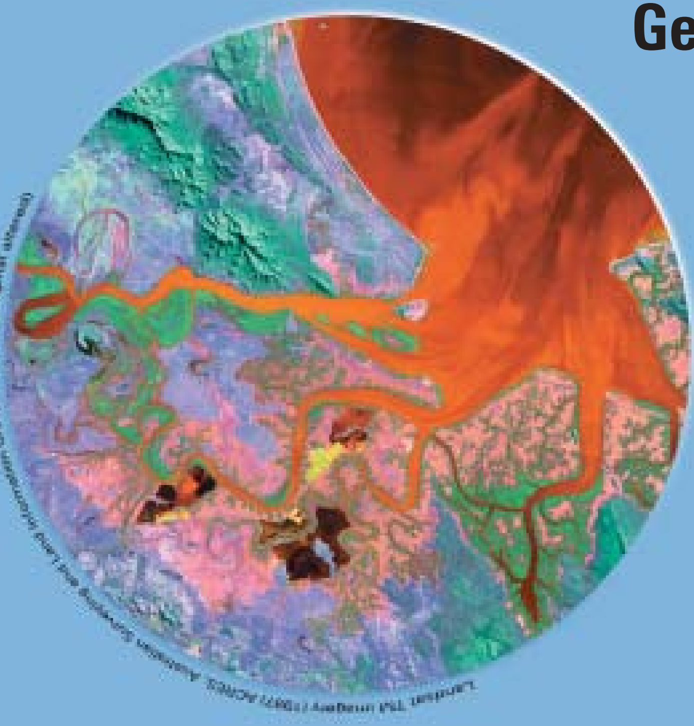
Cooperative Research Centre for Coastal Zone, Estuary & Waterway Management

Technical Report 47



Geomorphology and sediments of the Fitzroy River coastal sedimentary system - summary and overview

Brendan Brooke
Helen Bostock
Jodie Smith
David Ryan

June 2006

CSIRO

Central Queensland University – Where Students Come First.

Queensland Government – Natural Resources, Mines and Water

Griffith University

CRC for Coastal Zone Estuary & Waterway Management

Geomorphology and sediments of the Fitzroy River coastal sedimentary system – Summary and overview

Brendan Brooke, Helen Bostock, Jodie Smith and David Ryan

Petroleum and Marine Division, Geoscience Australia, Canberra, ACT.

June 2006

CRC for Coastal Zone Estuary & Waterway Management

Geomorphology and Sediments of the Fitzroy River coastal sedimentary system – Summary and overview

Written by:

Brendan Brooke

Helen Bostock

Jodie Smith

David Ryan

Published by the Cooperative Research Centre for Coastal Zone, Estuary

and Waterway Management (Coastal CRC)

Indooroopilly Sciences Centre

80 Meiers Road

Indooroopilly Qld 4068

Australia

www.coastal.crc.org.au

National Library of Australia Cataloguing-in-Publication data

Geomorphology and Sediments of the Fitzroy River Coastal Sedimentary System – Summary & Overview

QNRM 06296

ISBN 1 921017 50 3 (print)

ISBN 1 921017 51 1 (online)

Table of contents

List of figures iv

List of tables...v

Introduction 1

Benthic sediments and geomorphology 2

Beach ridges 5

Stratigraphy and sediment accumulation 7

Sediment source... 11

Overview.. 15

Holocene evolution.. 15

Changes in estuary morphology... 17

Modern sediment transport and accumulation.. 17

Sediment pathways 17

Sediment budget 18

Temporal variations in flood events.. 20

Conclusions 22

References 23

List of figures

Figure 1: Merged topographic and bathymetric DEM of the Fitzroy River floodplain, Keppel Bay, the continental shelf and reefs of the Capricorn Bunker Group 3

Figure 2: Map of sediment transport, accumulation and erosion in Keppel Bay....................... 4

Figure 3: A surveyed cross-section of the beach ridge plain at Long Beach, on the western margin of Keppel Bay 6

Figure 4: Subdivisions of the Fitzroy River coastal sediment basin.. 8

Figure 5: Concentrations of Th vs Sc for Fitzroy catchment soils and core sediments from this study 12

Figure 6: Downcore age plots showing the fraction of the five catchment soil types to sediments from floodplain core FK402... 13

Figure 7: Conceptual model of Holocene evolution of the Fitzroy River estuarine floodplain and Keppel Bay. 16

The major control on coastal landform development has been the Holocene rise in sea level. A) 9500 years ago, -20 m sea level; B) 8000 years ago, -10 m sea level; C) 5000 years ago, present sea level and; D) present day... 16

Figure 8: Sediment transport pathways and budget for the Fitzroy River coastal sediment system 19

List of tables

Table 1: Sediment mass accumulation data for the beach ridge accretion units. 6

Table 2: Sediment accumulation data for depositional zones in the Fitzroy River coastal system 9

Table 3: Modelled estimates of the percentage of catchment soil endmembers in the sediments 12

Table 4: REE characteristics of Keppel Bay, tidal creek and floodplain sediments and average Post-Archean Australian Shales (PAAS). 13

Table 5: A comparison of average weathering parameters across different regions in the study area. Higher values indicate a greater degree of weathering........................... 14

Introduction

This report provides an overview of the geomorphic and sedimentary characteristics of the Fitzroy River and Keppel Bay, which comprise one of the largest modern coastal sedimentary systems in Australia. The work reported here represents the *Sediments* component of the Coastal CRC Fitzroy AC Project. We summarise the individual reports that have been submitted on the various components of the Fitzroy River coastal system: the floodplain, estuary and tidal creeks (Bostock *et al.*, 2006a), the beach-ridge plain (Brooke *et al.*, 2006), Keppel Bay (Ryan *et al.*, 2006; Bostock *et al.*, 2006b); as well as the catchment source of coastal sediments (Smith *et al.*, 2006). The summaries are followed by an overview of the system that represents an initial integration of the new findings.

Our results provide new insights into the character and rate of evolution of the Fitzroy River estuary and Keppel Bay, from the Late Pleistocene to historical times. We reveal how riverine and shallow-marine processes that occurred thousands of years ago affect the present day structure of the coast and continental shelf. Importantly, we also identify rates of sediment accumulation for the last several thousand years, and the last hundred years. We compare these empirical data with estimates of the current sediment load of the Fitzroy River to formulate a preliminary sediment budget for the Fitzroy coast.

Catchment source areas of sediment collected in the estuarine floodplain, estuary and Keppel Bay were identified based on an analysis of trace element data and a comparison of these data with the results of an earlier study of the catchment and estuary (Douglas *et al.*, 2005). In combination with the sedimentation rates and the results of the hydrodynamic and sediment transport modelling (Radke *et al.*, 2006), these data provide a better understanding of the rate of coastal landform development, a means of identifying rates for sediment biogeochemical processes (nutrient burial, sulfate reduction), and an indication of the potential physical impact on the coast and offshore habitats brought on by changes in catchment land use.

Benthic sediments and geomorphology

The distribution of sediment types and the morphology of the seabed of Keppel Bay were identified through the analysis of bottom sediment samples, multibeam sonar bathymetry data and acoustic subsurface profiles of the seabed (Ryan *et al.*, 2006; Radke *et al.*, 2005). Using an unsupervised statistical clustering technique, the sediment data were classified into five distinct classes based on sediment grainsize, mineralogy (e.g. % feldspar and $CaCO^3$), and modelled seabed shear stress (the influence of waves and tidal currents). The sediment classes identified are estuarine muds, inner bay muddy sands, outer bay relict sands, and inner shelf carbonates. These sediment facies have distinctive composition, depositional environments, and source areas.

Multibeam sonar datasets of selected areas of Keppel Bay provide an unprecedented view of the seabed morphology. Large sediment dunes, located at Centre Bank and Jabiru Shoals indicate the direction of sediment transport along the bed of the bay (Figure 2). Deep, scoured channels in Keppel Bay show that erosion dominates some areas, whereas other channels are at least partially filled with sediment. Offshore from Keppel Bay out to the reefs of the Capricorn/Bunker Group the continental shelf is relatively flat. However, a palaeochannel of the Fitzroy River is clearly expressed in the bathymetric model of the middle shelf that was derived from Australian Hydrographic Office bathymetric data (Figure 1). This palaeochannel records the path that the river followed during the glacial period of low sea level. The channel runs 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.

Sediment cores and sub-bottom profiles indicate that much of the mud brought down by the Fitzroy River during floods accumulates in the mouth of the estuary and tidal creeks. The remainder of this fine sediment load is transported offshore and to the north in a ‘plume’. Sediment derived from the Fitzroy River can only reach the offshore reefs during major flood events as part of the flood plume. In contrast, the load of sand accumulates in the south of Keppel Bay and is transported onshore and northwards by tidal and wind-induced currents (Figure 2).

Outer Keppel Bay is relatively sediment-starved. Here, relict coastal and fluvial sediment is being reworked and transported onshore. Under the prevailing coastal atmospheric and marine conditions, sediments are moved onshore and alongshore to the north of Keppel Bay.

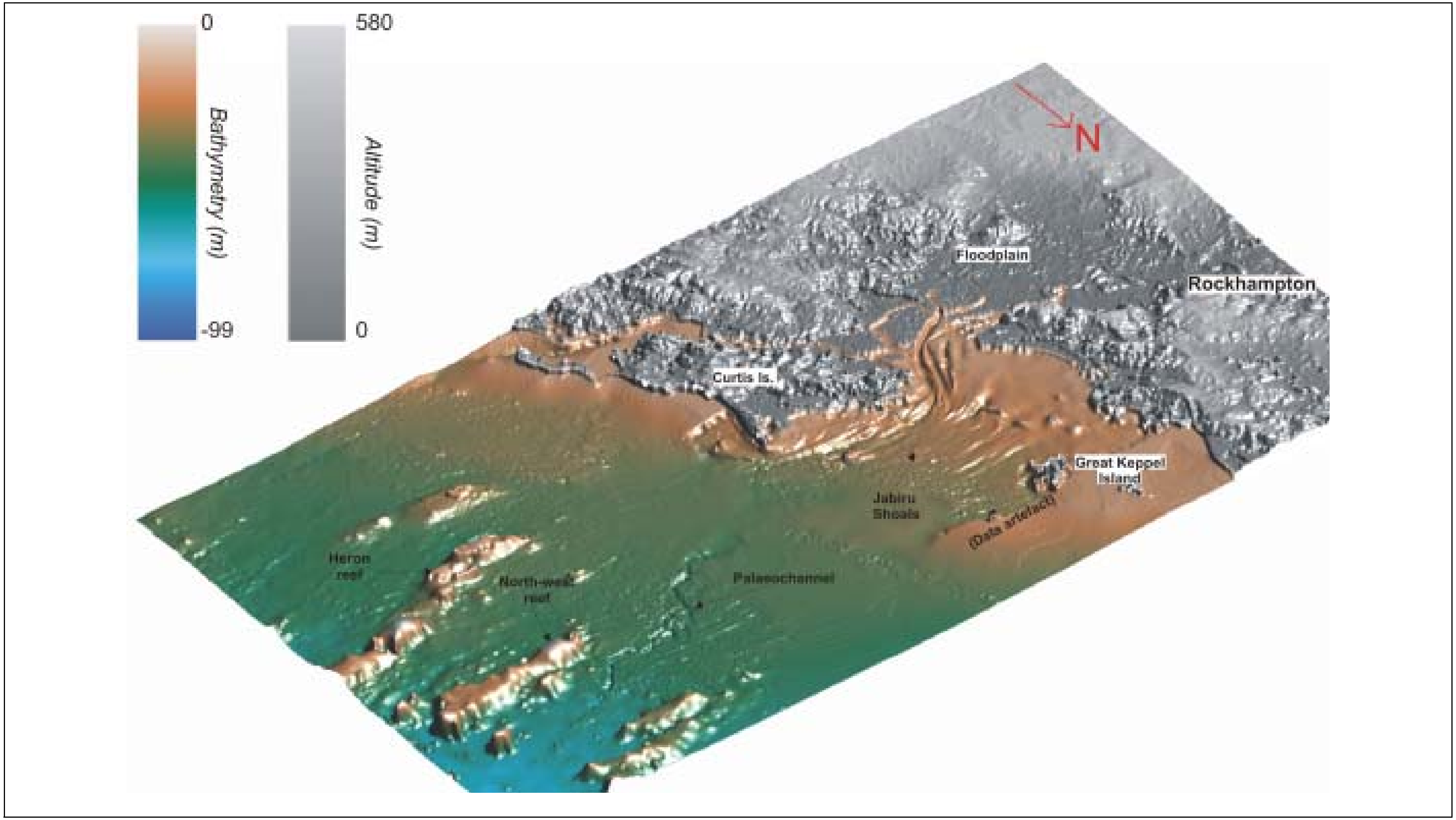


Figure 1: Merged topographic and bathymetric DEM of the Fitzroy River floodplain, Keppel Bay, the continental shelf and reefs of the Capricorn Bunker Group (bathymetric data from Webster and Petkovic, 2005).

.

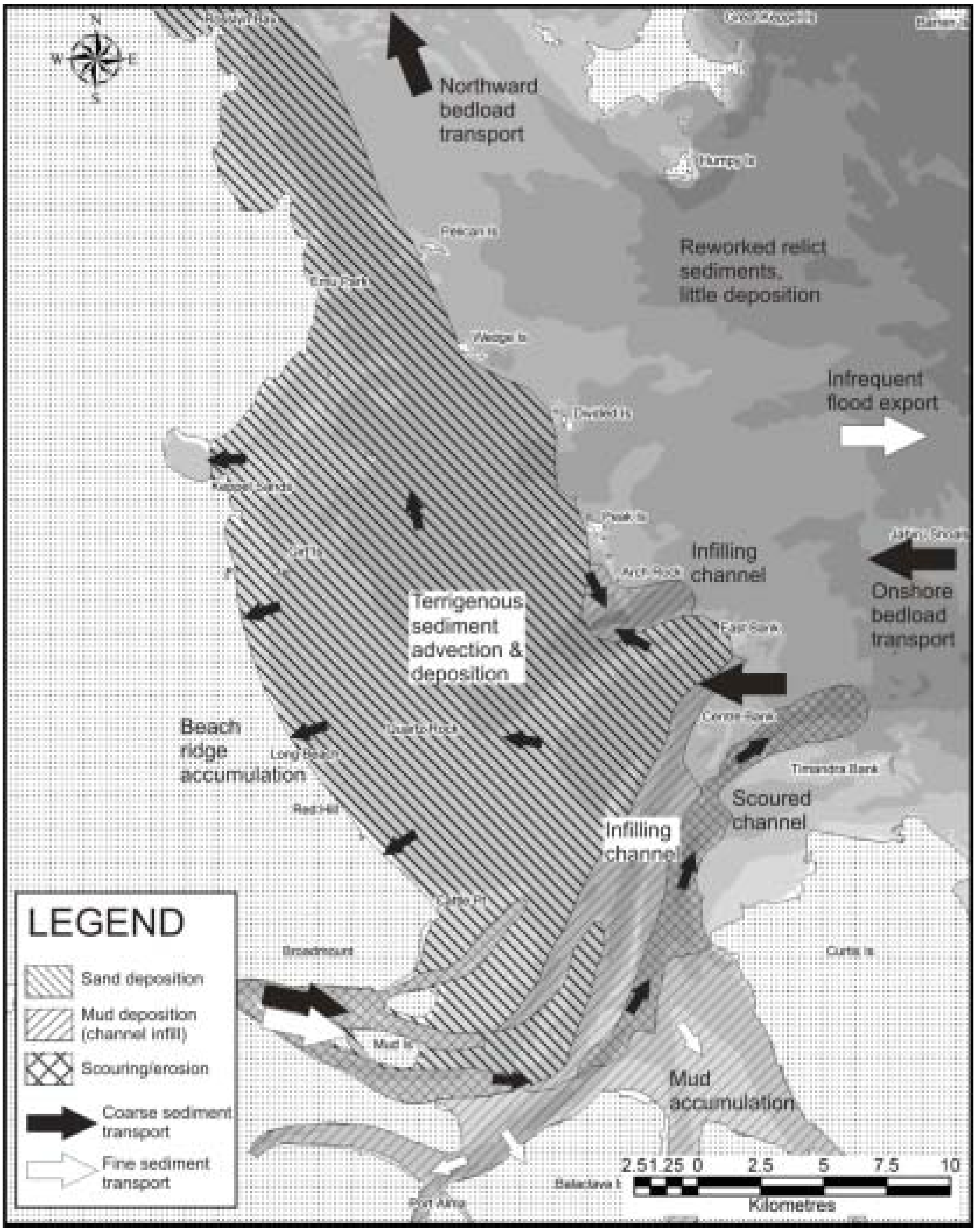


Figure 2: Map of sediment transport, accumulation and erosion in Keppel Bay.

Beach ridges

Beach ridges are regularly spaced, low amplitude (a few m thick) linear deposits of sediment that usually form on sandy coasts where waves and winds emplace sand in foreshore and backshore settings (Otvis, 2000). They can develop during storms, in quiescent periods or with both modes of deposition depending on local conditions (Beach Protection Authority, 1979). At Keppel Bay, ridges form during normal climatic conditions when tidal currents and onshore winds move sand onto the shoreline. Because beach ridges mark the former position and composition of the shoreline, a series of ridges can provide useful records of shoreline sediment accumulation, extension and past configuration.

Numerous geochronological studies of beach ridge successions have been able to reconstruct shoreline depositional regimes that operated tens of thousands of years ago. Few studies, however, have been able to gain reliable age control for ridge successions that extend from the present day back through the historical past and into the late Holocene.

In this study of the beach-ridge plain at Keppel Bay (Figure 2), we examined ridge morphology, sediment texture and geochemistry (Brooke *et al.*, 2006). A broad age framework for the ridges was provided by radiocarbon (^{14}C) ages and a detailed chronology using the optically stimulated luminescence (OSL) dating method (Figure 3). The depositional history and sediment composition of this succession of well-preserved beach ridges provides a detailed record of changes in the character and rate of beach sediment accumulation that includes:

1) During the last 1500 yrs ridges were emplaced in rapid episodes following periods of high sediment discharge from the Fitzroy River, approximately once every 500–200 years. During these episodes sand accumulated rapidly, up to 1093 kt yr^{-1}, which is far greater than the estimate for the current rate, 285 kt yr^{-1} (Table 1).

2) A marked decline in the rate at which sediment has accumulated on the coast during the last 1000 yrs may reflect a long-term decline in major rainfall events in the Fitzroy River catchment (Table 1).

3) Ridges deposited during the last 100 years record a distinct change in trace element composition that reflects a greater contribution from basaltic soils within the Fitzroy River catchment. This change is probably related to a change in the type(s) of sediment (soil) being delivered due to large-scale clearing of native vegetation in the Fitzroy Basin.

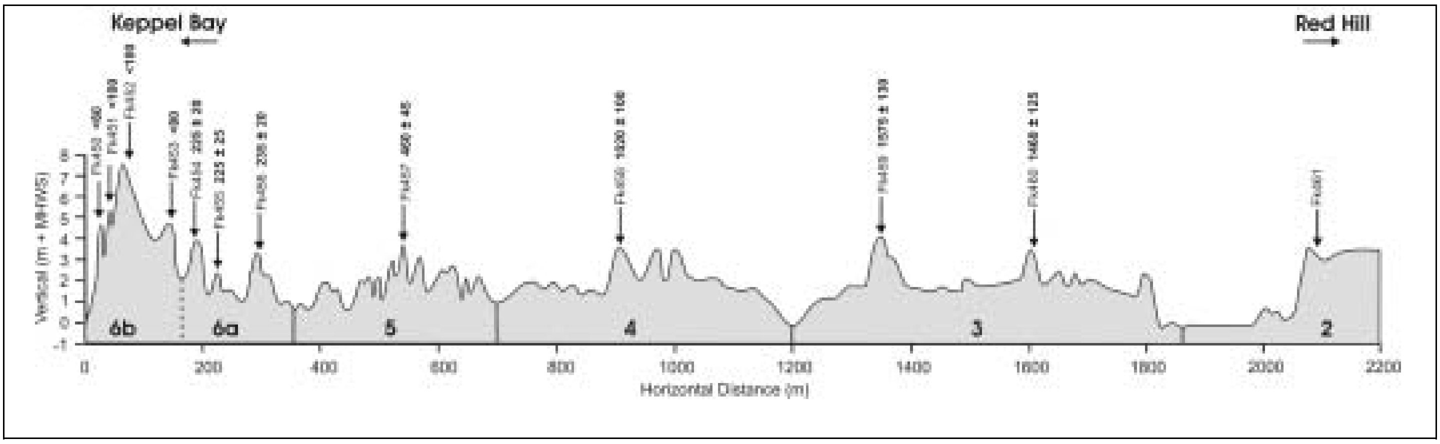


Figure 3: A surveyed cross-section of the beach ridge plain at Long Beach, on the western margin of Keppel Bay. Five accretion units (sets of ridges) are indicated by numbers (6b – 2).

Table 1: Sediment mass accumulation data for the beach ridge accretion units.

Maximum and minimum depositional periods (used to calculate the accumulation rates) are estimates of the time taken for an accretion unit to be deposited, based on the age uncertainties of the OSL ages.

Accretion Units	Area (km^2)	Volume (km^3)	Mass (Kilotonnes)	Deposition Period Min–Max (yr)	Accumulation Rate Max–Min (kt yr^{-1})
Unit 6	4.342	0.056	66 913	175–235	382–285
Unit 5	6.787	0.077	92 603	25–130	3704–712
Unit 4	10.169	0.118	142 057	25–130	5682–1093
Unit 3	6.822	0.078	93 387	25–130	3735–718
Total (last ~1500 yrs)	28.120	0.329	394 960	1335–1705	298–233

Stratigraphy and sediment accumulation

The stratigraphy and age of sediments that make up the estuarine floodplain of the Fitzroy River (downstream from Rockhampton), tidal creeks, and Keppel Bay were examined to reveal the Holocene evolution of this large coastal sedimentary basin (Bostock *et al.*, 2006a; Bostock *et al.*, 2006b). This study also identified the quantity of sediment in the basin and the rate at which it has accumulated. A stratigraphic framework for the basin was built based on sediment cores collected as part of the study, core logs provided by past drilling programs and acoustic sub-bottom profiles of Keppel Bay.

The arrangement of lowstand floodplain units, channel deposits and various shallow-marine units record the rise and then stabilisation of the sea during the early to middle Holocene. As sea level rose, the former floodplain of the Fitzroy River was flooded to form Keppel Bay and the mouth of the river moved inland towards Rockhampton. Sea level stabilised around 7000 years ago and since that time the estuarine basin between Rockhampton and the present day coast has been filling with shallow-marine, estuarine and floodplain deposits. As a consequence, the space available in the basin for flood deposits to accumulate has decreased over time.

The volume of Holocene sediment fill in the various depositional zones of the Fitzroy coastal basin was calculated using a GIS that included core and borehole data to define the thickness of the Holocene succession (Figure 4; Table 2). The mass of sediment was calculated assuming a constant density of 2.5 g cm^3 and porosities of 50% and 60% for the floodplain and Keppel Bay sediments respectively. Rates of Holocene average annual sediment mass accumulation for the various zones are shown in Table 2. Modern rates of average annual sediment mass accumulation were calculated for the northern bay and tidal creeks based on sediment cores for which we have obtained a reliable chronology for the historical period (last 100–200 yrs). Modern rates of accumulation for the floodplain were calculated using a modelled 100 year average annual sedimentation rate (Dougall *et al.*, 2005, Table 2).

The Holocene average annual sediment mass accumulation rate for the entire Fitzroy River coastal basin is 2587 kilotonnes yr^{--1} (Table 2). The Holocene rate varies quite significantly spatially, both between and within regions (Table 2). For example, the largest amount of sediment accumulates in the southern floodplain, 1922 kt yr^{--1}; and the rate for southern Keppel Bay, 97 kt yr^{--1}, is significantly higher than the northern bay, 9.6 kt yr^{-1} (Figure 4, Table 2). These spatial variations reflect the different depositional processes, energy levels and sediment transport pathways within the basin (Figure 2).

The rates of modern average annual sediment mass accumulation for the floodplain and northern Keppel Bay are considerably higher than the Holocene average annual rates for these areas (Table 2). The significance of these differences needs to be tested by further studies of modern floodplain sedimentation and by dating additional cores in Keppel Bay. The modern average annual rate of sediment accumulation for the entire Fitzroy River coastal basin is 3492 kt yr^{-1}. This is probably a more accurate indication of the current rate of accumulation than the Holocene rate as it factors in the rapid rate of sediment accumulation that occurs in the mangrove environments (Table 2). Average annual rates of accumulation, however, do not represent well the highly variable flood discharge record of the Fitzroy River. The record indicates there are extended periods of very little significant discharge and infrequent large discharge events with a recurrence interval of 5–10 years (Larcombe and Carter, 2005).

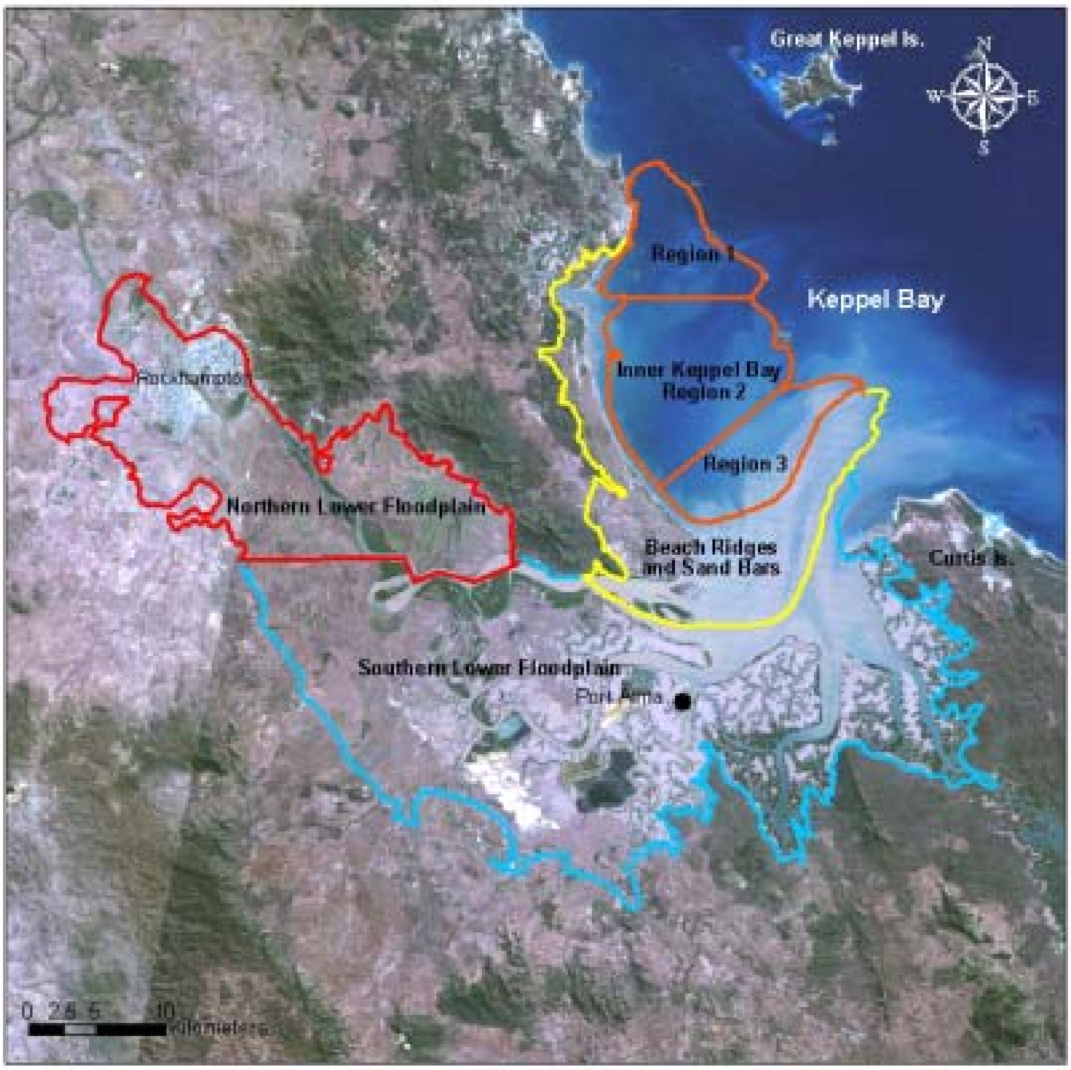


Figure 4: Subdivisions of the Fitzroy River coastal sediment basin.

Sediment volumes were calculated for each area and combined with the sediment age data to derive sediment accumulation rates and budgets for the last 7000 years.

Table 2: Sediment accumulation data for depositional zones in the Fitzroy River coastal system (Figure 1). The modelled modern accumulation rates are for areas of floodplain only.

Region	Surface Area (km^2)	Thickness (m)	Volume (m^3)	Total Mass (kg)	Mass Accum. (kt yr^{-1})	Mass of fines (%<63 µm) (kt yr^{-1})
Holocene average annual rates based accumulation over the last 8000 yrs						
Northern Floodplain	325	5	1.62×10^9	2.03×10^{12} (50% porosity)	254*	(97%) 246
Southern Floodplain and Estuary	820	15	1.23×10^{10}	1.54×10^{13} (50% porosity)	1922*	(80%) 1538
Beach Ridges and Sand Bars	225	9.5	2.14×10^9	2.14×10^{12} (60% porosity)	266	(5%) 13.3
Inner Keppel Bay Region 1	67	1	6.73×10^7	6.73×10^{10} (60% porosity)	9.6	(65%) 6.24
Inner Keppel Bay Region 2	133	2	2.66×10^8	2.66×10^{11} (60% porosity)	38	(65%) 25
Inner Keppel Bay Region 3	68	10	6.82×10^8	6.82×10^{11} (60% porosity)	97	(65%) 63
Holocene Total					**2586.6**	**1891.54**
Modern average annual rates based on accumulation rates from dated cores						
Tidal Creeks/ Mangroves	130	1.5 cm yr^{-1}	1.95×10^6	1.71×10^9 (65% porosity)	1706	(80%) 1365
Beach Ridges	4.342		5.57×10^7	6.69×10^{10} (60% porosity)	336	(5%) 16.8
Inner Keppel Bay Region 1 (VC05)	67	0.13 cm yr^{-1}	8.7×10^4	8.7×10^7 (60% porosity)	87	(65%) 57
Inner Keppel Bay Region 2	133	0.13 cm yr^{-1}	1.7×10^5	1.7×10^8 (60% porosity)	173	(65%) 112
Inner Keppel Bay Region 3	68	0.3 cm yr^{-1}?	2.04×10^5	2.04×10^8 (60% porosity)	204	(65%) 133
Modelled modern average annual rates (SedNet)						
Southern Floodplain	465	0.1 cm yr^{-1}	4.65×10^5	5.8×10^8 (50% porosity)	581	(80%) 465
Northern Floodplain	324	0.1 cm yr^{-1}	3.24×10^5	4.05×10^8 (50% porosity)	405	(97%) 393
Modern Total					**3492**	**2542**

* Includes data from core logs provided by past studies.

Satellite images and models of suspended sediment transport indicate that although the flood discharge of the Fitzroy River is largely confined to the main channel and bypasses the tidal creeks, tidal currents pump this sediment back into the tidal creeks from the mouth of the estuary over the proceeding weeks and months (Webster *et al.*, 2006). As a consequence, the tidal creeks and extensive mangroves of the lower estuary represent the major zone of sediment accumulation in the basin.

Curtis Island provides protection for southern Keppel Bay from the prevailing waves and littoral currents, which enhances sediment accumulation and shoreline progradation in this area. Rapid modern sediment accumulation in the mouth of the estuary and southern bay is evident in historical maps and aerial photographs that show extensive growth of intertidal flats, mud islands and mangroves (Duke *et al.*, 2003).

Sediment source

A detailed geochemical study of the fine fraction (<10 µm) of sediments from the Fitzroy River floodplain, tidal creeks and Keppel Bay was conducted to identify the major sources of catchment sediment and to examine temporal and spatial trends in source areas (Smith *et al.*, 2006). This work follows on from the recent study of the geochemistry of the Fitzroy River catchment and estuary by Douglas *et al.* (2005). Ratios of trace and rare earth elements (REE) were used as source indicators and weathering parameters. Additionally, the relative proportion of catchment-derived sediment sources to the Fitzroy River floodplain, tidal creeks and Keppel Bay were estimated using a Bayesian statistical model developed by Palmer and Douglas (2004). The five dominant sediment sources within the Fitzroy catchment are the Bowen Basin (BB), New England Fold Belt (NEFB), Surat Basin (SB), Thomson Fold Belt (TFB) and Tertiary Basalts (TB) (Douglas *et al.* 2005).

Hydrodynamic processes in the estuary and Keppel Bay lead to constant reworking and mixing of catchment-derived sediments. Sediments deposited on the floodplain, in the tidal creeks and in Keppel Bay are all derived from mixed sources, predominantly sedimentary and/or granitic with a basalt component. This reflects the large size of the catchment and the integration of weathering products from the various rock types in the Fitzroy River Basin. The Sc concentrations of samples from Keppel Bay, tidal creeks and floodplain sediments are plotted against Th concentrations in Figure 5. Most samples have Th/Sc ratios lower than the typical upper continental crust (UCC) ratio of Th/Sc = 1.0 (Figure 5), which indicates that recycled sediment is not the only source of these sediments and that a volcanic/basaltic component is present (McLennan *et al.*, 1990). It seems most likely that the tertiary basaltic soils are enriched in all the coastal samples relative to catchment abundances due to the preferential delivery of this material in flood plumes (Table 3). Changes over time in the relative contributions of Bowen Basin and New England Fold Belt sediments may reflect variations in the intensity of rainfall events in different parts of the catchment (Figure 6), which may in turn reflect changes in climate over the middle to late Holocene.

Table 3: Modelled estimates of the percentage of catchment soil endmembers in the sediments

Catchment Endmember	Bowen Basin	New England Fold Belt	Surat Basin	Tertiary Basalt	Thomson Fold Belt
Sediment Abundance (1)	26 ± 10	18 ± 7	16 ± 5	21 ± 6	19 ± 5
Catchment Abundance (2)	46.0%	19.0%	18.6%	9.5%	6.9%
Enrichment Factor	0.6	0.9	0.9	2.2	2.8

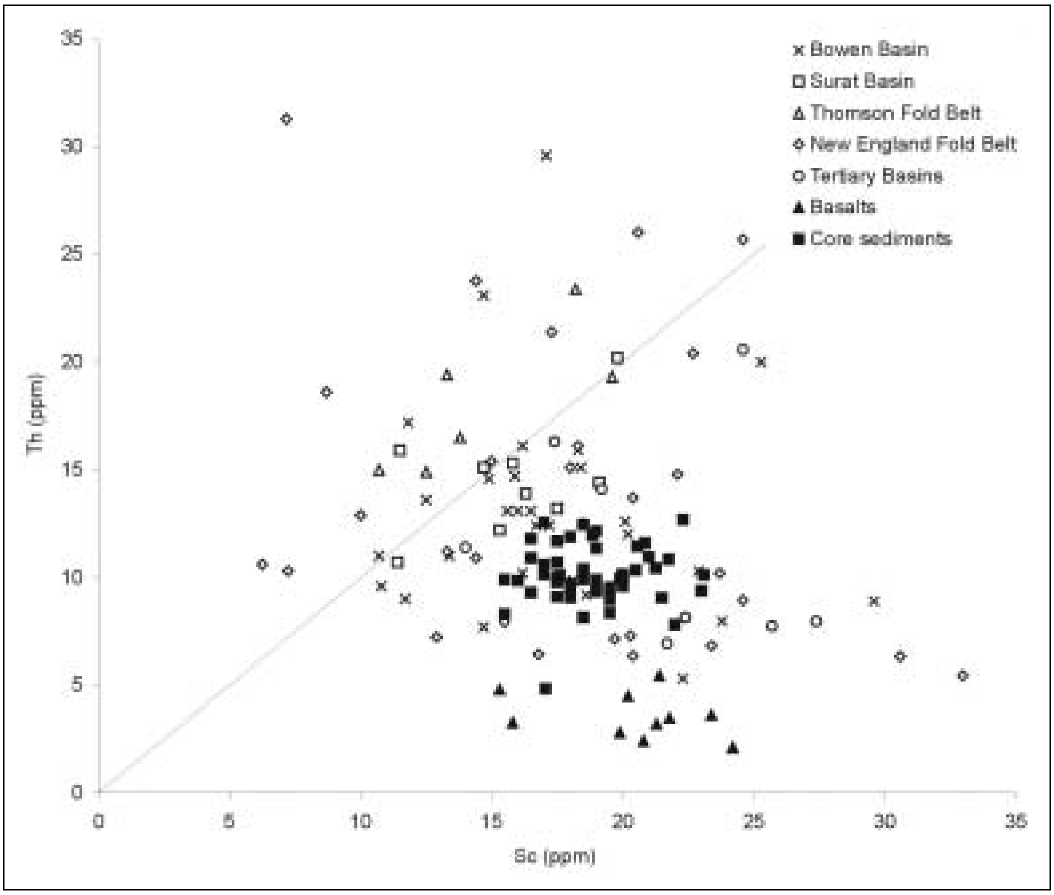


Figure 5: Concentrations of Th vs Sc for Fitzroy catchment soils and core sediments from this study.

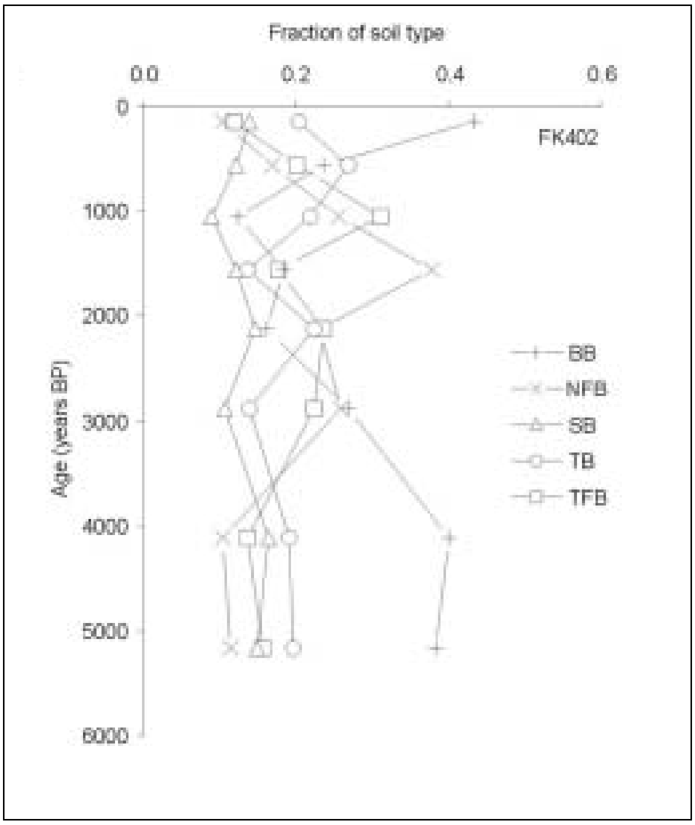


Figure 6: Downcore age plots showing the fraction of the five catchment soil types to sediments from floodplain core FK402. There is a switch between a dominant source from the Bowen Basin (BB) and New England Fold Belt (NFB). Note: SB = Surat Basin; TFB = Thomson Fold Belt; TB = Tertiary Basalts.

The rare-earth geochemistry of the samples is also indicative of mixed sources (Table 4) – the REE characteristics indicate that the original source area was felsic, while the negative Eu anomaly provides evidence for a differentiated source similar to granite (McLennan 1989, McLennan *et al.*, 1993; Taylor and McLennan 1985; 1995) but with the presence of basalts (Condie, 1993).

Table 4: REE characteristics of Keppel Bay, tidal creek and floodplain sediments and average Post-Archean Australian Shales (PAAS).

Region	**∑REE**	**Eu/Eu***	**La_N/Yb_N**	**Gd_N/Yb_N**
Keppel Bay cores	149 ± 10	0.78 ± 0.03	6.8 ± 0.6	1.5 ± 0.08
Tidal creek cores	152 ± 11	0.73 ± 0.04	6.9 ± 0.3	1.6 ± 0.09
Floodplain core	170 ± 13	0.85 ± 0.03	7.2 ± 0.7	1.4 ± 0.09
Keppel Bay surface	159 ± 9	0.80 ± 0.03	7.0 ± 0.3	1.5 ± 0.06
PAAS	183	0.65	9.2	1.3

Table 5: A comparison of average weathering parameters across different regions in the study area. Higher values indicate a greater degree of weathering.

Ratio	CIA*	Al_2O_3/K_2O	Rb/Sr	Rb/K_2O
Keppel Bay cores	76.5 ± 2.1	9.7 ± 0.6	0.72 ± 0.13	50.2 ± 4.1
Kameish Passage core	79.3 ± 2.0	9.0 ± 0.2	0.97 ± 0.16	47.9 ± 2.2
Casuarina Creek core	82.6 ± 0.9	11.1 ± 0.6	0.89 ± 0.05	58.0 ± 3.8
Floodplain core	83.0 ± 1.8	12.3 ± 1.2	1.14 ± 0.13	64.4 ± 6.3
Old floodplain surface	85.0	16.3	1.06	58.7
PAAS	*69.4*	*5.1*	*0.80*	*43.2*

*CIA = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$

The degree of weathering of the sediments reflects their age and source. Holocene-age floodplain sediments, which have been subject to subaerial weathering since deposition, are more weathered than sediments from Keppel Bay and the tidal creeks (Table 5). The tidal creek cores comprise sediment that has been reworked from Keppel Bay into the estuary. This sediment includes both flood deposits and, most likely, a component of reworked relict sediment eroded from the bed of the bay. Surface sediments in Keppel Bay are highly weathered due to a marine input of relict Holocene and late Pleistocene shelf deposits. In contrast, the middle to late Holocene coastal sediments from Keppel Bay are composed of flood deposits that have not been subject to subaerial weathering or reworking since deposition (Table 5).

Overview

Holocene evolution

The Holocene marine transgression and subsequent sea level stillstand have been the major physical processes that have shaped the Fitzroy River estuary and Keppel Bay. Prior to approximately 10 000 yrs ago Keppel Bay was a low-gradient floodplain of the palaeo-Fitzroy River. The river meandered across the plain down to a shoreline below and east of what is now the outer margin of Keppel Bay. By around 9500 years ago sea level had risen to approximately 20 m below the present level (Yokoyama *et al.*, 2006) and the shoreline sat on the margin of Keppel Bay (Figure 6). During the subsequent few thousand years, sea level rose up to its present level and the shoreline migrated landwards, with the mouth of the Fitzroy River following a track just to the north of Curtis Island (Figure 6).

The Holocene marine transgression extended up what was then a valley of the Fitzroy River to at least what is now Rockhampton. This valley must have been an area that was eroded by the Fitzroy River during the Last Glacial. Most likely, the increase in gradient of the river produced by the drop in sea-level during the glacial period resulted in the river eroding into its older floodplain and coastal deposits. Since around 7000 years ago, when sea level reached its present position, the valley has provided space for the accumulation of estuarine and then fluvial sediments. Over time, as shallow-marine deposits, including sands and estuarine muds, were covered by river sediments most of the estuarine basin has been transformed into a floodplain and salt flats. Deep drilling in the southern section of the basin near Port Alma has shown that older shallow-marine and fluvial deposits, probably laid down during the previous interglacial, are preserved below the Holocene estuarine deposits (Laycock, 1976).

Relict channels of the Fitzroy River are preserved in the outer section of Keppel Bay and indicate relatively little river-derived sediment has accumulated there. Relict river-mouth channels are preserved in the bay just to the north of Curtis Island (Figure 6). Some have been maintained by strong tidal currents while others are partially filled with sediment. In contrast, sediments from the Fitzroy River have accumulated in the inner bay and filled in and covered relict fluvial channels. Sand from the Fitzroy River deposited in Keppel Bay has also been reworked onshore to Long Beach. Over the last 2000 years these sediments have accreted to form a beach-ridge plain approximately 3 km wide that extends from Cattle Point north to Keppel Sands.

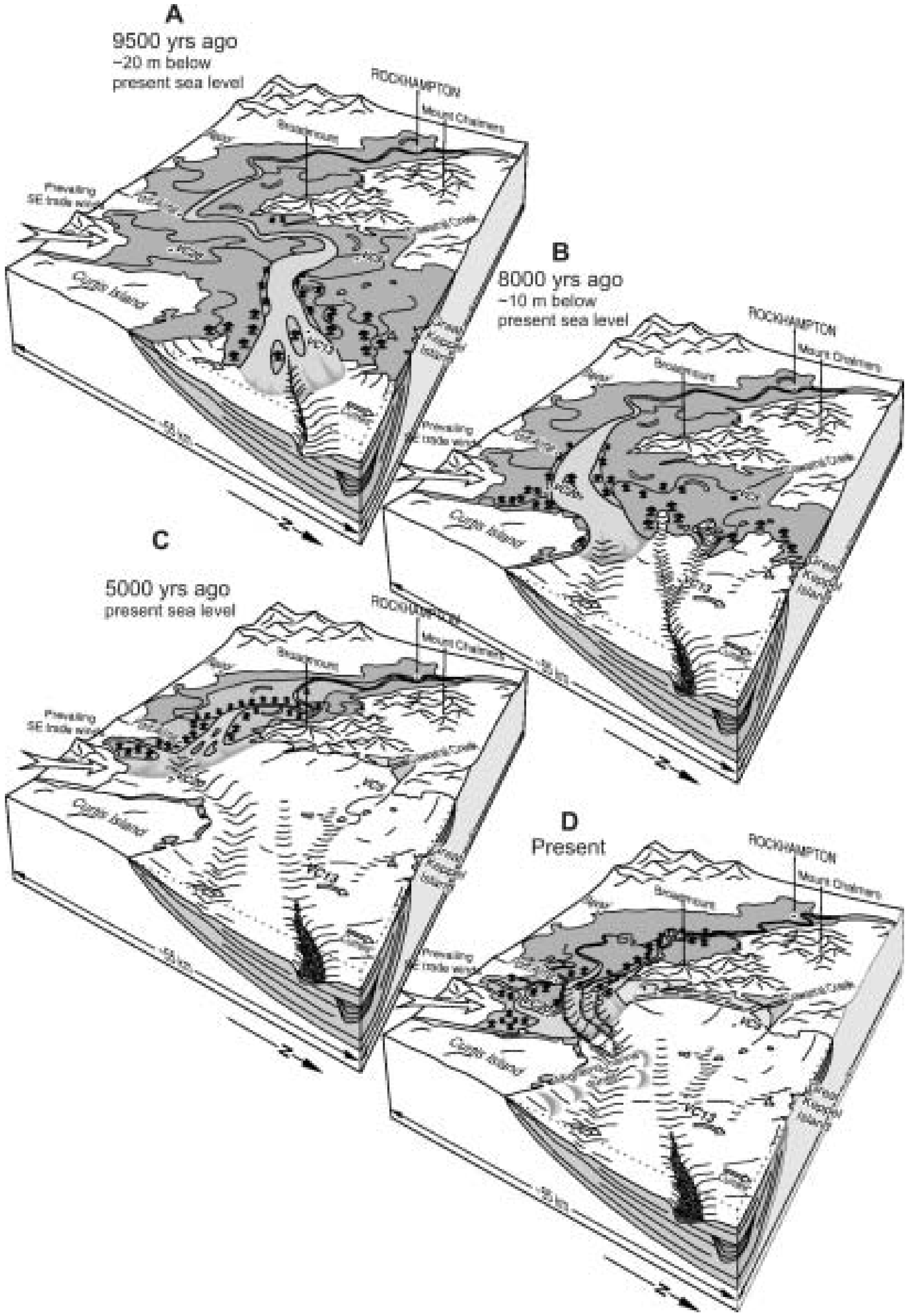


Figure 7: Conceptual model of Holocene evolution of the Fitzroy River estuarine floodplain and Keppel Bay.

The major control on coastal landform development has been the Holocene rise in sea level. A) 9500 years ago, -20 m sea level; B) 8000 years ago, -10 m sea level; C) 5000 years ago, present sea level and; D) present day.

Changes in estuary morphology

During the Holocene phase of deposition, the basin fill has accumulated vertically and the mouth of the estuary has built out to the east (Figure 6), eventually extending beyond the eastern confines of the valley formed by Broadmount Spur and the bedrock ridge SE of Pt Alma (Figure 4). The continued accumulation of estuarine and fluvial sediments has formed the present day extensive floodplain, salt flats and tidal creeks of the Fitzroy River below Rockhampton.

With the accumulation of sediment and formation of the estuarine floodplain the sedimentary function of the estuary has changed. Over time, relatively more of the river sediment load has been exported from the estuary as the accommodation space in the basin has been taken up. As a consequence, there has likely been a switch from an estuary that effectively traps fluvial sediment to a more deltaic-type environment where a greater proportion of this sediment is exported from the estuary.

Modern sediment transport and accumulation

Sediment pathways

The spatial arrangement of sediment types within the Fitzroy River estuary and Keppel Bay reflects the input and remobilisation of terrestrial and marine sediment. Mud brought down in flood events accumulates in and around the mouth of the Fitzroy River estuary (Figure 2). A component of the fine sediment load, however, is exported out of Keppel Bay into the lagoon of the Great Barrier Reef as part of the flood plume.

Tidal currents in the southern bay and mouth of the estuary pump river deposits back into the estuary, where they accumulate in the tidal creeks and mangroves. Sediments deposited in Keppel Bay can also be reworked by tidal and wind-generated currents. For example, sand is reworked onshore onto Long Beach, along the western margin of the bay, and northwards out of the bay (Figure 2). The provenance and trace element composition of these sediments is similar due to the integration of weathering products from the various catchment rock types and their mixing and reworking after deposition on the coast (Tables 3, 4). In contrast, marine sediments on the middle shelf, that are largely relict coastal deposits, are reworked into the bay by advection. The greater age, history of subaerial exposure and consequent highly weathered state of this component of the surface sediment of Keppel Bay is reflected its trace element ratios.

The geomorphic features of Keppel Bay influence the sediment transport pathways outlined above. The bay was formerly a low relief floodplain and now offers little accommodation space for the accumulation of modern river-derived sediments. Therefore, much of these flood deposits are reworked onshore or northwards out of the bay. The major area of sediment accumulation is in the southern end of the bay. Here, Curtis Island provides protection from the prevailing south-easterly winds compared to the rest of the bay, which allows flood deposits to accumulate and tidal currents to maintain an open river mouth. In contrast, the Burdekin River mouth is more exposed to the prevailing onshore winds and associated currents and waves that help trap sandy flood deposits within the mouth of the river.

Relict channels in Keppel Bay provide sites where modern sediments have accumulated. In the inner bay the relict river channels are largely filled in, however, in the middle and outer bay these deeper areas form sites of accumulation. In the mouth of the estuary and further seawards, just to the north of Curtis Island, there are large inactive and relict tidal channels that provide similar sites of sediment accumulation. However, this area is an energetic and dynamic environment where the focus of tidal flow can shift and channels can switch between erosional and depositional regimes.

Sediment budget

The modern estuarine floodplain provides little accommodation space for sediment (Figure 7). Likewise, relatively little sediment appears to be accumulating in Keppel Bay, between approximately 87 kt yr^{-1} in the northern bay to around 204 kt yr^{-1} in the southern bay. In contrast, the tidal creeks/mangroves and estuary mouth form the major area of sediment accumulation, with a rate of 1365 kt yr^{-1} (Figure 7). In this region there has been rapid growth of mud islands and mangroves forest during the historical period (Duke *et al.*, 2003).

The average annual rate of sediment accumulation for the entire Fitzroy River coastal basin (estuarine floodplain, beaches and Keppel Bay) is approximately 2587 kt yr^{--1} over the last 8000 years, or approximately 3492 kt yr^{--1} during the historical period (Table 2). We have compared these accumulation rates with two relatively comprehensive estimates of the modern average annual sediment discharge of the Fitzroy River. Kelly and Wong (1996) used sediment rating curves for floods over the last 30 years to calculate an average annual sediment discharge past Rockhampton of 8800 kt yr^{--1}. In contrast, a modelled estimate of the 100 year average annual load of fine sediment discharged from the mouth of the Fitzroy River is 4575 kt yr^{--1} (SedNet model, Dougall *et al.*, 2005).

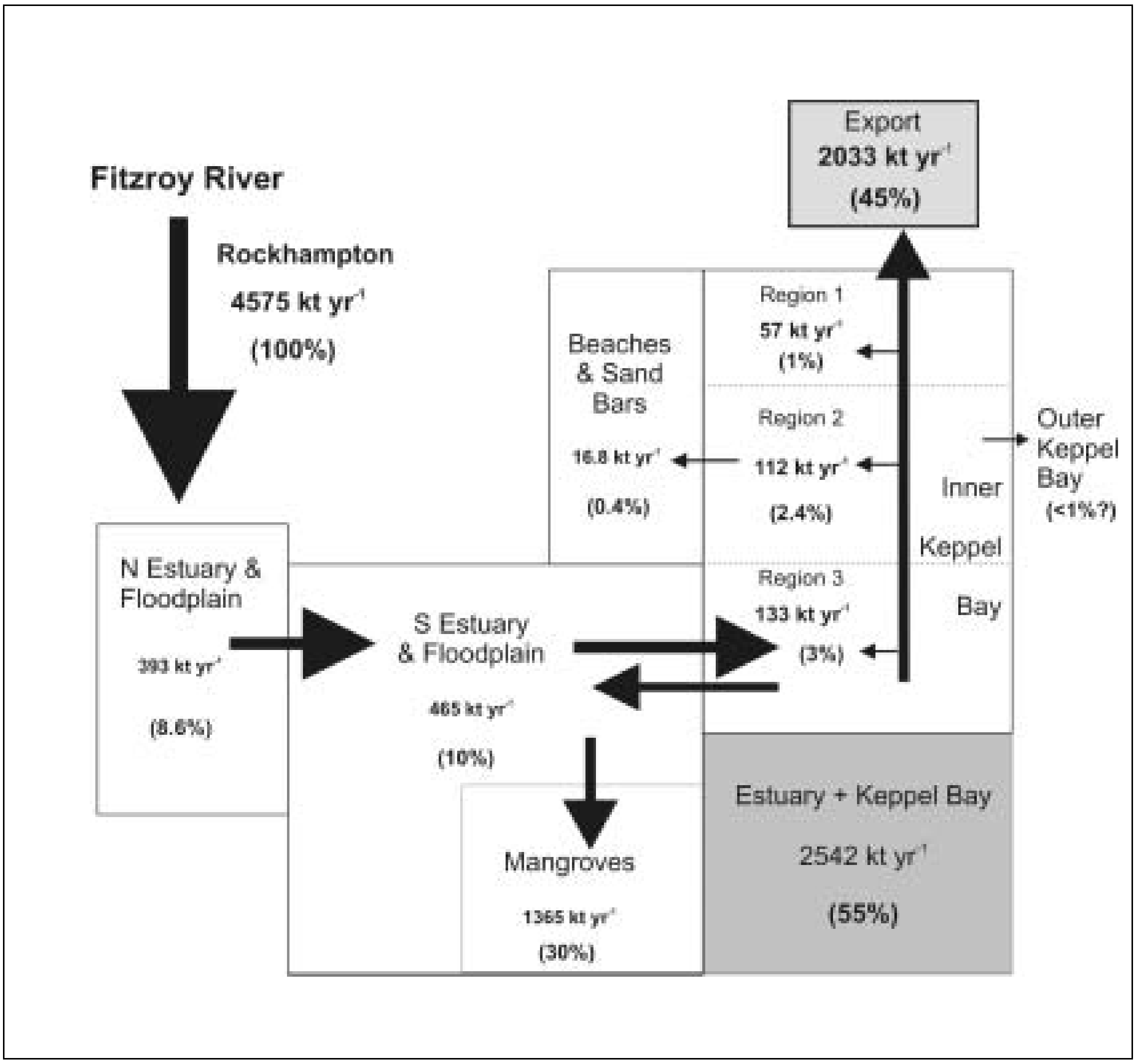


Figure 8: Sediment transport pathways and budget for the Fitzroy River coastal sediment system. The long-term average annual rate of accumulation of fine (<63 µm) sediment in the various compartments of the system are indicated (kt yr^{-1}). For comparison with the modern river load, the mass of sediment estimated to have been stored in each compartment per year is expressed as a proportion (%) of the long-term average annual suspended sediment load at Rockhampton (4575kt yr^{-1} = 100%, Dougall et al., 2005).

Based on the Kelly and Wong (1996) value, our Holocene and modern rates of sediment accumulation, 2586 and 3492 kt yr^{--1} respectively, are equivalent to 30–40% of the average annual terrestrial sediment load of the Fitzroy River.

A comparison of the modelled (SedNet) average annual fine sediment load discharged at the mouth of the river, 4575 kt yr^{-1}, with the modern average annual rate of fine sediment accumulation in the estuary and Keppel Bay, 2542 kt yr^{--1}, suggests that around 56% of the sediment load accumulates in the Fitzroy coastal basin. In summary, the sediment accumulation rates and river sediment discharge estimates indicate between approximately 30% and 56% of sediment brought down the river in flood flows accumulates in the coastal basin and the remainder is exported from Keppel Bay (Figure 7).

A small proportion of the exported sediment accumulates in depressions in outer Keppel Bay, while the majority is transported north by tidal and wind-generated currents. It is likely that this sediment accumulates in beaches and tidal inlets between Keppel Sands and Broad Sound. A similar process of longshore transport and down-current accumulation of reworked flood deposits has been reported for the coast north of the Burdekin River (Orpin *et al.*, 2004).

Temporal variations in flood events

Average annual river sediment loads and accumulation rates do not relate well to the modern sedimentary regime of the Fitzroy River and coast. Estimates of average annual sediment discharge of the Fitzroy River vary widely due to a lack of useful field measurements and the highly variable timing of significant flood events. In many years very little sediment is exported out of the system. Only during relatively high-magnitude discharge events (greater than 3000 kt suspended sediment) can a significant proportion of terrestrial sediment be exported through the estuary, Keppel Bay and then into the southern lagoon of the GBR. In the low-magnitude floods of 1996–97 wet season, for example, Furnas (2003) calculated an annual sediment discharge of 2230 kt and most of this sediment was probably trapped in the estuary and inner bay, with very little exported out of Keppel Bay. It is also worth noting that high-magnitude floods are required to inundate the majority of the estuarine floodplain. As a consequence, only during these events will any sediment accumulate there.

Sediment is predominantly discharged during large flood events with recurrence intervals of 5–10 years or longer that are usually linked to the passage of tropical cyclones into the catchment. For example, the flood event induced by cyclone Joy in 1991 (Devlin *et al.*, 2001). Sediment discharge, therefore, can be highly variable between years. Longer term climate cycles, such as ENSO, also strongly influence the frequency and magnitude of flood events and lead to periods of several years where the sediment load of rivers are significantly higher or lower than the annual average.

Trace element data for Keppel Bay core samples show changes in the relative contributions of sediments from the Bowen Basin and New England Fold Belt during the middle and late Holocene. This suggests that there have been variations over time in the intensity of rainfall events in different parts of the catchment, which may also reflect the influence of long term climate cycles on the composition of river sediment loads.

Conclusions

The Sediments component of the Fitzroy AC Project provides the following insights into the Fitzroy River coastal sedimentary system:

1) The formation of the estuarine floodplain in the middle to late Holocene has reduced the accommodation space for sediment in the basin. As a consequence, over time the estuary has become more deltaic, with a greater proportion of sediment exported to Keppel Bay rather than trapped in the estuary.

2) The present day morphology of Keppel Bay and spatial patterns of deposition, erosion and sediment type are strongly influenced by relict landforms and sediments of glacial age. Palaeochannels of the Fitzroy River have been sites of terrestrial sediment accumulation in the inner bay but little of this sediment has accumulated in the outer bay. In the southern bay, large channels are present that are either erosional, maintained by strong tidal currents, or form areas of deposition.

3) Modern sediments are transported out of the bay to the north by tidal and wind-generated currents. Similar processes rework relict, heavily weathered coastal sediments from the middle shelf into Keppel Bay.

4) The deposition of sediment by the Fitzroy River occurs during significant flood events. The frequency of these events is related to long-term climate cycles (e.g. ENSO) and varies considerably between years and phases of climate. Beach ridge deposits provide a record of deposition that suggests a decrease in large flood events over the last 1000 years.

5) Between approximately 30–56% of the average annual sediment load of the Fitzroy River accumulates within southern Keppel Bay or is remobilised by tidal currents and accumulates in the lower estuary. The remainder is deposited further out in Keppel Bay and is then largely remobilised and transported northwards out of the bay.

References

Beach Protection Authority, (1979). Beaches of the Capricorn Coast. Beach Protection Authority, Brisbane.

Bostock, H.C., Ryan, D.A., Brooke, B.P., Hancock, G. and Pietsch, T. (2006a). *Holocene evolution and modern sediment accumulation on a tropical macro-tidal coast - Keppel Bay, southeast Queensland, Australia*. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Technical Report No. 50.

Bostock, H.C., Ryan, D.A., Brooke, B.P., Packett, R., Hancock, G.J, Pietsch, T., Moss, P. and Harle, K. (2006b). *Sediment accumulation and Holocene evolution of the Fitzroy River lower floodplain, southeast Queensland, Australia.* Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Technical Report No. 48.

Brodie, J., McKergow, L.A., Prosser, I.P., Furnas, M., Hughes, A.O. and Hunter, H. (2003). *Sources of sediment and nutrient exports to the Great Barrier Reef World Hertiage Area.* Australian Centre for Tropical Freshwater Research, report number 03/11.

Brooke, B., Ryan, D., Radke, L. Pietsch, T., Olley, J., Douglas, G., Flood, P. and Packett, B. (2006). *Records of changes in sediment accumulation, sea level and land-use over the last 2,000 years preserved in beach deposits at Keppel Bay, Queensland, Australia.* Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Technical Report No. 51.

Condie, K.C. (1993). Chemical composition and evolution of the upper continental crust: Contrasting results from surface samples and shales. *Chemical Geology,* 104, 1–37.

Devlin, M., Waterhouse, J., Taylor, J. and Brodie, J. (2001). Flood plumes in the *Great Barrier Reef: spatial and temporal patterns in composition and distribution.* Great Barrier Reef Marine Park Authority, Research Publication No. 68, 113 pp.

Douglas, G., Ford, P., Palmer, M.J. and Noble, R. (2005). Identification of sediment sources in the Fitzroy River Basin and Estuary, Queensland, Australia. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Technical Report, No. 13.

Dougall, C., Packett, R. and Carroll, C. (2005). Application of the SedNet model in partnership with the Fitzroy Basin community. In Zerger, A. and Argent, R.M. (eds) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005.

Duke, N.C., Lawn, P.T., Roelfsema, C.M., Zahmel, K.N., Pedersen, D.K., Harris, C., Steggles, N. and Tack, C. (2003). *Assessing historical change in coastal environments: Port Curtis, Fitzroy River Estuary and Moreton Bay regions.* Cooperative Research Centre for Coastal Zone, Estuary and Water Management, Milestone Report.

Kelly, J.N. and Wong, W.T. (1996). Sediment transport in the Fitzroy River during flood events. In: I. Rutherford and M. Walker, (Eds) *Proceedings of the 1st National Conference of Stream Management in Australia,* (pp. 19–21). Merrijig: IEA.

Larcombe, P. and Carter, R.M. (2004). Cyclone pumping, sediment partitioning and the development of the Great Barrier Reef shelf system: a review. *Quaternary Science Reviews,* 23, 107–135.

Laycock, J.W. (1976). Brine occurrences in Queensland – Assessment of Port Alma brine fields. Queensland Department of Mines Record 1976/24.

McLennan, S.M. (1989). Rare earth elements in sedimentary rocks: Influence of provenance and sedimentary processes. *Reviews in Mineralogy,* 21, 169–200.

McLennan, S.M., Hemming, S., McDaniel, D.K. and Hanson, G.N. (1993). Geochemical approaches to sedimentation, provenance, and tectonics. In: Johnsson, M.J., and Basu, A. (eds). Processes Controlling the Composition of Clastic Sediments. Geological Society of America Special Paper 284, 21–40.

Orpin, A.R., Brunskill, G.J., Zagorskis, I. and Woolfe, K.J. (2004). Patterns of mixed siliciclastic-carbonate sedimentation adjacent to a large dry-tropics river on the central Great Barrier Reef shelf, Australia. *Australian Journal of Earth Sciences,* 51, 665–683.

Otvis, E.G. (2000). Beach ridges – definitions and significance. *Geomorphology,* 32, 83–108.

Palmer, M.J. and Douglas, G. (2004, submitted). A Bayesian statistical model for endmember analysis of sediment geochemistry, incorporating spatial dependencies *Applied Statistics*.

Radke, L.C., Ford, P.W., Webster, I.T., Atkinson, I. and Oubelkheir, K. (2006). *Keppel Bay: Physical Processes and Biogeochemical Functioning.*

Cooperative Research Centre for Coastal Zone, Estuary & Waterway Management, Technical Report No. 34.

Radke, L.C., Ford, P.F., Webster, I., Douglas, G., Oubelkheir, K., Atkinson, I., Robson, B., Verwey, P., MacKenzie, K. and Clementson, L. (2005). Results of two dry-season surveys of Keppel Bay and Casuarina Creek: Biogeochemical properties of the water column and underlying sediments. Geoscience Australia, Record 2005/18. 121pp.

Ryan, D.A., Brooke, B.P., Bostock, H., Collins, L.B., Buchanan, C., Siwabessy, J., Margvelashvili, N., Radke, L., Skene, D. and Hamilton, L. (2006). *Geomorphology and sediment transport in Keppel Bay, south-east Queensland, Australia.* Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Technical Report No. 49.

Yokoyama, Y., Purcell, A., Marshall, J. F. and Lambeck, K. (2006, in press). Sea level during the early deglaciation period in the Great Barrier Reef, Australia. *Global Planetary Change.*`