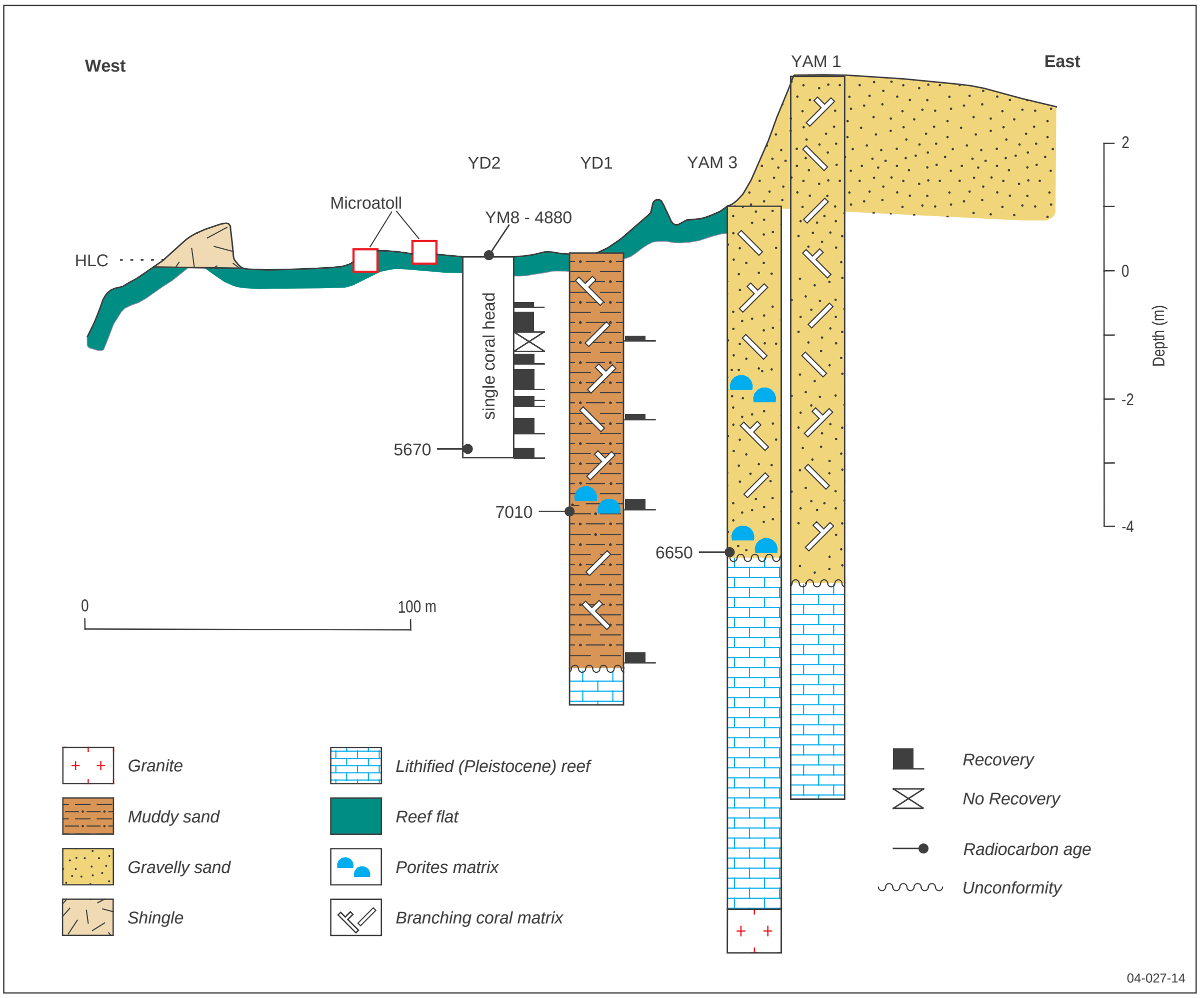

Figure 4.16. Stratigraphic profile showing the general growth history of corals in Torres Strait (redrawn from Woodroffe et al., 2000). Modern reefs were established at a depth of ~6 m around 7,000 years ago, grew to sea level about 5,000 years ago and have since grown laterally.

during the last interglacial. However, the foundations of the northern margin of Warrior Reefs are unconsolidated weathered Pleistocene soils (Harris et al., 1992), indicating that reefs also grew wherever suitable foundations existed.

Along with the corals, the *Halimeda* banks on the outer shelf probably started growing soon after Torres Strait was flooded. Seismic profiles indicate that some of the banks were initiated and anchored on antecedent Pleistocene limestone highs. Like the coral reefs, the morphology of the *Halimeda* banks was strongly influenced by the dominant east-west tidal currents. Cores collected through a *Halimeda* bank on the outer shelf show evidence of uninterrupted deposition during the Late Quaternary (Harris et al., in press[a]).

Shallow cores taken on the middle and outer shelf in the east, where the southern margin of the Fly River Delta extends into Torres Strait, contain sediments that reveal a Late Quaternary history of estuarine/deltaic deposition during transgression, followed by a transition to open shelf conditions during highstand (Fig. 4.17; Harris et al., in press[a]). The transgressive estuarine/deltaic sequence is dominated by fine-grained siliciclastic clay with silt laminations. A unit of poorly-sorted homogenous calcareous sandy mud unconformably overlies the laminated mud unit. The physical properties of the sediment (i.e., bulk density, p-wave velocity, porosity) are comparable with values obtained for shelf sediment on the GBR (e.g., Heap et al., 2001). The unit has a similar texture and composition to sediments found in open shelf regions in Torres Strait. Radiocarbon ages from peat deposits in the laminations indicate that the lower unit was deposited very rapidly, while ages from the upper unit indicate that Late Holocene sedimentation rates on the open shelf are low.

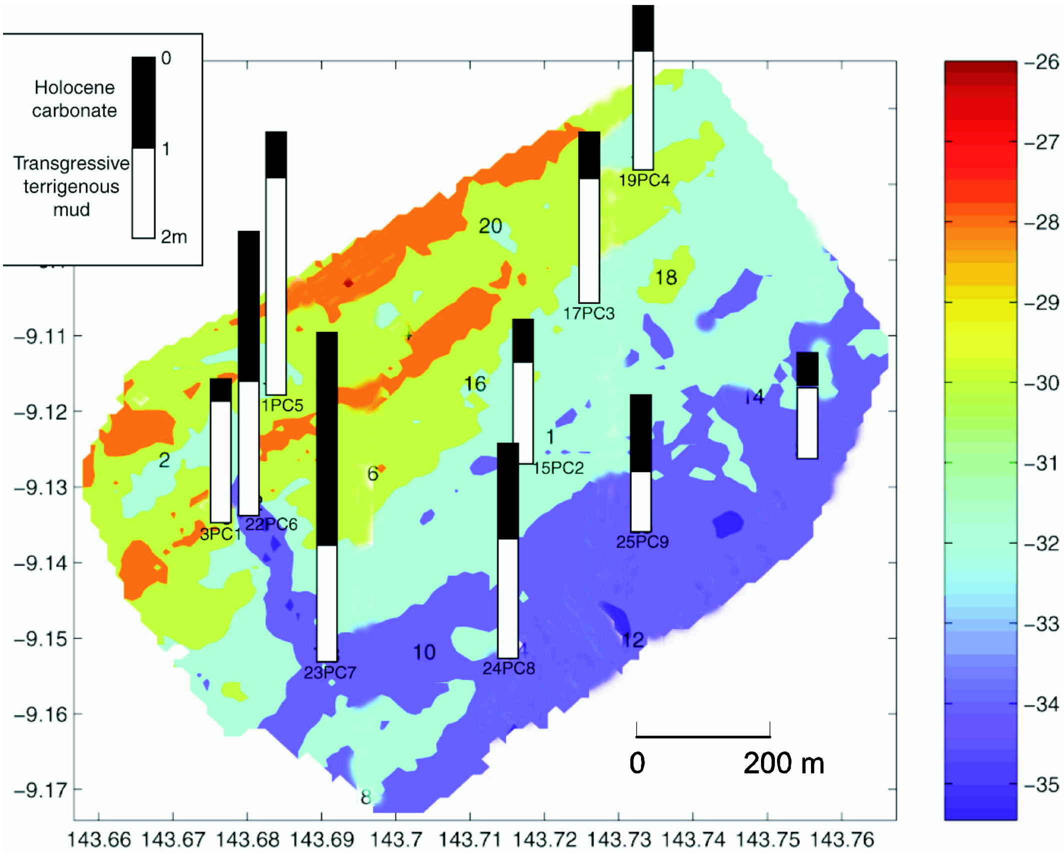

Figure 4.17. Map showing the bathymetry of the inner shelf region of Torres Strait and late-Holocene stratigraphy from cores shallows collected from the southern margin of the Fly River delta. The stratigraphy is divided into two main units, an upper unit of poorly-sorted carbonate-dominated muddy gravelly sand and a lower unit of terrigenous-dominated laminated clay and silt beds. The carbonate unit is thin, indicating low modern sedimentation rates.

5. Implications for Regional Marine Planning

Conservation of habitat diversity of the benthic environment through Regional Marine Planning requires information on the geomorphology, sediment type, and hydrodynamics of various habitats types. We briefly outline some examples showing the applicability of the information contained in this report to regional marine planning, specifically habitat mapping and sediment and biotic relationships.

5.1. HABITAT MAPPING

Habitats on the outer shelf of the Arafura Shelf are some of the deepest shelfal examples on the Australian continental shelf and would have been the first to be established during the last post-glacial transgression. Not only are these habitats unusual and significant due to their depth on the continental shelf, they also have had an extended period of time to evolve and adapt to their environments. They will provide valuable insights into the evolution of shelf habitats during the Holocene, and may also help predict the responses of shallow-water areas to possible future rising sea levels.

The southern Gulf of Carpentaria is Australia's largest shelf province of fine-grained terrigenous-dominated sediment, and thus the largest potential repository for particle-associated contaminants from the catchment, especially heavy metals. No other region of the Australian shelf contains such an extensive area of seabed habitats related to terrigenous sediments. While contaminant concentrations will be diluted by the vast amounts of terrigenous sediment present, the Gulf of Carpentaria is a shallow receiving basin, with negligible transport of sediments to the deeper ocean, and the contaminants have little opportunity to be exported. This region is an example of where catchment management strategies and land-use practises have the potential to affect the health and long-term viability of seabed habitats on a large scale.

In Torres Strait, the complex bathymetry, naturally occurring hard-grounds, energetic hydrodynamic conditions, and highly variable sediment transport processes result in a complex distribution of shallow water substrate types and habitats. Hard-grounds provide a suitable geological substrate for diverse assemblages of benthic organisms, which themselves attract many reef-dwelling and pelagic organisms. The occurrence of widespread bedforms in Torres Strait implies a very mobile bed. Defining the location and extent of mobile bedforms helps determine sediment transport pathways and the possible effects of mobile sediments on the adaptability and long term survival of seabed habitats. In these regions, habitats would be expected to evolve quickly or be somewhat resistant to rapid changes to sediment or substrate types. Hard-grounds and mobile sandy bedforms also occur in the southern and western regions of the Gulf of Carpentaria, and while the total extent of these regions is unknown, they should exhibit similar associations. In contrast, over most of the Arafura Shelf and in the Gulf of Carpentaria the relatively low-energy conditions and thin sediment cover indicate stable seabed habitats that only respond to significant changes such as those caused by tropical cyclones.

The existence of at least three submerged patch reefs in the southern Gulf of Carpentaria raises important management questions regarding their protection and possibly the long-term survival of corals in the region. Even though the submerged reefs in the Gulf are located within the latitudinal belt of 10-15°S, predicted to be most affected by sea surface warming and coral bleaching due to global warming (Sheppard, 2003), they are likely to be important seed stock for regenerating coral assemblages in regions where surface-dwelling corals (e.g., Torres Strait) are affected by bleaching. This is because the deeper water above the submerged reefs reduces the amount of harmful solar radiation reaching the corals, and ameliorates diurnal over-heating of the surface waters. Relatively unaffected submerged reefs like those in the Gulf could provide a refuge for corals and larvae for reseeding bleached corals. The evidence indicates that this has actually happened in the past, because the seed stock for surface-dwelling corals that died during lower sea levels can hardly have come from elsewhere. Mapping the distribution and abundance of submerged reefs should be a priority for government agencies responsible for the management and protection of these important living marine resources, particularly in the face of rising global temperatures (Hughes et al., 2003).

Seagrass communities are important nursery grounds for juvenile tiger and endeavour prawns (Staples et al., 1985). Seagrasses are also the principal food for dugongs and green turtles. However, an assessment of the importance of seagrasses in the Gulf of Carpentaria for biota suggests that only the seagrass beds in shallow waters act as important settlement and nursery areas for tiger prawns (Loneragan et al., 1994). In fact, the assemblage of seagrass appears to be more important to specific species of juvenile prawns than to post-larvae. Community type rather than total species abundance may thus affect the survival or emigration of post-larval prawns. The large area of seagrass beds in the Northern Planning Area needs conservation for the long term maintenance of the tiger prawn fishery and the survival of large populations of dugongs and turtles (e.g., Coles and Lee Wong, 1985).

5.2. SEDIMENT AND BIOTA RELATIONSHIPS

In the Gulf of Carpenteria, the distribution of commercially important prawn species shows some relationship with sediment type (Somers, 1987). Although water depth generally accounts for most of the variation in abundance, the concentration of mud in the surface sediments is also a significant factor for all but a few species. The abundance of several species (*Penaeus esculentus*, *Metapenaeus endeavouri* and *Penaeus latisulcatus*) is negatively associated with mud concentrations. Unlike the adults, juveniles of all species are largely confined to shallow (<20 m) inshore waters (Somers, 1987).

A survey of the infaunal benthos in water depths of >20 m in the Gulf of Carpentaria showed that the abundance and species density are positively correlated to grain size, with highest numbers associated with the sands and muddy sands along the east and southeast margins of the Gulf (Long and Poiner, 1994). By contrast, poorly-sorted muds and sandy muds in the central, western and northwest regions contain the lowest abundances of infauna. The greatest abundance of suspension feeders is associated with the sandy sediments the south and southeast, while the greatest abundance of deposit feeders is associated with the muddy sediments of the central Gulf (Long and Poiner, 1994). Few (<1%) herbivores are present anywhere in the Gulf.

In Torres Strait, the distribution of Trochus shells (*T. niloticus*) is closely associated with substrate type. Comparing Trochus abundances with Landsat images (which were used to identify habitats) showed that Trochus shells are most abundant in shallow (<15 m) water along the windward reef margins, that have a cover of coral and rubble/algal pavement. From the area of this substrate type, a standing stock of 186,000 commercially-sized individuals (or 14 tonnes) was estimated to exist in Torres Strait (Long et al., 1993). Other studies have demonstrated that the abundance and diversity of epibenthic macrobiota in Torres Strait also shows a close relationship with substrate type, with the greatest diversity and abundance of biota associated with hard substrate (Pitcher et al., 1992).

5.3. SUMMARY

Geoscience data will always play a vital role in the management of Australia's ocean resources because we can never have a complete inventory of all biota for the seabed. But we *can* map geomorphology and sediment type relatively easily, and then infer biodiversity or habitat types from these surrogate data. Determining the distribution, abundance and nature of seabed habitats using geomorphic and sedimentary information enables environmental managers to identify unique regions that may require protection—including candidate areas for marine protected areas—as well as allowing quantitative comparisons to be made between regions that can be incorporated into management strategies. Moreover, quantifying the temporal and spatial stability of habitats requires historical information that can be readily inferred from surface and subsurface sediments and biota. Knowledge of the stability of habitats is vital for future planning decisions, because management strategies will need to be tailored differently for habitats that evolve quickly compared to those that evolve more slowly.

Understanding the relationship(s) between geomorphology and sediment/substrate type and biota is the most significant issue associated with Regional Marine Planning. Further research into the nature of these relationships, to advance our understanding of the complex interactions that characterise seabed environments, should be a high priority for government agencies, universities and other research organisations. Expanding and enhancing national databases containing baseline geological and biological data for Australia's oceans must also be a high priority.

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7. Appendix A
Classification of Acoustic Facies

Echograms from echo-sounders (e.g., depth sounders/side scan sonar) provide useful data on changes in seabed reflectivity, as determined by surface sediment texture and composition (including biota), and micro-topography. Different echo-character types form through the interaction between the seabed and the echo-pulse. Sediments can affect the echo return by their type, layering, structure and topography (Flood, 1980). Because similar echo-types can be returned by different seabed types, additional information from sediment samples, seabed photographs, and/or multibeam sonar is required to define the echo-types in terms of sedimentary processes.

A classification scheme for 3.5 kHz echograms was developed by Damuth (1973, 1975) based on an earlier classification scheme for 12 kHz systems (Holister, 1967). The echo-character of the seabed is classified into three main categories based on parameters including clarity and continuity of echoes and seabed morphology, as follows:

I. Distinct echoes;
II. Indistinct echoes – prolonged; and
III. Indistinct echoes – hyperbolae.

Table 7.1. Seabed echo-types (Damuth, 1980).

Class	Sub-Class	Type	Description
Distinct		IA	Sharp continuous with no sub-bottom reflectors
		IB	Sharp continuous with numerous parallel sub-bottom reflectors
		IC	Sharp continuous with non-conformable sub-bottom reflectors
Indistinct	Prolonged	IIA	Semi-prolonged with intermittent parallel sub-bottom reflectors
		IIB	Prolonged with no sub-bottom reflectors
	Hyperbolae	IIIA	Large, irregular hyperbolae with varying vertex elevation (>100 m)
		IIIB	Regular Single hyperbolae with varying vertices and conformable sub-bottom reflectors
		IIIC	Regular overlapping hyperbolae with varying vertex elevation (<100 m)
		IIID	Regular overlapping hyperbolae with vertices tangent to the seafloor
		IIIE	Type IIID hyperbolae with intermittent zones of distinct (IB) echoes.
		IIIF	Irregular Single hyperbolae with non-conformable sub-bottoms

These three echo-types are further sub-divided into sub-types based on the presence or absence of a sub-bottom reflector, prolonged extent, and relationship of hyperbolae to the seabed (Table 7.1).

The acoustic character of hard-copy echograms collected during Geoscience Australia surveys to the Arafura Sea and Torres Strait were interpreted for the Northern Planning Area. The resultant acoustic maps were corroborated with available sediment, bathymetric and multibeam sonar data, to better determine seabed geology, morphology, and sedimentary processes.