Cooperative Research Centre for Coastal Zone, Estuary & Waterway Management

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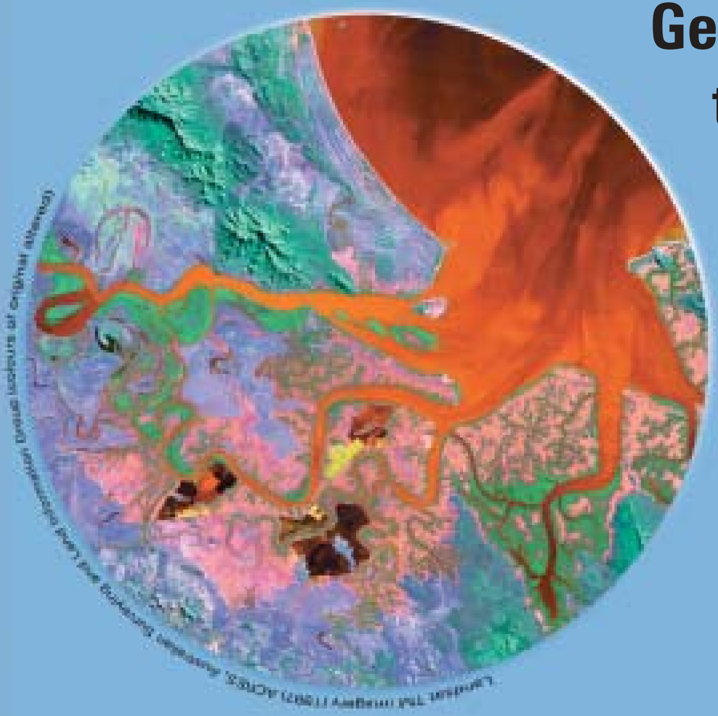

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Non-technical summary

Much of the world's coastline experiences high tidal range, or macrotidal, conditions, and the associated turbidity and heightened sediment dispersal. On tropical coastlines, the processes that control sediment transport through macrotidal estuaries are not well understood. A particular concern for the environmental managers of these environments is determining the amount of sediment that is transported from coastal catchments, through tide-dominated estuaries, and into the coral reef environment. This requires accurate mapping of estuarine and seabed sediment distribution, and an understanding of the processes of erosion, transport, and deposition of both fine and coarse sedimentary material.

The Great Barrier Reef (GBR), adjacent to the coast of Queensland, Australia, is a tropical coral reef environment that comprises an outer coral-dominated environment, and an inner lagoon dominated by catchment-derived sediments. Numerous studies have attempted to measure the input of sediments to the northern GBR from large rivers such as the Burdekin. However, comparatively little attention has been paid to the effects of rivers such as the Fitzroy in the southern GBR province.

Keppel Bay is a macrotidal environment that represents the interface of the large catchment of the Fitzroy River with the southern GBR continental shelf. In this study, we assessed the distribution of sediments and their depositional characteristics using a combination of sediment sampling, and acoustic (sonar) seabed mapping tools. Using statistical techniques, we classified the seabed sediments of Keppel Bay into five distinct classes, based on sediment grainsize, chemical composition, and modelled seabed shear stress (the influence of waves and tidal currents). The sonar imagery provides an unprecedented view of sediment dunes, which indicate directions of sediment transport, and deep, eroded channel features in Keppel Bay. This information suggests that much of the river mud accumulates in the mouth of the Fitzroy River, and the remainder is transported offshore and to the north by a buoyant 'plume'. Sands accumulate in the south of Keppel Bay and are transported onshore by tidal currents. Outer Keppel Bay is dominated by the shoreward transport of older material from the continental shelf. In general, river sediments can only reach the offshore reefs during major flood events, whereas during non-flood conditions, sediments are moved onshore and to the north.

Introduction

Tide-dominated coastal systems are characterised by comparatively high rates of sediment transport and the exchange of large quantities of sediment with the coastal ocean (Dalrymple *et al.*, 1992; Boyd *et al.*, 1992). Globally, meso- to macrotidal coasts occur in both tropical areas such as Central America (Carriquiry and Sánchez, 1999), northern Australia (Woodroffe *et al.*, 1985; Woodroffe *et al.*, 1989; Wolanski and Spagnol, 2003) and south-east Asia (Baker *et al.*, 1995; Gastaldo *et al.*, 1995; Kineke *et al.*, 2000), as well as temperate regions, such as western Europe (Berné *et al.*, 1993; Tattersall *et al.*, 2003), and Canada (Dalrymple *et al.*, 1990). Although some of the larger northern hemisphere tide-dominated systems have become reasonably well studied (e.g. the Severn, Gironde, and Bay of Fundy), the complex and variable patterns of sediment transport from tropical tide-dominated estuaries and deltas through to continental shelves is not well documented, partially due to the difficulty of working in these turbid, high tidal range coastal environments.

Human impacts in the coastal zone, ranging from overexploitation of resources, habitat modification, and global climate change continue to threaten biodiversity and subsequent provision of ecosystem services (Jackson *et al.*, 2001). A particular concern of global scale for environmental managers is the yield of terrestrial sediment from coastal catchments that reaches coral reefs, which has implications for coral health and ultimately the distribution of reefs (McLaughlin *et al.*, 2003; Golbuu *et al.*, 2003; Brodie *et al.*, 2003; Furnas, 2003; Woolfe and Larcombe, 1999; Hutchings *et al.*, 2005). Therefore, coral reef management initiatives can benefit from a better understanding of the processes responsible for the distribution of terrestrial sediments once they reach the marine environment.

The northeast continental margin of Australia comprises the largest modern example of a warm-water coral reef complex, the Great Barrier Reef (GBR). A number of researchers have investigated the processes controlling sediment transport from the Burdekin River to the northern GBR lagoon (Fielding *et al.*, 2003; Neil *et al.*, 2002; Orpin *et al.*, 2004), however, processes of sediment transport in the southern region remain poorly documented. It is recognised, nonetheless, that the inner shelf of the southern GBR differs from the northern reef tract in that the shelf is wider, macrotidal, and experiences less frequent and strongly ENSO-linked cyclone events (Devlin *et al.*, 2001). The focus area, Keppel Bay, is located in the southern GBR and represents an interface between a large, seasonal coastal catchment, a macrotidal inner-shelf, and the carbonate-dominated outer GBR shelf.

Here we examine the seabed geomorphology and mechanisms of sediment transport within the mouth of the Fitzroy River and the adjacent open coast of Keppel Bay. We use a range of sediment and acoustic data to better understand the connectivity of the Fitzroy River catchment, Keppel Bay, and the southern GBR lagoon. This report represents a sub-component of Milestone Report AC65.

Regional setting

The Great Barrier Reef Shelf

The GBR shelf borders the north-eastern coast of Australia, between the latitudes of 10°41’ S and 24°30’ S, and spans both wet and dry tropical climate zones (Maxwell, 1968). The shelf widens to the south and has been broadly classified into longitudinal zones. These include a terrigenous sediment-dominated inner shelf between depths of 0–22 m, a mainly sediment-starved middle shelf from 22–40 m, and an outer shelf tract below 40 m primarily dominated by reefs and carbonate sedimentation (Maxwell, 1968; Larcombe and Carter, 2004). Only the outer GBR comprises pure coral-algal carbonate facies, as the relatively large inner and middle zones, or the GBR lagoon, experiences both carbonate and terrigenous sedimentation (Heap *et al.*, 2001; Maxwell, 1968; Orpin and Woolfe, 1999; Orpin *et al.*, 2004). The GBR lagoon receives siliciclastic sediment from numerous rivers that discharge along the Queensland coast, most notably the Fitzroy and Burdekin Rivers (Alongi and McKinnon, 2005; Neil *et al.*, 2002; Orpin *et al.*, 2004). A recent study of sediment loads delivered to the GBR lagoon estimated that sediment load has increased by a factor of at least four since European settlement (Neil *et al.*, 2002).

The continental shelf in the southern GBR region is up to 200 km wide (Page and Dickens, 2005), and gradually slopes to the shelf margin, which is lined with numerous reef platforms that form the Capricorn and Bunker Groups (Maiklem, 1968). These platform reefs differ from the ‘ribbon’ reefs of the northern GBR in that they are divided by wide channels, therefore the southern GBR lagoon experiences greater exposure to oceanic currents and swell energy. Earlier work on the southern Queensland continental shelf by Marshall (1977) found high-feldspar terrigenous sands to the north-east of Keppel Bay, and predominantly carbonate sands to the south-east. Surface water circulation on the GBR continental shelf is dominated by the southward flowing East Australian Current (EAC), from which a clockwise gyre brings cool, nutrient rich waters into the southern GBR (Kleypas and Burrage, 1994). The region experiences relatively stable southeasterly ‘trade’ winds from May to December. Tropical cyclones generally occur between December and April, and are accompanied by heavy rain, strong winds, and erosive middle shelf current flows (Marshall, 1977; Larcombe and Carter, 2004).

Study area

Keppel Bay is a large, turbid, macrotidal embayment that forms the interface of the Fitzroy River Basin with the GBR Lagoon and Coral Sea (Figure 1). The study area encompasses 1135 km^2 between the bedrock Great Keppel and

Curtis Islands, and straddles the Tropic of Capricorn in the southern region of the Great Barrier Reef Marine Park (GBRMP). The large, extensively cleared 144,000 km^2 catchment of the Fitzroy River is geologically diverse, and includes the Thompson Fold Belt, the New England Fold Belt, the Bowen Basin, and the Surat Basin. The southern portion of the study area is bordered by salt flats, mangroves, and tidal creeks associated with the mouth of the Fitzroy River. Keppel Bay is bounded to the west by Long Beach and an elongate beach-ridge plain that extends northwards to the rocky coast adjacent to Great Keppel Island. A comprehensive study of modern sediments and hydrodynamics of the central Queensland coast that includes Keppel Bay was undertaken by the Queensland Government in the late 1970s (Beach Protection Authority, 1979). The study found that sediments from the Fitzroy River are transported into Keppel Bay predominantly during flood events, and sand is then advected northwards. Stained, probably relict terrigenous sediments were identified in waters below the 20 m isobath.

Large-volume floods in the Fitzroy River are produced by intense summer rainfall events produced by monsoonal depressions and cyclones, and are linked to the longer-term El Niño Southern Oscillation (ENSO) climate cycle (Devlin *et al.*, 2001; Kelly and Wong, 1996). Tides within Keppel Bay are semi-diurnal, with a maximum tidal excursion of 5 m. The tides typically rise and fall across gently sloping beaches with average widths of approximately 200 m, and enter Keppel Bay from the south, and exit to the north (Patterson, 1980). Inshore water temperatures range from 14 to 37ºC (Coates, 1998).

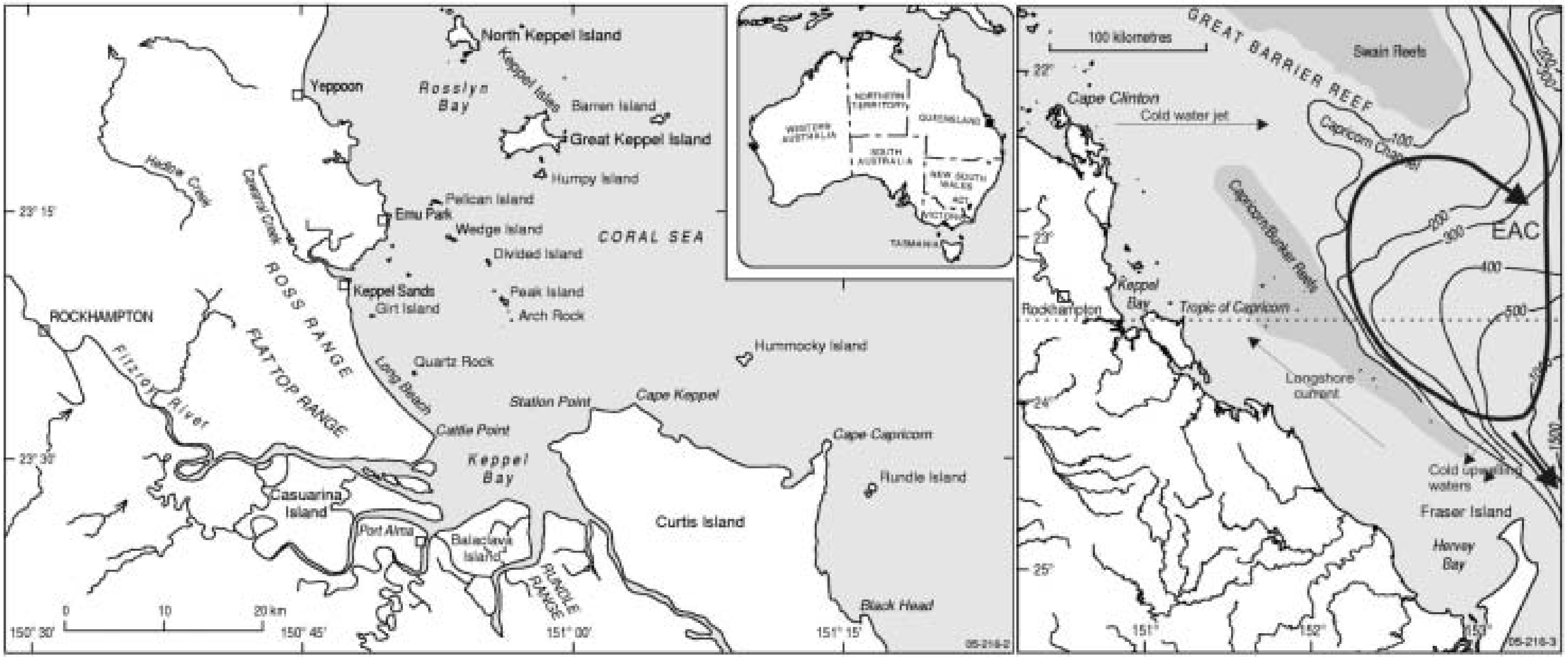

Figure 1: Location of the Fitzroy River, Keppel Bay, and the southern Great Barrier Reef region, north-eastern Australia.

Materials and methods

Study design

This study of the surface sediments and benthic geomorphology of Keppel Bay was undertaken as part of a large, interdisciplinary research project that aims to characterise the transport of pollutants from the catchment of the Fitzroy River, through Keppel Bay, to the GBR shelf (Noble *et al.*, 2005). This work builds upon the Beach Protection Authority (1979) work by strategically sampling the mapped sediments, and further characterising these depositional environments using a combination of sediment analyses, modelled seabed shear stress, multibeam bathymetry, and sub-bottom profiles. The relationships between, geomorphology, benthic sediments, sediment transport, human impacts and habitat distribution are then explored.

Field program and data acquisition

Sediment sampling, using a hand deployed 0.5 litre grab-sampler, was conducted during three dry season field surveys in 2003 and 2004 (Radke *et al.*, 2005) with the objective of obtaining a wide spatial coverage of samples. A total of 141 sediment samples were acquired from throughout Keppel Bay, however sample coverage was constrained by inaccessible shallow sand banks and the size of the study area (1135 km^2). A Datasonics CAP-6600 Chirp II acoustic profiling system (Datasonics, 1999; Bostock *et al.*, 2005) was used to characterize the broad scale seabed morphology and shallow subsurface of Keppel Bay. The system was set to sweep though a frequency range of 1–10 kHz, providing a range resolution of approximately 7.5 cm. A relatively high-resolution (centimetre vertical, decimetre horizontal) Reson™ Seabat 8125 multibeam sonar system was used to delineate beforms and physical features of the substrate for targeted areas. The multibeam system emits acoustic energy at a frequency of 455 kHz, and resolves signals returning from the seabed into 240 focussed beams in an arc 120° across track, and 1° along track. Bathymetry data were acquired for areas of interest that were identified in sub-bottom profiles, such as Centre Banks, Peak Island/Arch Rock, the main shipping approach channel, and the Port Alma swing basin (Figure 2). To provide an indicator of the hydrodynamic energy across Keppel Bay, seabed shear stress was modelled and transformed into a grid of mean and maximum bed velocities and shear stress. The velocities were simulated with a 3-d fine-resolution nonstationary nonlinear hydrodynamic model (Walker, 1999), driven with realistic winds, surface elevation and fresh water discharge. The predicted currents were used to calculate bottom friction assuming log-profile distribution of the horizontal velocity components within the bottom boundary layer. The modelled period covered neap-spring tidal cycles characterised with calm weather conditions.

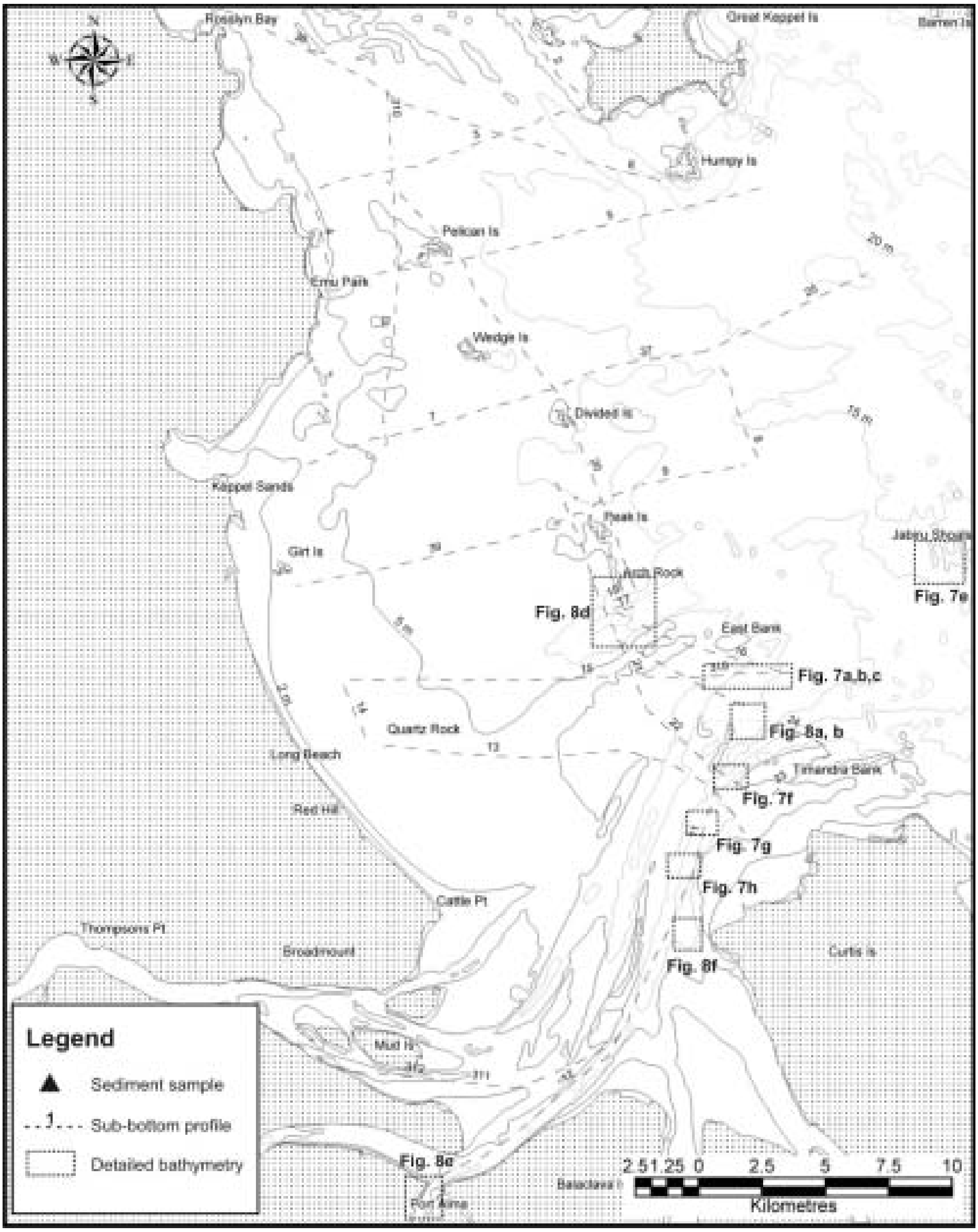

Figure 2: Sediment sample sites, chirp sub-bottom profile lines, and multibeam echo sounder coverage in Keppel Bay. Bathymetric contours simplified from Australian Hydrographic Service (2000).

Data analysis

Maps of sample locations and data interpolation were undertaken using ESRI^{TM} ArcGIS 8.3 software, and projected into the UTM Zone 56 (south). Grain size analyses were conducted on sediment samples using standard mesh-sieves, providing the mud:sand:gravel ratio, and also with a Malvern laser grain size analyser, providing a volume-percentage grainsize data (Folk and Ward, 1957; Folk *et al.*, 1970). The proportion of $CaCO_3$ was determined using the $CaCO_3$ 'bomb' gas evolution method (Muller and Gastner, 1971), and selected sediment grab samples were analysed for mineralogy using X-ray diffraction (Radke *et al.*, 2005). Interpolated percentage gravel, sand, mud, $CaCO_3$, feldspar, as well as grainsize sorting, bathymetry, and maximum shearstress layers were merged to form a multiband raster in the ERMapper 8.4 software. An ISOCLASS unsupervised classification algorithm (Richards, 1993) was used to transform the multiband raster data into appropriate thematic information classes. The algorithm determines natural groupings or clusters of properties in the 8 dimensional feature space of the input data. Each data cell is then placed into a user specified number of classes constrained by parameters defining where classes are to be split or merged (Richards, 1993). A maximum of five cluster classes was selected, which showed maximum statistical separability of the data clusters, whilst minimising obvious data artefacts.

The 32-bit SEG-Y format sub-bottom profiles were imported into Chesapeake TechnologiesTM SonarWeb Pro software for post-processing, and interpretation (Bostock *et al.*, 2005). The echo character of sub-bottom profile lines was interpreted using a classification scheme based on the Damuth (1975, 1980) method. This procedure effectively summarises numerous sub-bottom profiles, providing a means by which relative changes in sediment type may be assessed. The character of bottom returns for all data were examined to develop a classification system specific to Keppel Bay (Table 1). Although relatively qualitative, this method has been effectively used to classify both deep and shallow-water sediments in numerous studies (e.g. Blum and Okamura, 1992; Whitmore and Belton, 1997).

Single beam acoustic bathymetry data were acquired from the Hydrographic Office (Australian Hydrographic Service, 2000; Webster *et al.*, 2005), providing a broad-scale bathymetric representation of Keppel Bay. Multibeam sonar data were processed using Caris HIPS/SIPS 6 software, and soundings were decimated into 0.25 m^2 grid cells. All bathymetry data for Keppel Bay is corrected to mean low water.

Table 1: Echo character classification scheme for Keppel Bay, modified from Damuth (1975, 1980).

Echo Character	**Interpretation**	**Equivalent Damuth (1975, 1980) Classification**
1) Distinct with no sub-bottom reflectors	Poor penetration, massive sand	IA
2) Semi-prolonged with intermittent parallel sub-bottom reflectors	Shallow single reflector at 1-4m depth, muddy sands	IIA, IIB
3) Distinct with non-conformable sub-bottom reflectors	Prograding angled bedding, muddy sands to sandy muds	IC
4) Semi-prolonged with numerous parallel sub-bottom reflectors	Thick, well bedded, low density, muds	IIA–IB

Results

Surface sediments

Physical properties

Eight spatial datasets were analysed to assess the physical character of the Keppel Bay benthic environment (Figures 3. and 4). These include bathymetry derived from navigation data (Australian Hydrographic Service, 2000; Webster *et al.*, 2005), maximum seabed shear stress predicted by a numerical model (Walker, 1999), proportions of $CaCO_3$ and feldspar, and sediment grain properties including percentages of mud, sand and gravel, and grainsize sorting. Bathymetrically, Keppel Bay is shallow and low gradient, with an average slope of 0.05° between the coast and the 20 m isobath (Figure 3a). Seabed geomorphology is more complex in the south, comprising deep (15–20 m) channels, interspersed with shoals such as Timandra Bank, Centre Bank and East Bank. A bedrock ridge crops out through the centre of the bay as a line of reefs and islands. There are large-scale longitudinal subaqueous dunes between Rosslyn Bay and Great Keppel Island, indicating northward bedload sediment transport.

The seabed shear stress model (Figure 3b) shows high potential for sediment transport adjacent to the Fitzroy River mouth, associated with the deeper tidal channels (Figure 3a). High seabed shear stress occurs on shoal areas, such as Centre Bank, however there is a region of moderate shear stress in inner Keppel Bay. Carbonate bioclastic material (predominantly gravel-fraction bivalves and gastropods) occurs primarily in outer Keppel Bay (Figure 3c). The highest proportions of feldspar appear close to Long Beach, and tend to be low in the north east of the study area (Figure 3d). The proportions of mud, sand and gravel in sediment samples (Figure 4a, b, and c) indicate that fine sediments occur in channels, and adjacent to northern Long Beach. Gravel-bearing sediments are generally associated with shoal areas such as Centre Banks, and adjacent to Long Beach. Sediments tend to be well sorted in these areas and in shoals adjacent to Cattle Point (Figure 4d).

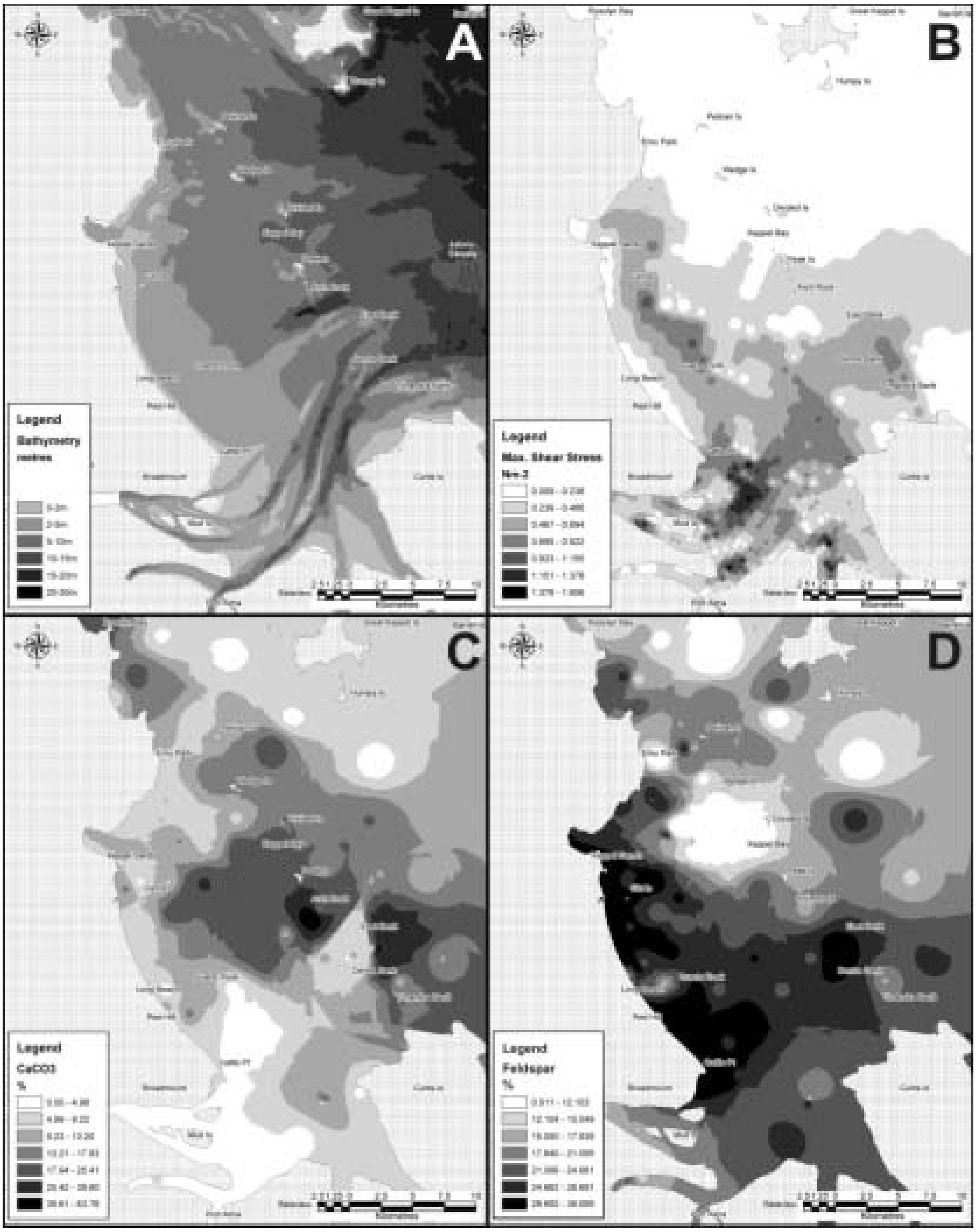

Figure 3: Interpolated surficial properties of Keppel Bay, including A) bathymetry, B) maximum seabed shear stress, C) % $CaCO_3$, and D) % feldspar content.

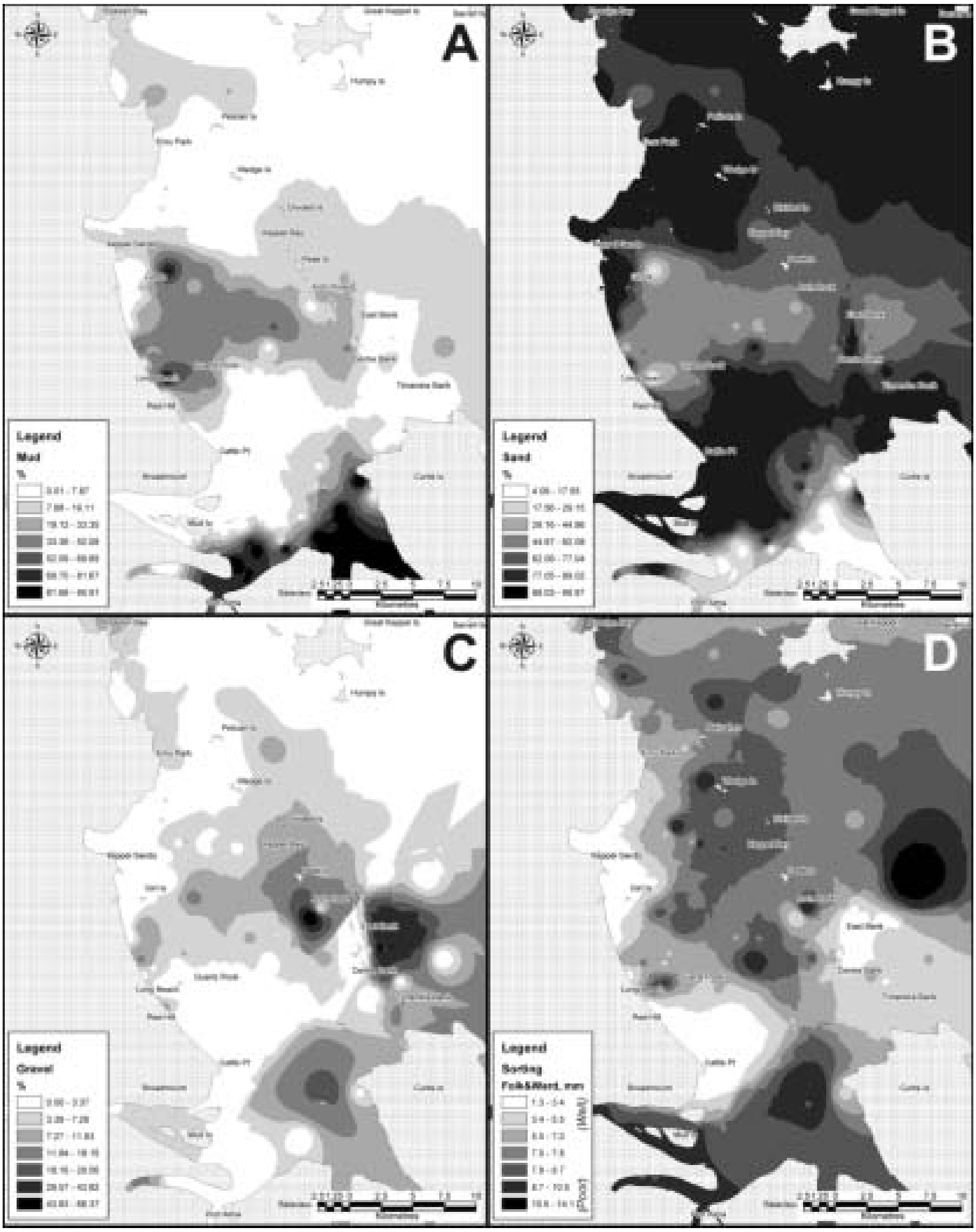

Figure 4: Interpolated sediment grain properties of Keppel Bay, including A) % Mud, B) % Sand, C) % Gravel, D) sorting coefficient (Folk and Ward, 1957).

ISOCLASS unsupervised classification

The surficial sedimentary features of Keppel Bay (Figures 3, 4) were integrated to identify and spatially delineate five discrete seabed facies (Figure 5). Summary statistics for the sedimentary properties of each of the five facies are provided in Table 2.

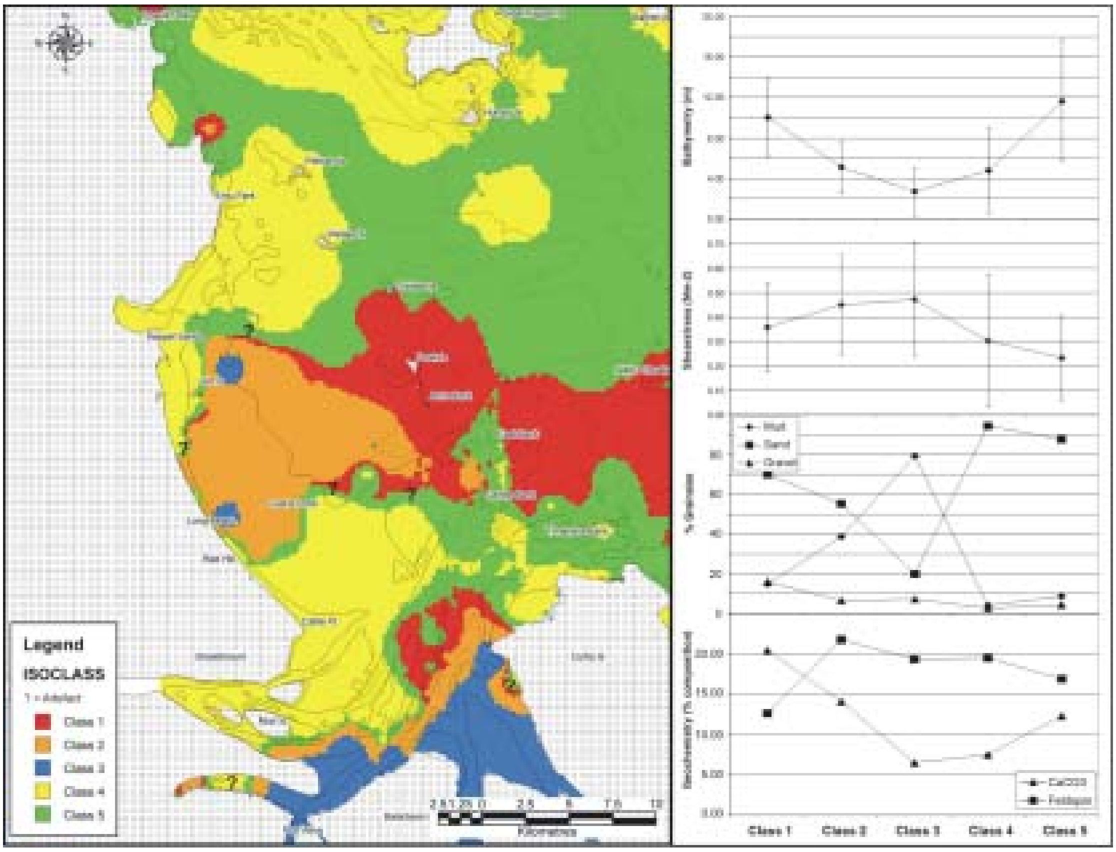

Figure 5: Results of the ISOCLASS unsupervised classification of bathymetry, seabed shear stress, percentage compositions of CaCO3 and feldspar, grainsize sorting, and percentages of mud, sand, and gravel. Plots of sample statistics are shown for each class.

Table 2: Statistics for the 5 surface sediment facies areas in Keppel Bay. Increasing value of sediment sorting parameter indicates poorly sorted sediments (Folk and Ward, 1957).

Variable		Inner shelf Carbonates	Inner bay Muddy sand	Estuarine mud	Inner bay Sand	Outer bay Relict sand
	Area (km^2)	**152.84**	**116.20**	**61.24**	**364.36**	**440.00**
Sorting (um)	Range	9.07	7.76	7.04	8.61	12.41
	Mean	6.72	7.02	8.17	6.18	7.40
	St. Dev	1.76	1.41	1.13	2.10	1.60
Depth (m)	Range	19.83	15.93	13.39	18.69	23.98
	Mean	10.02	5.08	2.72	4.81	11.66
	St. Dev	3.82	2.57	2.35	4.24	5.93
% $CaCO_3$	Range	60.96	25.70	16.91	25.89	22.59
	Mean	20.40	14.09	6.50	7.53	12.30
	St. Dev	7.35	6.34	2.59	3.15	3.93
% Feldspar	Range	30.42	39.54	32.27	35.72	36.47
	Mean	12.63	21.72	19.30	19.48	16.86
	St. Dev	6.15	7.92	4.38	6.78	3.93
% Gravel	Range	56.58	24.43	16.53	13.23	20.53
	Mean	16.01	6.58	7.27	2.38	4.38
	St. Dev	9.64	4.00	4.38	2.50	3.37
% Mud	Range	31.02	38.04	40.41	17.07	25.10
	Mean	14.79	38.69	79.27	3.95	8.78
	St. Dev	5.55	7.63	8.98	2.54	5.01
% Sand	Range	46.93	41.99	35.80	17.67	24.43
	Mean	70.15	55.15	19.97	94.60	87.57
	St. Dev	7.66	7.69	8.20	2.61	5.58
Max. Shear	Range	0.96	1.10	1.52	1.41	1.09
Stress	Mean	0.36	0.45	0.47	0.31	0.23
	St. Dev	0.18	0.20	0.23	0.27	0.17

The classification map (Figure 5) displays an acceptable level of spatial homogeneity, however, high variability and a low density of samples in the channel area in southern Keppel Bay have led to some unrealistic heterogeneity. The reliability of the classification surface is dependant on the density of sample sites, and the interpolation techniques used. Steep gradients in surface values have produced artefacts on the classified map, for example in the vicinity of Keppel Sands and Girt Island (Figure 5).

Marine acoustics

Sub-bottom profiles

The four classes of sub-bottom profiles reflect differences in echo character, which is largely influenced by the proportion of mud and degree of bedding in the sedimentary deposits (Table 1; Figure 6). The north and outer areas of the bay and the nearshore adjacent to Long Beach exhibit distinct to semi-prolonged echograms, indicating a massive, well packed sand (Table 1). The presence of semi-prolonged echograms with intermittent sub-bottom reflectors in these areas also suggests muddy sands. In contrast, southern Keppel Bay (south of Peak Island and west of Quartz Rock, Figure 6) features echograms that are distinct to semi-prolonged with numerous sub-bottom reflectors. These echograms may be interpreted as primarily muddy sediments that are better penetrated by the acoustic signal. In general, northern and outer Keppel Bay are characterised by dense, sandy material, whereas the southern portion of Keppel Bay is highly heterogenous and comprises thick, well-bedded deposits. Infilled channels occur in numerous locations, particularly below the relatively planar seabed sediments that lie between Long Beach and the line of islands in the centre of the bay (Pelican, Divided, Peak and Arch islands). Lower density muddy sediments appear in the sub-bottom profiles in the vicinity of Port Alma, within the main tidal channels of the Fitzroy River mouth.

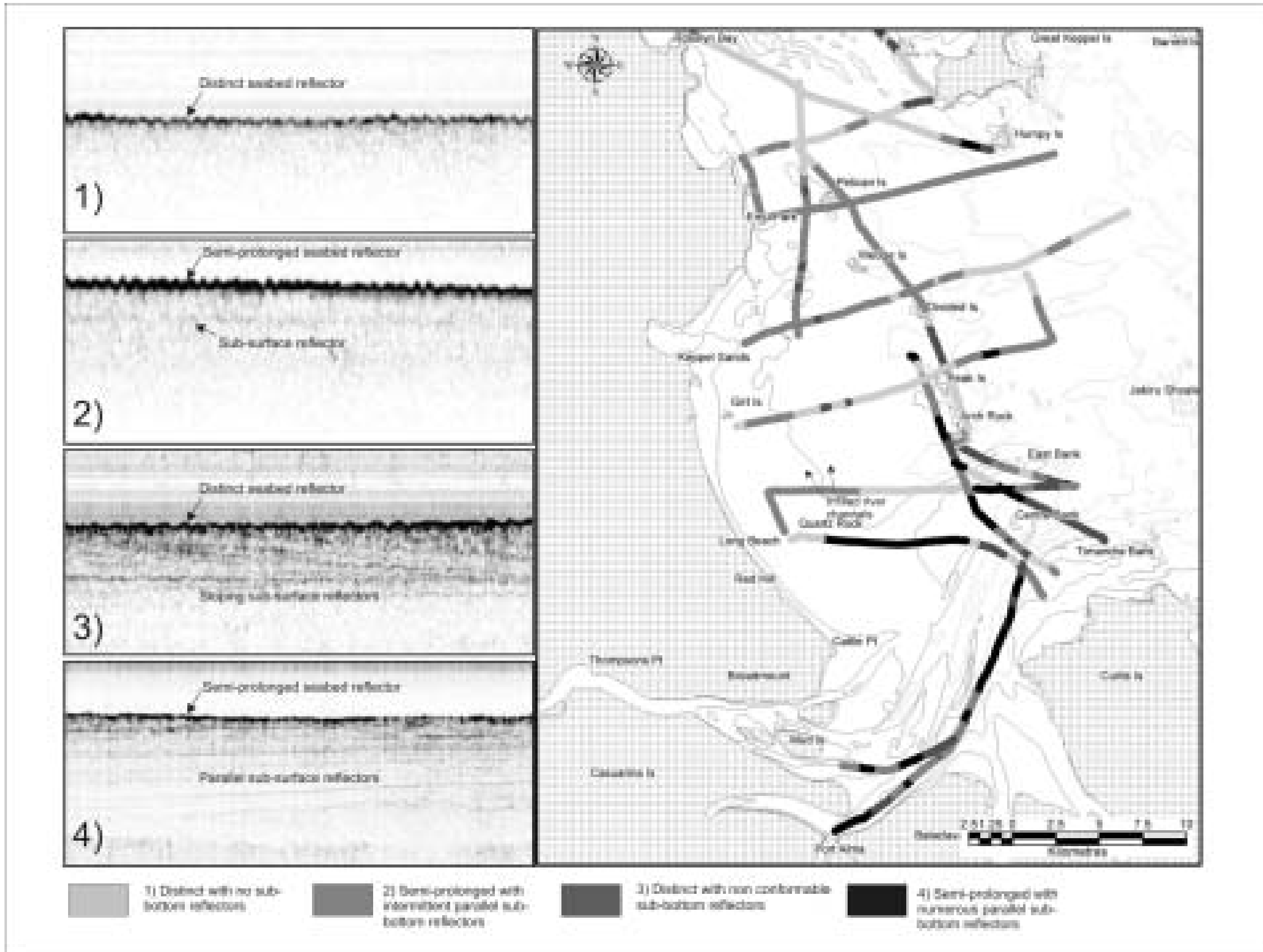

Figure 6: Sub-bottom profile echo character classes derived from chirp system, based on the system developed by Damuth (1975, 1980), including examples of sub-bottom profiles, and map of acoustic echo character classes.

Sonar bathymetry

An overview of the bathymetry of Keppel Bay and the adjacent continental shelf, derived from single beam sounding data, is provided (Figure 7). Inner Keppel Bay (between Curtis and Great Keppel islands) appears mostly flat (Figure 3a), with numerous channel incisions in the south and outer parts of the bay. The continental shelf itself is relatively broad and shallow, and to the west of the reefs of the Capricorn/Bunker Group is relatively flat (Figure 7), however, a bathymetric feature corresponding to a major palaeochannel or relict incised valley of the Fitzroy River can be seen offshore from Keppel Bay. The channel appears to run in a north-easterly direction (between North West Reef and Douglas Shoal), and is of comparable width and sinuosity to the modern day Fitzroy River. The sinuosity ratio of the channel is 1.56, consistent with a stable meandering river system, which typically occur on slopes of <2° (Rosgen, 1994).

The seabed morphology of selected representative areas of Keppel Bay is revealed in detail by the multibeam sonar dataset (Figs 2, 8, 9). The area mapped on Centre Bank features a field of large asymmetric dunes or sand ribbons (Figure 8a; Dalrymple and Rhodes, 1995). Relict truncated beds are exposed in the underlying planar surface, steeply dip to the north-west and are partially covered by the mobile dunes (Figure 8a, 8d). The dunes rise from an average depth of 10.5–7 m water depth (Figure 8a), with a wavelength (λ) of 100–150 m. The dunes are overprinted by much smaller ripples, with amplitudes of 0.2 to 0.5 m, and λ of 5–10 m (Figure 8c). Further subaqueous dunes, with similar magnitude and orientation, occur on Jabiru Shoals at the eastern margin of the bay (Figure 8e).

Various beforms are evident in the multibeam bathymetry of the main shipping channel. These include V-shaped, barchanoid, symmetrical and asymmetrical dunes, oriented in various directions (Figure 8f, g, h). Additionally, smaller ripple features (Figure 8c) are common in shallower sandy areas.

Evidence of significant erosion of the seabed is also apparent in parts of the shipping channel (Figure 9a, b, c, f). Exposed truncated and inclined beds were observed in both the multibeam and sub-bottom profiles (Figure 9a, b, c). The multibeam example (Figure 9b, 9c) shows bedding oriented in a NNE-SSW direction, partially overlain by a large subaqueous dune. Evidence of the scouring and erosion of mud is also apparent immediately west of Curtis Island (Figure 9f). This erosion of the mud deposits probably adds to the turbidity of the estuary.

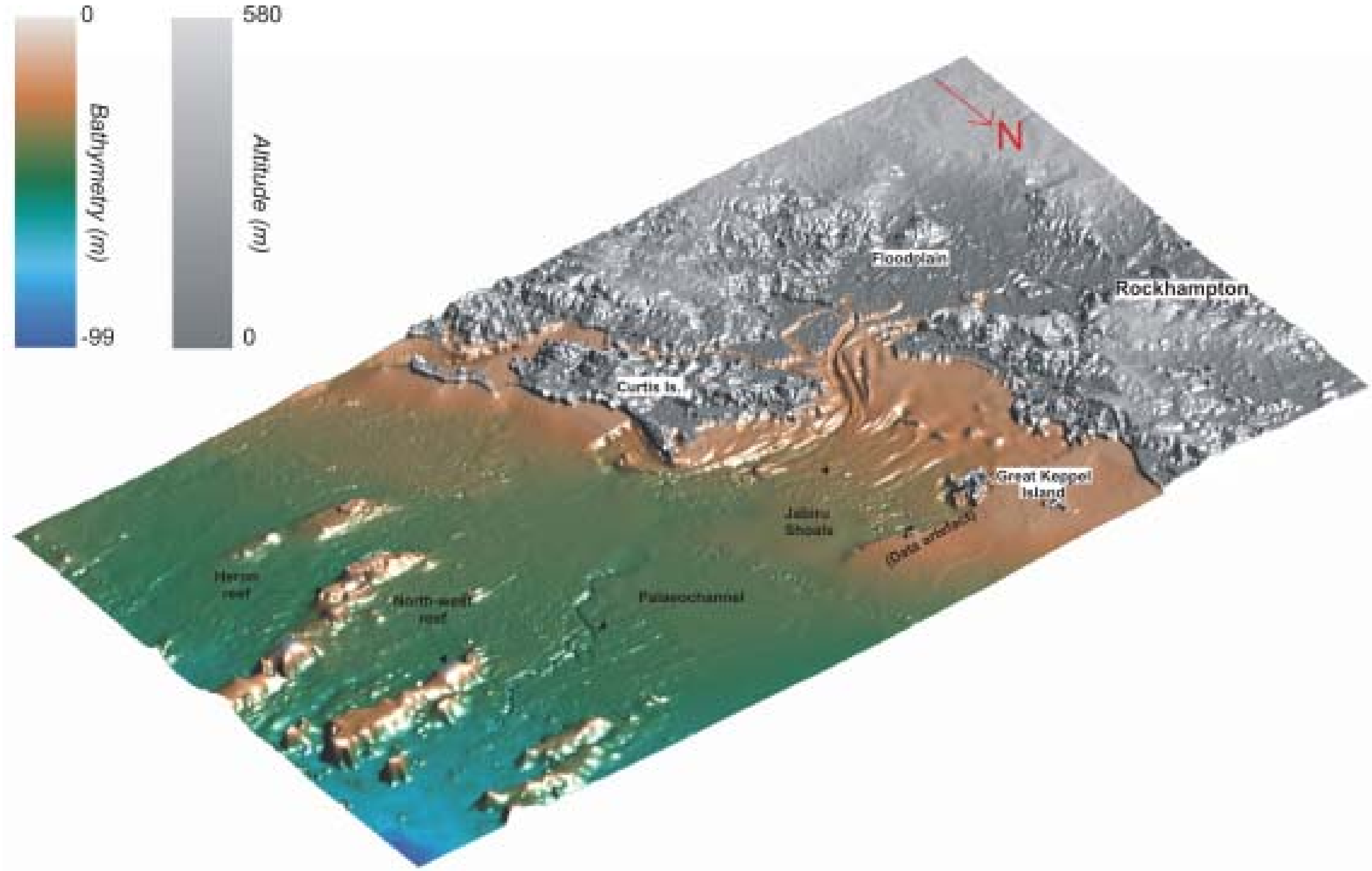

Figure 7: Digital elevation model of the Fitzroy River floodplain, Keppel Bay, the continental shelf, and reefs of the Capricorn Bunker group, after Webster and Petkovic (2005).

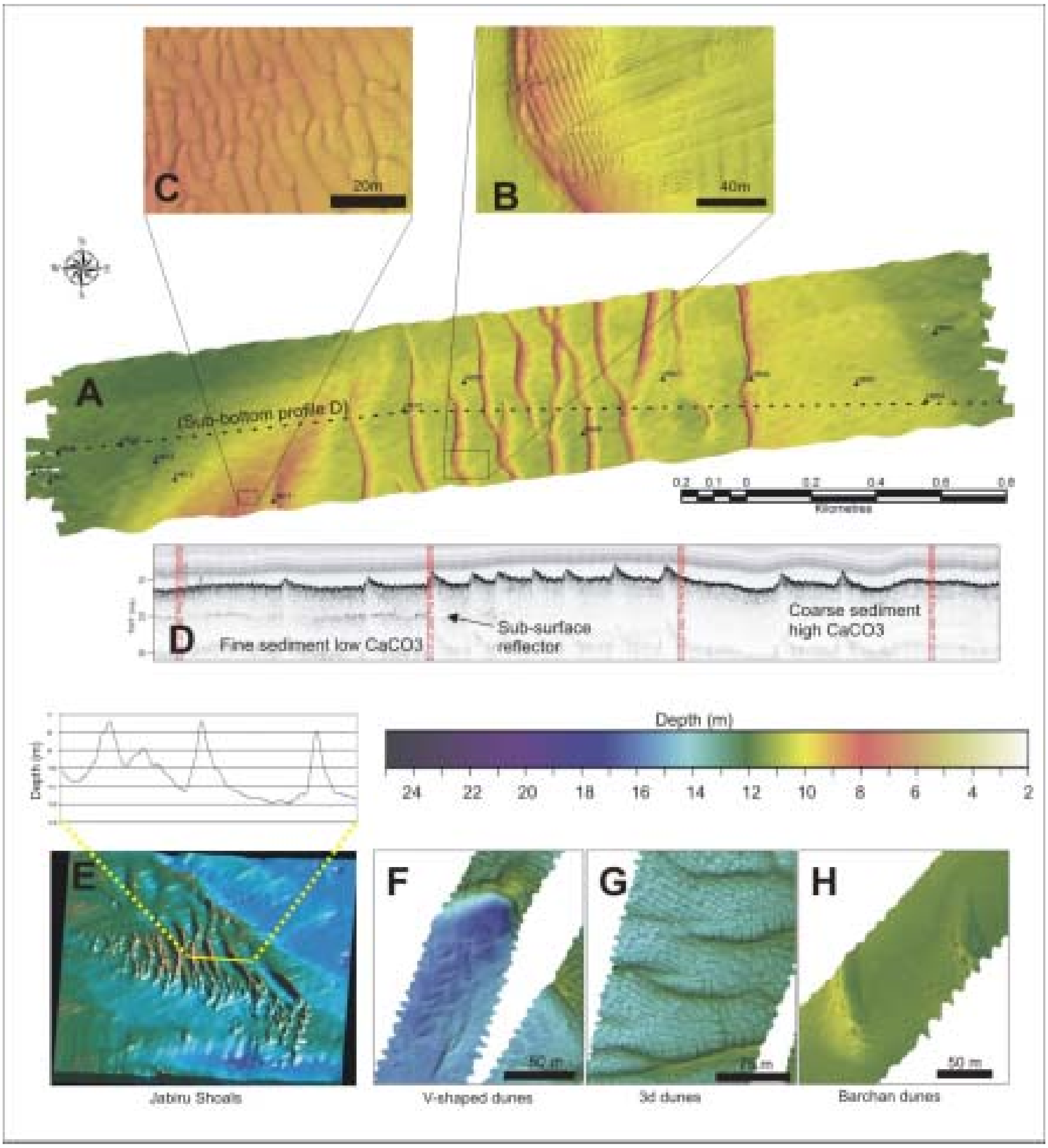

Figure 8: Selected sonar data for the seabed of Keppel Bay, including multibeam sonar for the Centre Bank dunes (A, B) and wave ripples (C); sub-bottom profile across Centre Banks (D); single-beam acoustics DEM of Jabiru Shoals (E); and various multibeam sonar examples of sediment bedforms from the shipping channel (F, G, and H).

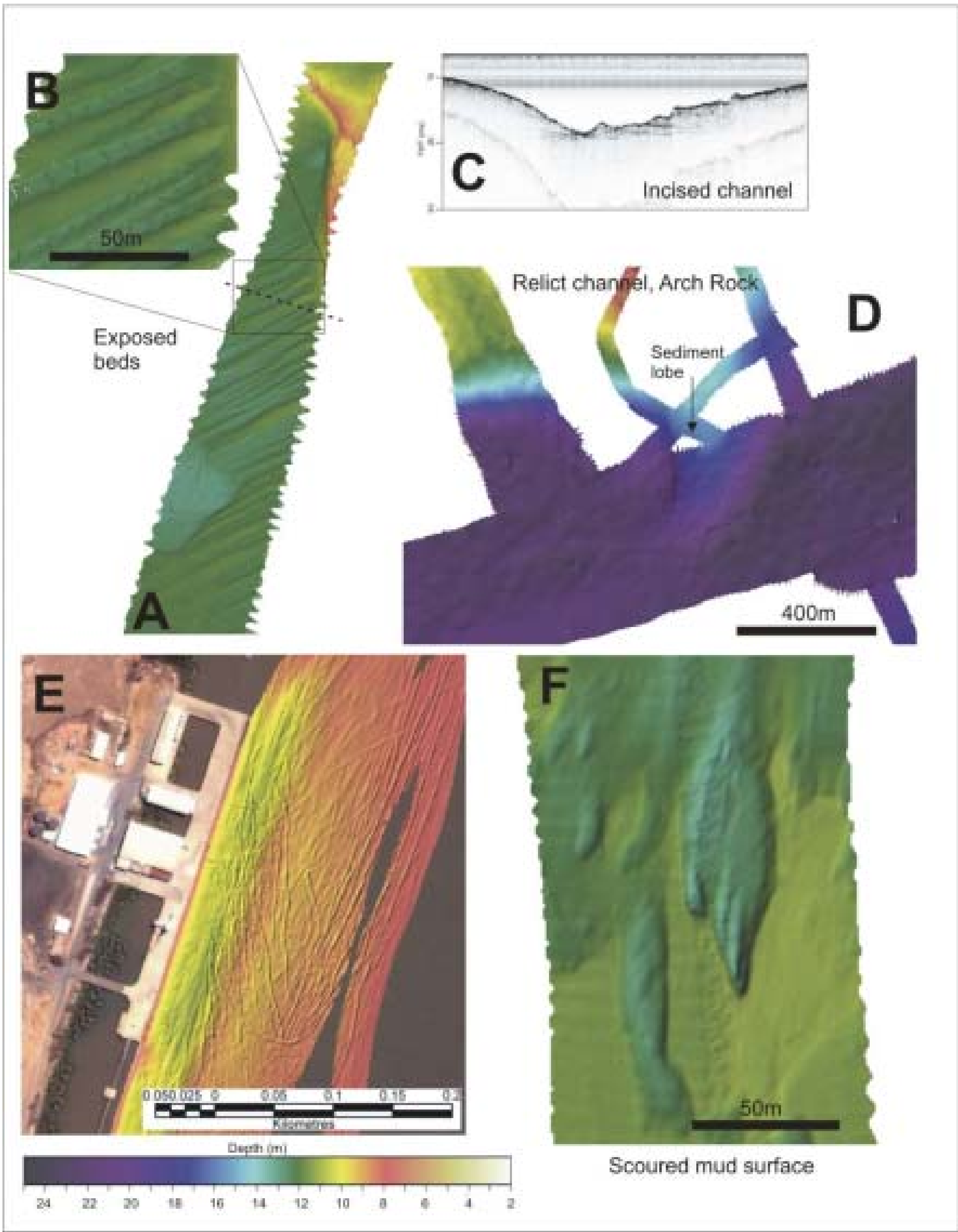

Figure 9: Selected sonar data for the seabed of Keppel Bay, including multibeam sonar for truncated sediment beds (A, B); sub-bottom profile for the same (C); deep relict channel near Arch Rock (D); propeller scour marks at Port Alma (E)*; and scoured mud surface in shipping channel (F).*

The deep channel to the south of Arch Rock (Figure 9d) has a predominantly smooth surface, 20 to 22 m deep. Small mounds (0.5 m relief) occur on both the northern and southern margins of the channel at slightly less than 15 m depth, which are likely to be coral or algal bioherms. A lobe of sediment extends from

Arch Rock into the channel, suggesting that it is being infilled with mostly carbonate sediments derived from around the islands to the north (Figure 9d). The shallow seabed in this area (<12 m depth) features a hummocky morphology which may reflect clumps of seagrass or macroalgae.

The swing basin for ship access in Port Alma, a commercial port located within Raglan Creek one of the deeper tidal creeks to the south of the Fitzroy River mouth. The multibeam data shows a mainly planar muddy seabed (Figure 9e). Backscatter intensity imagery and grab samples from this area indicate that the substrate is predominantly mud. Scours in the swing basin and shipping channel are clearly evident in the imagery. These numerous linear depressions appear to be propeller scour produced by the merchant ships that visit the port. These scours are approximately 0.5 m deep and 5 m wide (Figure 9e).

Discussion

Geomorphology of Keppel Bay

Keppel Bay has been shaped through the interplay of macrotidal currents, and the wind and wave regime with bedrock islands, relict seabed morphology, and sediment input from terrestrial and marine sources. We have characterised the seabed of Keppel Bay into five geomorphic facies using an ISOCLASS procedure (Figure 5) and characterise the geomorphology in sub-bottom profiles, multibeam sonar and bathymetry data. These facies include: Estuarine Muds, Inner Bay Sands, Inner Bay Muddy Sands, Inner Shelf Carbonates and Outer Bay Relict Sands. These facies and their full geomorphic context are described below.

Estuarine muds

Tidal currents have produced and maintain the muddy intertidal flats, elongate channels, and sand banks in the estuary mouth and southern bay (Figure 3a), which are typical of macrotidal systems in other regions (Dalrymple *et al.*, 1992; Fitzgerald *et al.*, 2000). As Curtis Island is located immediately to the southeast of the mouth of the Fitzroy River, it protects this area from the dominant wind and wave regime. As a consequence, fine sediments accumulate in the river mouth and southern Keppel Bay adjacent to the main tidal channels (Figures 4a, 5), and the area between Port Alma and Curtis Island. Very low density sediment, probably prograding estuarine mud banks, also occurs in the vicinity of Port Alma (Figure 5). Seabed shear stress values are very high in banks in the estuary mouth and southern bay, possibly due to tidal amplification in the funnel shaped channels, and result in significant fine sediment resuspension (e.g. Figure 9f). Sediments on the channel bed appear to be coarse, likely representing the lag from the eroded muddy deposit. Dunes on the channel bed north of Balaclava Island indicate multi-directional transport of this bedload, which would switch over the tidal cycle. Chirper profiles show that the channels are underlain by thick, relatively well bedded sediments, which suggests that in this area the channels are infilling. Similar depositional settings for fine sediment have been described in other northward-facing bays in the GBR (Orpin *et al.*, 2004; Neil *et al.*, 2002), however, in Keppel Bay this deposition occurs proximal to the river mouth rather than in distal bays as is the case for the Burdekin River (Orpin *et al.*, 2004).

Inner bay sands and muddy sands

The line of islands and reef in the middle of Keppel Bay effectively divide the inner and outer bay. Here, enhanced tidal flow adjacent to the outcrops maintains the relict channels (e.g. Arch Rock, Figure 9d). These channels are evident throughout Keppel Bay and mostly record past courses of the river channel during periods of low sea-level (middle and outer bay) and currently active and abandoned tidal channels (southern bay; Figure 3a).

Inner Keppel Bay is dominated by the large sand bank that extends north from the mouth of the Fitzroy River (Figure 4b), and sand facies occur adjacent to Long Beach, and in much of the northern inshore area. These deposits typically comprise well-sorted and coarsely skewed sandy sediment, low proportions of mud, gravel, and $CaCO_3$, and high feldspar. Chirper lines in this region also indicate mainly sand, with little subsurface bedding evident in lines to the north. These sediments are typical of the sand that is deposited in Keppel Bay during flood events (Beach Protection Authority, 1979). To the south-east of Quartz Rock, more distinct bedding in the sub-bottom profiles suggests significant accumulation of this river-derived sediment (Bostock *et al.*, 2005). In the south of this facies area, a large sand bank extends from Cattle Point towards East Bank. Muddy sand facies also occur in the middle of Keppel Bay through to Long Beach. This shallow region comprises moderately sorted muddy sand with minor gravel. Seabed shear stress is relatively high, suggesting significant sediment reworking and transport. The proportion of feldspar is relatively high, and $CaCO_3$ moderate (typically *in situ Turitella* gastropods), reflecting the strong input of Fitzroy River sediment and localised biogenic input. Remnant infilled channel features are visible on several chirp lines in this area (Figure 6), indicating that it has long been an area of sediment accumulation. However, semi-prolonged echograms for most of the area covered by this facies show little stratigraphic information.

Outer bay relict sands

Surface sediments in the deeper water northern and eastern parts of Keppel Bay comprise poorly sorted quartz sand with moderate proportions of $CaCO_3$, feldspar and lithic grains, and relatively low proportions of mud and gravel (Figure 4). This sediment is being reworked into the bay from offshore. Bed shear stress in this area is very low, and chirp sub-bottom profiles indicate predominantly well-sorted sands with little discernable bedding. This facies is primarily composed of terrigenous sediment and represents the stained, relict shelf deposits described by the Beach Protection Authority (1979), and Marshall (1977). The adjoining continental shelf shows bathymetric evidence of a palaeochannel of the Fitzroy River (Figure 7), suggesting that the quantity of sediment that has accumulated on the shelf has been insufficient to fill the channel depression. From this, it may be inferred that sediment accumulation rates on the shelf are probably low, and rates of onshore sediment transport or erosion are probably high. This contrasts with the palaeochannel of the Burdekin River, which has been covered by modern sediments and was revealed using sub-bottom profiles (Fielding *et al.*, 2003).

Inner shelf carbonates

The outer southern portion of Keppel Bay, bordering the eastern part of Centre Bank and the Peak Island/Arch Rock area is very dynamic, with highly variable bathymetry due to channels (Figure 3a). The shallow banks of the middle, outer and northern bay are mantled by large-scale bedforms that indicate these relatively coarse sediments are derived from further offshore (Figure 8). Sediments are moderately sorted, and coarse skewed with relatively high proportions of gravel and sand, while $CaCO_3$ is high, comprising both reworked and fresh biogenic material, and feldspar is low. The area known as Centre Banks straddles this facies and the Outer Bay Relict Sands, and most likely these different types of sediments are mixed in this area (Figure 5). The area shoals to a depth of 3 m, is bordered by deep channels (20 m), and strong tidal currents, up to 3.5 knots, have been reported here (Australian Hydrographic Service, 2000). Shallow sub-bottom reflectors imply this is an area of sediment accumulation. The orientation of the asymmetric dune bedforms suggests that sediment is being transported in a westerly (onshore) direction. A significant change in sediment character occurs across Centre Banks as $CaCO_3$ (gravel) decreases, while feldspar and the degree of sediment sorting increase. This suggests that the coarse, poorly sorted carbonate-rich sediment of the shelf to the south-east of Keppel Bay (Marshall, 1977) is prograding over the finer, feldspathic material derived from the Fitzroy River.

Sediment sources, sinks and pathways

The distribution of the seabed facies (Figure 5), bedforms and zones of sediment accumulation identified in sub-bottom profiles (Figure 6) enable the development of a conceptual sediment transport model for Keppel Bay (Figure 10). The deposition of terrestrial sediment by the Fitzroy River occurs during flood events with a recurrence interval of at least two years (Devlin *et al.*, 2001). Sand and mud is deposited in the mouth of the estuary and southern inner Keppel Bay and forms a major or predominant component of the Inner Bay Muddy Sand, Estuarine Mud and Inner Bay Sand facies (Figure 5). A large component of the flood plume carries fine sediment out of Keppel Bay (Figure 10). Plumes often move northwards driven by southeasterly winds, however, dispersal to the east can result in turbid flood waters reaching Heron Reef on the outer shelf, as occurred in the flood event of 1991 (Brodie *et al.*, 2003). However, it is likely that this material does not significantly accumulate on the middle or outer shelf, and is advected onshore (Figure 7; Larcombe and Carter, 2004).

During the last 100 years the accumulation of fine sediment in and east of the river mouth has led to the expansion of mud banks and the development of new islands (Duke *et al.*, 2003). This style of muddy sediment accumulation is also reported for tide-dominated estuaries and deltas on the coast of northern Queensland (Bryce *et al.*, 1998, Dalrymple *et al.*, 1992) and the Fly and Sepik Rivers of New Guinea (Neil *et al.*, 2002; Walsh and Nittrouer, 2004). In Keppel Bay, however, fine sediment has also accumulated in protected pockets of the inner bay adjacent to Quartz Rock and Girt Island, and in relict channels in the outer Keppel Bay (Fig 4a). In the mouth of the estuary, this fine sediment is being eroded by tidal currents (Figure 9f). The asymmetrical tidal currents then move this fine sediment into the mangrove lined reaches of the estuary (Figure 10).

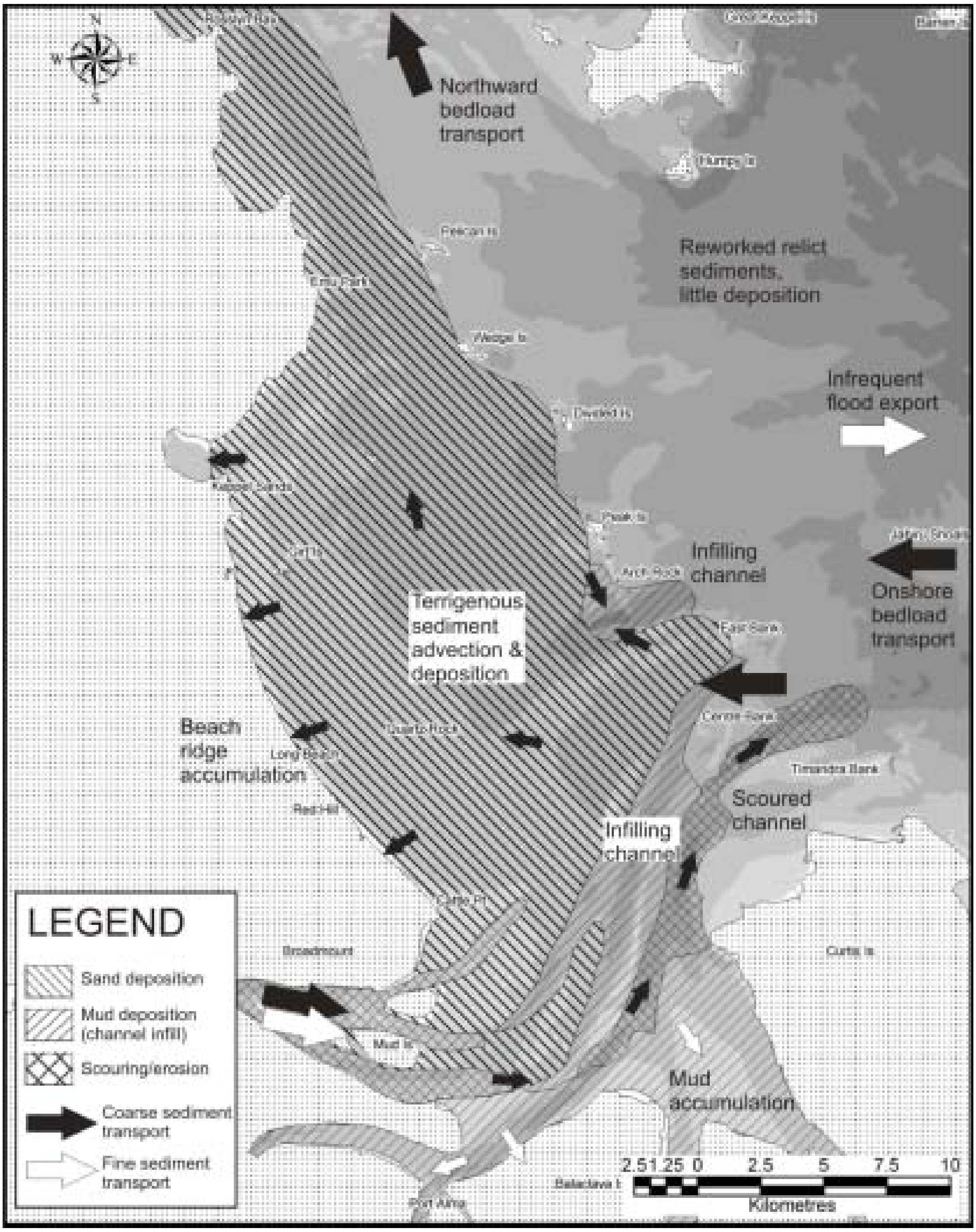

Figure 10: *Process related conceptual model of Keppel Bay, showing areas of fine and coarse sediment deposition, scouring, and sediment transport pathways.*

The continental shelf adjacent to Keppel Bay is significantly wider and the shelf-edge reefs less extensive than the northern GBR, which results in a greater wave fetch and swell exposure in the south (Maiklem, 1968). In combination with the macrotidal regime, onshore sediment transport, a dominant process under ‘dry season’ conditions in these tide-dominated systems (Bryce *et al.*, 1998), is pronounced in Keppel Bay. During the average prevailing marine conditions, the bedload material deposited during floods is moved northwards and onshore by advection (BPA, 1979; Figure 10). This sand is sorted as it moves alongshore and into Long Beach, where it accumulates in extensive intertidal and shallow subtidal flats and is ultimately reworked onto the beach and foredune. The extensive beach-ridge plain landward of Long Beach indicates there has been a long-term supply of this sand to the inner bay from the Fitzroy River (Beach Protection Authority, 1979).

Northern Keppel Bay is characterised by sandy sediments derived from the Fitzroy River, the Inner Bay Sand facies, and supplied from offshore, the Outer Bay Relict Sand (Figure 5). Large-scale longitudinal subaqueous dunes to the west of Great Keppel Island demonstrate that sand is being moved out of the bay to the north (Figure 10). In contrast, the outer north-eastern part of Keppel Bay presently appears to be sediment starved in terms of Fitzroy River sediment, and is characterised by well-sorted quartz sand of the Outer Bay Relict Sand facies. Low rates of sediment accumulation in this area are indicated by the presence of palaeo-channels that lack any significant accumulations of modern sediment.

Large-scale bedforms at Centre Bank and Jabiru Shoals in southern Keppel Bay show that coarse carbonate-rich sand is moving into the bay by advection from the shelf to the south and east of Cape Keppel (Outer Bay Relict Sand; Figures 5, 10). This sediment is probably mixed with the modern river-derived sediments (Inner Bay Sands) as it moves into the middle bay. Marine biogenic carbonate is a significant component of most surficial sediment facies in Keppel Bay, comprising approximately 7 – 20% of these deposits (Figure 5). Carbonate appears to be produced within the inner bay, for example well-preserved *Turitella* are ubiquitous in the Inner Bay Sand facies; and *in situ* carbonates are common around the islands of the middle bay. The Outer Bay Relict Sand and Inner Shelf Carbonates facies, in contrast, are characterised by shell fragments that are often stained, abraided and likely reworked from the inner shelf into the outer and middle bay (Figure 5). The study of Marshall (1977) also indicated a connection between the continental shelf and Keppel Bay because the southern GBR shelf province, characterised by high proportions of $CaCO_3$, extends to the southeast margin of Keppel Bay.

Models of the regional pattern of sedimentation on the GBR shelf suggest that only limited quantities of terrigenous sediment are transferred across the shelf, particularly in the central GBR coast (Orpin *et al.*, 2004). This lack of across-shelf transport is similar to the pathway of coarse Fitzroy River-derived sediment in Keppel Bay (Figure 10). The observed pattern of sedimentation within Keppel Bay fits previously published depositional models for a proximal terrigenous source and an indented depositional mainland coast adjacent to the GBR (Woolfe and Larcombe, 1999; Neil *et al.*, 2002). These models portray a terrigenous sediment wedge that is thickest immediately downdrift of the river or major sediment source, with additional areas of accumulation in northward facing, quiescent embayments further downdrift. The analysis of sediment samples from depositional sites to the north of Keppel Bay, in estuaries such as Corio Bay, Shoalwater Bay and Broad Sound (Cook and Mayo, 1977) is required to test whether the modern Fitzroy River sediment system extends such long distances downdrift as the models suggest.

Conclusions

Our assessment of the geomorphology and surface sediment facies of Keppel Bay provides the following new insights into the benthic sedimentary processes in tropical, macrotidal systems.

1. Relict fluvial channels and abandoned tidal channels were found to exert a strong control on the distribution of depositional environments in the bay. This was in addition to tidal currents, the local wind and wave regime and the bedrock configuration.

2. Five seabed facies were identified on the basis of sediment and shear stress data comprising various proportions of local river-derived quartzose-feldspathic sand and mud, local biogenic carbonate, and reworked marine quartzose and carbonate sediments.

3. Sediment and acoustic data were used to identify various pathways of sediment in Keppel Bay: i) Modern fluvial sediments deposited in the bay are reworked by advection northwards and onshore; ii) Mud deposits in the mouth of the estuary in places are scoured by tidal currents. This sediment likely adds to the turbidity of the bay and accumulates in the mangrove areas of the estuary; iii) Relict terrigenous and marine sediment is moved by advection into the bay from the shelf.

4. Multibeam bathymetry and sub-bottom profiles provide additional insights into the character of the seabed facies areas in terms of their stability, sediment transport direction and depositional history.

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