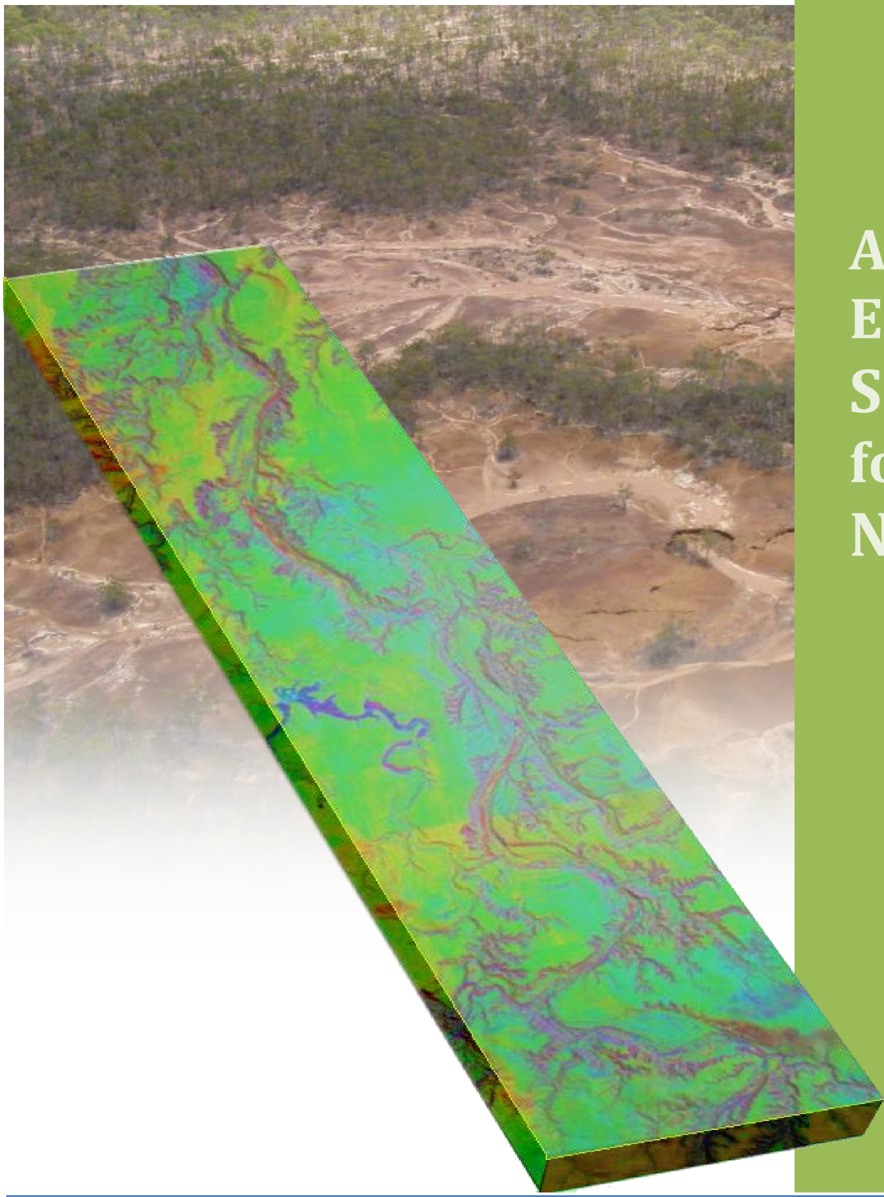

An Empirically-based Sediment Budget for the Normanby Basin

Andrew Brooks, John Spencer, Jon Olley, Tim Pietsch, Daniel Borombovits, Graeme Curwen, Jeff Shellberg, Christina Howley, Angela Gleeson, Andrew Simon, Natasha Bankhead, Danny Klimetz, Leila Eslami-Endargoli, Anne Bourgeault

Australian Rivers Institute

Griffith University

Appendix 12: Geochemistry and provenance of sediments from Princess Charlotte Bay

Griffith UNIVERSITY

CARING FOR OUR COUNTRY

IMPORTANT

This document is current at the date noted. Due to the nature of collaborative academic publishing, this content is subject to change and revision. Please see the Cape York Water Quality website for more info: **http://www.capeyorkwaterquality.info**

This Version: 3/03/2013

Appendix to the Final Report prepared for the Australian Government's Caring for our Country - **Reef Rescue initiative**

CAPE YORK WATER QUALITY

Appendix 12 Geochemistry and provenance of sediments from Princess Charlotte Bay, Northern Great Barrier Reef

Prepared by: Jon Olley*, Andrew Brooks, John Spencer, Timothy Pietsch, Daniel Borombovits, Christina Howley and Graeme Curwen

*Corresponding author: j.olley@griffith.edu.au; +61 7 37357805

DRAFT FOR PUBLICATION

Abstract

Sediment geochemistry is used to identify the primary sources of the sediment delivered to Princess Charlotte Bay in the northern section of the Great Barrier Reef. Principle component analysis of the geochemistry (34 major, trace and rare earth elements) of sediments (n=64) collected from the bay and it estuaries indicate that they consist primarily of three components; marine derived carbonates, quartz silt/sand and terrestrially derived silt-clays. A geochemical mixing model, incorporating all of the major sources, indicates that these components respectively constitute 28 ± 2, 26 ± 3, and 46 ± 5% of the bay sediment sampled. The model also demonstrates that the terrestrial silt-clay component is dominated (81 ± 2%) by sediment derived from the coastal plain and the Bizant River. The Bizant River derives its sediment primarily from erosion into the lowland floodplain and coastal plain. Previous studies using catchment scale modelling identified surface soil erosion in the upper catchments as supplying >80% of the sediment delivered to the bay. Our results show that erosion from the upper catchments makes a relatively small contribution to the sediment present in the bay (< 10% of the total and ~ 19% of the silt-clay fraction). Coastal plain erosion has not previously been identified as a significant contributor to sediment delivered to the Great Barrier Reef Lagoon. Our preliminary (conservative) assessment of a 185 km^2 area of the coastal plain suggests that this area generated between 175Mt and 220Mt of sediment over the last 500 to 1000 years.

1. Introduction

The Great Barrier Reef World Heritage Area (GBRWHA) extends along the Queensland coast for 2000 km. The coast adjoining the GBRWHA has a diverse range of wet and dry tropical catchments, covering an area of 423,000 km^2. Catchments draining the eastern portion of Cape York contribute continental runoff to around a 750 km stretch of the northern section of the GBRWHA. Coral reefs in this section of the marine park are closer to the coast than in the southern portion and are therefore potentially more vulnerable to terrestrial derived pollutants. The Laura-Normanby River (24,350 km^2) which drains into Princess Charlotte Bay (PCB) in this region has been identified using catchment scale modelling as the third largest contributor of sediment to the GBRWHA (e.g. Prosser et al., 2001; Brodie et al., 2003) and as such is a priority for erosion mitigation measures (Brodie et al., 2003).

The earliest study of sediments in PCB reported a large near shore terrigenous mud wedge which transitioned into relict sand and carbonate rich sediments off-shore (Frankel, 1974). The carbonate content of the sediments is highest closest to the reefs, although carbonate is present throughout the region due to *in situ* production by molluscs, echinoids and foraminifera (Sahl and Marsden, 1987). Recent mapping has confirmed the presence of a large near-shore mass of mud (Mathews et al., 2007) which thins toward the reef in the PCB. Torgensen et al., (1983) found that the sediment mineralogy and isotopic chemistry in this region were largely homogenous with only a slight increase in $CaCO_3$ content from the shore to the reef; with the sediments consisting predominantly of marine carbonates (43%), quartz silt sands (52%) and terrigenous clay (4%). They also reported sedimentation rates of 2.3 to 6.1 mm year. Bryce et al., (1998) surveyed the Normanby estuary and its delta and constructed a cross-sectional profile from 16 km inland to 16 km off-shore. They described the near-shore surface sediment as green-grey shelly marine muds, overlying slightly sandy mud, resting on a hard concretion-armoured surface with iron-staining which they interpreted as being the pre-Holocene basement. Chivas et al., (1983) estimated using ^{210}Pb dates of the surface sediments that the Holocene sediments could have accumulated in the last 1700 years.

Several studies have examined suspended particulate matter (SPM) transport in the bay during the dry-season. Sahl and Marsden, (1987) reported that tidal flow impart a strong offshore component to the transport, and strong southeast winds impart an alongshore component that transports SPM out of the bay to the northwest. They describe the SPM as primarily terrigenous material derived from re-suspension of sediment in the estuaries on the southern part of the bay. However, this conclusion conflicts with that of Wolanski et al. (1992), who found that net transport of fine sediment in the lower and mid-estuary of the Normanby was landward, driven by tidal processes. This was supported by Bryce et al., (1998) who also observed a net landward movement of sediment during the dry season estimating that 56,000 $\pm$ 22,000 tonnes of fine sediment would be moved landward past the mid-estuarine site in one year and deposited in the upper-estuary. However, the effect of wet season flows on sediment transport into or from the bay is largely unknown.

In the current study we determine the spatial sources of sediments in the bay using sediment tracing techniques. Determining the spatial source of transported sediments with sediment tracing involves measuring sediment properties that are capable of distinguishing sediments derived from a different areas of the catchment (Collins et al., 1996; Collins et al., 1998; Olley et al., 2001). The geochemical characteristics of eroded sediments are strongly influence by those of the soils and ultimately the rock-types from which they are derived (Caitcheon et al., 2006). Different underlying parent rock materials often results in spatial sources with distinct geochemical compositions (Olley et al., 2001; Douglas et al., 2003). Sediments eroded from soils derived from a particular rock type often maintain these distinct geochemical properties during sediment generation and transport processes (Caitcheon et al., 2006; Hughes et al., 2009). Sediment geochemistry has been widely used to identify the spatial sources of sediments delivered to waterways ((Collins et al., 1996; Collins et al., 1998; Olley and Caitcheon, 2000; Hardy et al., 2010; Weltje and Brommer, 2010).

To determine the sources of marine and estuarine sediment, we compare the geochemistry of sediment samples collected from 46 sites across PCB and from 3 of its major estuaries with samples collected from each of the major tributary rivers. The relative contribution of each of the tributary rivers to the samples from each site in the bay are determined using a geochemical mixing model. The relative contribution of marine carbonates, coastal-plain sediments and quartz silt/sand to each sample is also determined. In addition we examine down-core (0 to 60 cm) variations in source contributions at one site located about 10 km off-shore toward the centre of the bay. High resolution LiDAR imagery of a 22.4km^2 area and Google™Earth imagery (2012) are also used to evaluate the extent of erosion on the coastal plain. These data are used to test the hypothesis that soil erosion in the upper catchments of rivers draining into Princess Charlotte Bay (PCB) dominates the sediment delivered to the bay.

2. Study site description

The catchment area draining into PCB covers an area of approximately 27,600 km^2. The major tributary catchments include the Laura-Normanby River (24,350 km^2), and the Steward River (2500km^2) located just to the north (Figure 1). Between these catchments are the Hann and North Kennedy Rivers in the south and southwest, the Annie and Morehead Rivers and Saltwater Creek to the North (Figure 1). The majority of the catchment area is of relatively low relief with a gentle slope towards PCB. Topography in the upland areas ranges from undulating rises to steep mountain ranges, with deeply dissected sandstone plateaus and intervening plains. Mean annual run-off between 1986 – 2009 is estimated from this study at 4,600 GL/year (± 3400 GL – 1 stdev). The catchments are located in the dry tropics where climate is characterised by extreme rainy (summer) and dry (winter) seasons with 95% of the annual rainfall occurring between the months of November and April. Mean annual rainfall varies from 800 mm to 1600 mm across the catchments with higher rainfall occurring in the mountains along the eastern and southern borders of the catchment. Mean maximum monthly temperatures in the region range from approximately 29°C in June to 36°C in November. Mean minimum monthly temperatures range from approximately 17°C in August to 24°C in February. The resident population for the entire catchment area is believed to be less than 500. Outside of the conservation areas, grazing is the most extensive land use in the catchment. Cattle properties tend to be large, with low cattle density compared to other regions.

3. Methods

3.1 Sample collection

River samples: Time-integrated samplers (Phillips et al., 2000) were used to collect samples of suspended sediment during flow events in each of the sub-catchments. These samplers have been widely adopted in sediment tracing research (Hatfield and Maher, 2009; Walling et al., 2008; Collins et al., 2010). Time-integrated samplers effectively trap a representative sample of sediment with an effective particle size of <63μm (Phillips et al., 2000); sampling through the hydrograph including the rising and falling limbs. The samplers were deployed ~0.5 metre above the low water level for the entire wet season and collected at the beginning of the dry season. At most locations two samples were collected over two wet seasons. Sediment drape deposits, e.g. fine sediment that appeared to have been recently deposited such as mud drapes on channel-bed sand, were also sampled at each site. At the Bizant River sampling site three samples of *in situ* material from the eroding banks were also collected. Sampling locations are shown in Figure 1.

Bay samples: At 46 sites in the bay sediment cores between 40 and 120 cm were recovered using a cable hammer corer. This consisted of a 120 cm PVC 50 mm tube fitted with a one way valve at the top onto which attached a cage containing a sliding weight. The coring device was lowered into the water and supported on the bottom by one cable and another cable attached to the weight was used to raise and lower the weight, effectively hammering the tube into the bed sediments. In this current study we have removed the upper 5 cm of sediments from each of the cores for analysis. At location PCB24 a second core (60 cm) was recovered and sectioned in the field in 2 cm intervals.

Estuarine samples: Grab samples of surface sediments (upper 10 cm) were collected from the Marrett, Normanby and Kennedy Estuaries using an Ekman grab sampler. Samples were collected along transects that started at the estuary mouth and went up stream for ~ 2 km.

Coastal Plain samples: Samples of *in situ* material were collected from eroding surface at two location on the coastal plain (n=5).

3.2 Sample processing and analysis

Prior to analysis all samples were sieved to remove any coarse fragments (>500 μm; these consisted almost entirely of shell and coral fragments and samples of the >500 um fraction were composited to characterise the marine carbonate component of the PCB sediments). The river samples were further fractionated to recover the less than 10 μm fraction. This size fraction has been recently shown, during flood plume sampling on the Burdekin River which drains into the Great Barrier Reef Lagoon to the south, to be the particle size fraction being transported into the Lagoon (Bainbridge pers comm.). All the river samples were individually slurried with water and settled to the point where the fine fraction, less than 10 μm, was decanted, dried and recovered for analysis. The samples were analysed at the Queensland Government Department of Science, Information Technology, Innovation and the Arts (DSITIA) Chemistry Centre, with lithium metaborate fusion and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) for the major element concentrations and Inductively

Coupled Plasma-Optical Emission Spectrometry (ICP-OES) for the trace elements concentrations. The elements above detection limits are listed in Table 1.

The total carbon content was determined on 12 samples from the bay using a Sercon Europa EA-GSL elemental analyser and mass spectrometer at the Australian Rivers Institute, Griffith University. These samples were selected to cover the range of marine carbonate concentrations (estimated from the geochemistry). The organic carbon components of these sediments are expected to be low (see Torgensen et al., (1983); organic carbon n=71, mean 0.50% standard deviation 0.26%). The total carbon content is used to estimate the marine carbonate component ((TOC% – 0.5) x 8.33) in the 12 samples with these results being compared to the estimates from the geochemical mixing model.

3.3 Data analysis

Concentrations of the elements in the sediment samples collected from PCB, its major estuaries and in samples collected to characterise the source end members (each of the nine rivers, quartz silt sands and marine carbonates) were first compared and assessed to ensure that the bay and estuary samples fell within the concentration ranges of the source end members. Principle component analysis was applied to the geochemical data from the surface samples collected from the bay. This is used to identify the key geochemical components present in the sediments. The Kruskal-Wallis H-test was used to identify the geochemical properties which distinguish between the source end members (each of the nine rivers, quartz silt/sands and marine carbonates). Those having test statistic $p > 0.05$ were excluded from further consideration, as previously applied by Collins et al., (1998; 2010) as were elements falling outside the source end member concentrations. Then linear discriminant analysis was applied to the remaining geochemical properties to identify the optimum combination of properties which distinguished between the sources. The percentage of the sources correctly classified by each individual geochemical property was assessed. Next, starting with the individual property that provided the highest proportion of correctly classified sources, tracers were added in turn and the proportion of source samples correctly classified calculated using linear discriminant analysis. Parameters were added such that with each addition the number of sources correctly classified was maximised. This process was used to identify the best suite of geochemical parameters which discriminate between all of the sources.

This suite of geochemical properties was then used in a distribution mixing model to determine the relative contribution of different end member sources to the bay sediment through simultaneously minimising mixing model difference (MMD):

$$MMD = \sum_{i=1}^{n} \left| \frac{\mathbf{C}_i - \left(\sum_{s=1}^{m} \mathbf{P}_s \mathbf{S}_{si}\right)}{\mathbf{C}_i} \right| \qquad \text{(Equation 1)}$$

where n is the number of elements included in the model determined by the above selection process; C_i is the bay sample geochemical property (i); m is the number of sources; P_s is proportion derived from that source, such that $0 \leq P_s \leq 1$, and the sum of all source proportions equals 1; and S_{si} is the distribution of element (i) in source. Student's t-

distributions were modelled for each source element (S_{si}). The Student's *t*-distribution provides more weighting to the tails of the distribution than the normal distribution and is an appropriate distribution when the number of samples is small (i.e. <30) (Krause et al., 2003). The Student's *t*-distribution has the same mean as the sample grouping with a dispersion parameter based on multiplying the standard deviation by $n^{-1/2}$, where n is the number of samples (Krause et al., 2003; Wilkinson et al., 2011). Non-negative constraints were applied to all source and bay elements.

Following Laceby and Olley (in prep), the best combination of contributions from each of the sources was determined using the Optquest algorithm in *Oracle's Crystal Ball software*. In Optquest the contribution from each source is varied and all randomly generated mixtures are assessed to determine the minimum mean of MMD (from Equation 1). In Optquest, the proportional contribution from each source (P_s) is modelled as a truncated normal distribution ($0 \le x \le 1$) with mixture mean (μ_m) and standard deviation (σ_m) following the research of Caitcheon et al., (2012) and Olley et al., (in press) on fallout radionuclides. For each sample the Goodness of Fit (GOF) was used to determine the mean relative deviation of the modelled results from the measured data for each sample, using the equation:

$$GOF = 1 - \left(\frac{1}{n} * MMD\right) \qquad \text{1) (Equation 2)}$$

where n equals the number of elements in Equation 1 and MMD is the result of Equation 1. A GOF value of 1 indicates that modelled data perfectly match geochemistry of the bay sediment.

4. LiDAR Data and aerial imagery

To assess the extent of erosion on the coastal plain we used Google™Earth imagery (2012) and Light Detection and Ranging data (LiDAR) of three strips of the coastal plain covering a combined area of 22.4 km^2. The LiDAR was flown in September 2011 by Terranean (now RPS), Brisbane, Australia. Flight lines were designed to achieve a point density of 2.3 points per square metre and 43% overlap over the project areas. The flying height was (nominally) 600 metres above ground level. The LiDAR points were classified as ground and non-ground points using automatic filtering followed by interactive checking and re-classification. The automatic classification was performed using *TerraScan software*. Once the point clouds had been formed and classified. Raster surfaces were generated from the LiDAR LAS files. The ground pixel spacing of the rasters is one metre. The rasters were provided in ESRI ASCI grid format. The Google™Earth (2012) imagery was classified into five classes (deep water, shallow water, highly reflective non-vegetated surfaces, light vegetation and dense vegetation). These were then converted to rasters and then to polygons. The polygons associated with the highly reflective non-vegetated surfaces, which represent the area of eroded coastal plain, were then edited to remove any erroneously classed areas.

5. Results

At all of the sites sampled in the bay the sediments consisted of a varying mixture of three primary components; shell and coral fragments, quartz silt/sand and grey-green clay. At two locations PCB27 and PCB38 the cores penetrated into a hard red-grey mottled clay which we assume to be the pre-Holocene Basement described by Bryce et al., (1998); and well as the surface samples, samples of this material have also been analysed in this component of the study.

Concentrations of selected elements in the sediment samples collected from PCB, its major estuaries and in samples collected to characterise the source end members (each of the nine rivers, quartz silt sands and marine carbonates) are presented in Figure 2. Data from the basal samples from cores PCB27 and PCB38 are also shown. For all of the elements shown most of the surficial bay and estuarine samples fall within the range of the source end members, and therefore could be derived as mixtures of these sources. Notable exceptions to this are Na_2O (and Ba not shown). The bay and estuarine sediments have clearly gained Na_2O from exposure to the marine environment; similarly Ba has been lost. Consequently, these elements are not considered further in this analysis.

The data from the base of cores PCB27 (depth 60cm) and PCB38 (depth 60cm) are clearly different to the surficial bay sediments. These samples consisted of hard red-grey mottled clay, compared to the shell and coral fragments, quartz silt/sand and grey-green clay which make up the other samples collected from the bay and estuaries. Concentrations of U, V, La, Ce, and Nd for one or both these samples fallout side the range of the source end members sampled. This indicates that these samples could not be derived from a mixture of the material derived from these sources or have been alter significantly by diagenesis. We assume that this material is the pre-Holocene Basement described by Bryce et al., (1998). At this stage its origin remains unknown and warrants further investigation.

Most of the variation (75.8%) in the bay geochemical data is explained by two principle components (Figure 3). Principle component 1 which explains 61.6% of the variance is primarily related to the marine carbonate associated elements (CaO and Sr; Table 1) and the silt/clay associated elements (those strongly correlated with Al_2O_3; Table 1). Principle component 2 is primarily related to the marine carbonate associated elements and SiO_2 which is associated with quartz silt/sand. The relationship between these three primary components in the bay sediment and estuarine samples and the source end member samples is shown in Figure 4 as a ternary plot (Al_2O_3-CaO-SiO_2). In this figure the marine carbonate source component plots close to 100% CaO, the quartz silt/sand close to 100% SiO_2 and the terrestrial derived river silt-clays along the Al_2O_3-SiO_2 axis. The data from the estuarine and bay samples clearly fall between the source end member data; with the estuarine samples enriched in SiO_2 relative to the bay samples.

Kruskal-Wallis H-test was used to identify the geochemical properties which distinguish between the source end members. This test only identifies if an element distinguish one or more sources from the others, and because of the extreme difference between the marine carbonate and quartz silt/sand, and these two end members and the river samples, if the test was applied to all of the source end member data all of the elements would pass. The marine carbonates and the quartz silt sands are clearly distinguished primarily by their CaO and SiO_2 contents, respectively. Consequently, we applied the test only to the river samples to determine which elements provide a distinction between these nine more geochemically closely related sources. From the river sample data only three elements failed the Kruskal-Wallis H-test (Sm, Gd and Tm; Table 2).

Using linear discriminant analysis the remaining elements were ranked by the proportion of sources they correctly classified (Table 2); this time including the marine carbonates and the quartz silt/ sands. Starting with the element that provided the greatest proportion of sources correctly classified (V) elements were added sequentially until the best suite of elements discriminating between all of the sources was determined (Table 2).

These elements which include major and trace elements, and rare earth elements, were then used in the mixing model to determine the relative contribution of each of the sources to the samples collected from the bay and its estuaries. The GOF for the 64 surface samples collected from the bay and the estuaries ranged from 0.75 to 0.98 with a mean of 0.93 $\pm$ 1; for the 30 samples from the core collected at PCB24 it ranged from 0.94 to 0.98 with a mean of 0.96 $\pm$ 1. There was also very good agreement between the modelled estimates of the marine carbonate component and those estimated from the total carbon (Figure 5); all the data are consistent with the 1:1 line at 1 σ. The high GOF and the data in Figure 5 indicate a high level of confidence in the mixing model results.

The mean mixing model results, the relative contribution of each of the source end members to the surficial sediment samples collected from PCB and its estuaries are presented in Figure 6. The data indicate that the marine carbonate component increases toward the reef, as described by Frankel (1974). There is also quartz silt/sand present around these reefs, presumably equivalent to the relict sands described by Frankel (1974). Quartz silt/sand also make up a significant component of the samples collected from near and in the estuaries. Sediment derived from the Stewart River can be detected just off-shore from the river mouth and at one site toward the centre of the bay. Sediments with chemistry consistent with a proportion having been derived from the Morehead and Hann Rivers are identified near the mouth of the North Kennedy River. The North Kennedy and Annie Rivers, and Saltwater Creek make insignificant contributions (Figure 5 and Table 3). Approximately 46% of the surficial sediment sampled from the bay is predicted to be derived from the catchment silt-clay sources. The largest contributions of terrestrial derived silt-clays are predicted to come from the Bizant River (51 $\pm$ 1%) and Coastal Plain (30 $\pm$ 1%), a smaller contribution from the Normanby River (9 $\pm$ 1%) and the remainder (10%) from a mixture of the other catchments. It is assumed that the Bizant River samples are representative of the broader lowland floodplain, not just the Bizant River itself, but further sampling is required to confirm this.

Down-core variations in selected element concentrations from the core samples collected from site PCB 24 (Figure 1) are shown in Figure 7; together with the predicted relative contribution of each of the source end members to the sampled sediments. The predicted source contributions are relatively uniform down to 44 cm with coastal plain, marine carbonates and quartz silt/sand dominant, and the Normanby making the most significant contribution from the riverine sources. The contributions at the base of the core are similar to those in the upper section. There is a transition in source contributions between 44 and 54 cm with an increasing input from the Stewart and other rivers. This reverts back to a mixture similar to the upper section of the core at 54 cm. At this stage we have no indication of the degree to which the sediments down the core have been mixed. If limited mixing is assumed the data suggest that the mix of sediment delivered to the bay has been relatively stable for at least the last ~70 years using the maximum sedimentation rate (6.1mm/yr) estimated by Torgensen et al., (1983).

Using the minimum (2.3mm/yr) and maximum (6.1mm/yr) deposition rates estimated by Torgensen et al., (1983) we have estimated the contribution of each of the source end members to the bay in Ktonnes per year (Table 3). The bay area is 2385 km^2 of which our samples cover 1750 km^2. We have confined our estimate to the area sampled and used a sediment density of 1.5t/m^3 for the bay sediments. This gives a total annual deposition of between 6000 and 16000 Kt/yr of which ~9% or between 530 and 1400 Kt come from the riverine sources (240 and 630 Kt from the Normanby River).

The dominance of sediment derived from the coastal plain and the Bizant River was unexpected. The Bizant River derives its sediment primarily from incision into the lowland floodplain and coastal plain. To further assess the contribution from the coastal plain we have used a LiDAR digital elevation model of a 22.4 km^2 area of the coastal plain and Google™Earth imagery (2012) of the coastal floodplain. The Google™Earth (2012) imagery was classified to map the highly reflective non-vegetated surfaces which we consider provides a good representation of the areas of coastal plain erosion. The mapped extent is shown in Figure 8 and covers 185 km^2. Remnants of the previous surfaces are evident across the coastal plain. We have used the LiDAR data to estimate the average elevation of the basal and remnant surfaces these are 1.61 $\pm$ 0.02 m (n=44) and 2.32 $\pm$ 0.08 m (n=45), respectively (Figure 8). The difference between these is 0.71$\pm$ 0.08 m. We consider this estimate to be conservative. If we assume that these remnant areas represent the pre-erosion surface then (using a sediment density for the coastal plain material of 1.5 t/m^3; note this is likely to be an underestimate) then between 175Mt and 220Mt has been eroded from this area.

5.1 Discussion

Previous studies using catchment scale modelling identified surface soil erosion in the upper catchments of rivers draining into PCB as supplying >80% of the sediment delivered to the bay (Prosser et al., 2001, Brodie et al., 2003). Recent work (Olley et al., subm.) has highlighted that the catchment sediment sources are dominated by sub-surface sources, principally bank erosion and gully erosion.

Principle component analysis of the chemistry of surficial sediments (34 major, trace and rare earth elements) collected from Princess Charlotte Bay and it estuaries indicate that the sediments consist primarily of three components; marine derived carbonates, quartz silt/sand and terrestrially derived silt-clays. A geochemical mixing model incorporating all of the major terrestrial sources indicates that the terrestrial component is dominated (81 ± 2%) by sediment derived from the coastal plain and the Bizant River, which is a distributary of the Normanby-Laura River. The Bizant derives its sediment primarily from erosion into the coastal plain. Erosion from the upper catchments which drain into the bay makes a relatively small contribution to the sediment present in the bay (< 10% of the total and ~ 19% of the silt-clay fraction). The low delivery of sediments from upper catchment sources is probably the result of deposition within the channel network and floodplains of the extensive low gradient alluvial plains in the lower reaches of the rivers which drain into the bay.

Coastal plain erosion has not previously been identified as a significant contributor of sediment delivered to the Great Barrier Reef Lagoon. Our study shows that in PCB it is the dominant source of terrestrially derived sediment. During the sampling of the bay, which was conducted in the dry season, we observed the high turbidity of tidal waters returning to the bay from the estuaries and coastal plain. A significant proportion of the coastal plain is inundated at full tide. The high turbidity of returning tidal waters was also noted by Sahl and Marsden, (1987); and by one of the authors (C. Howley) of six previous occasions while sampling the lower estuaries. This tidal transport of sediments into the bay occurs twice daily and potentially is the dominate mechanism by which terrestrial sediment is delivered to the bay. However this conflicts with the finding of Wolanski et al. (1992) and Bryce et al., (1998) who observed a net landward movement of sediment during the dry season. In our view the timing and processes involved in the transport of sediment from the coastal plain to the bay requires further study. Furthermore, it is possible that the sediment delivered via tidal processes remains within the near shore zone, and is only transported into the middle of the Bay or to the Reef during major flood events.

The data from the base of cores PCB27 (depth 60cm) and PCB38 (depth 60cm) are clearly different to the surficial bay sediments. These samples consisted of hard red-grey mottled clay, compared to the shell and coral fragments, quartz silt sand and grey-green clay which make up the other samples collected from the bay and estuaries. At this stage the origin of this basal material remains unknown and warrants further investigation.

Chivas el al., (1983) estimated using a limited number of ^{210}Pb dates that the Holocene sediments, which overlie this basal material in the bay could have accumulated in the last 1700 years. Chappell (1982) proposed that reduced the silt input from the catchment for the period 5000 to 2500 years ago favoured the formation of chenier (shell) ridges. These ridges are now heavily dissected. Our results indicate that sediments from the coastal plain that were deposited behind these beach ridges now dominate the sediment being delivered to the bay. Our preliminary assessment of a 185 km^2 area of the coastal plain suggests that this area could have generated between 175Mt and 220Mt of sediment since the coastal erosion process began. Pietsch et al., (in prep.) estimated using optical dating that deposition ceased on the remnant surface ~500 years ago. Sometime after this the unit began to erode. While the trigger and exact timing of this erosion remains to be determined, possible mechanism include the incision of the Bizant River and capture of additional flow from the Normanby, increased cyclonic activity (insert reference), changes in sea-level (insert reference), breaking of the coastal barrier by wave action, or the development of intrinsic instability due to deposition behind the coastal barrier.

5.2 Conclusions

The hypothesis that soil erosion in the upper catchments of rivers draining into Princess Charlotte Bay dominates the sediment delivered to the bay is not supported by the data presented in this study. The determination of sediment provenance using geochemistry shows that the bay sediments are dominated by three components; marine derived carbonates, quartz silt/sand and terrestrially derived silt-clays. The terrestrially derived silt-clays constitute about 46% of the sediments in the bay. A geochemical mixing model incorporating all of the major terrestrial sources indicates that the terrestrial component is dominated (81 $\pm$ 1%) by sediment derived from the coastal plain and the Bizant River. The Bizant derives its sediment primarily from erosion into the coastal plain. From the data presented it is concluded that erosion of the coastal plain is the dominate source of terrestrial sediments to Princess Charlotte Bay.

Acknowledgements

This study was jointly funded by the Australian Government Caring for our Country Reef Rescue program, and Griffith University. We are grateful to Ted Lee, the Laura Rangers, Thomas Brooks-Wallace, Jo Hoyle, Jenny Spencer, Jason Carroll, Trent Cini, Bungie Scott, and the Pelican crew for assistance with fieldwork. Dr Patrick Laceby is thanked for useful discussions and his review of early drafts of this manuscript.

References

Bainbridge, Z. (2012 pers. com.). Australian Centre for Tropical Freshwater Research, James Cook University.

Brodie, J., McKergow, L.A., Prosser, I.P., Furnas, M., Hughes, A.O., Hunter, H.,(2003). Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area. ACTFR Report 03/11. pp. 192

Bryce, S., Larcombe, P., Ridd, P.V., (1998). The relative importance of landward-directed tidal sediment transport versus freshwater flood events in the Normanby River estuary, Cape York Peninsula, Australia Marine Geology, 149, 55-78.

Caitcheon, G., Douglas, G., Palmer, M., (2006). Sediment Source Tracing in the Lake Burragorang Catchment. CSIRO Land and Water, Canberra.

Chappell, J., (1982). Sea level and sediments: some feature of the context of coastal archeological sites in tropics.Archaeol. Oceania 17, 69-78.

Chivas, A.R., Torgersen, T., Andrew A.S., (1983). Isotopic tracers of recent sedimentary environments in the Great Barrier Reef in the Proceeding of the inaugural Great Barrier Reef Conference, August 28th, 1983, Townsville. 83-88.

Collins, A.L., Walling, D.E., Leeks, G.J.L., (1996). Composite fingerprinting of the spatial source of fluvial suspended sediment: a case study of the Exe and Severn river basins, United Kingdom. Géomorphologie: relief, processus, environnement, 41-53.

Collins, A.L., Walling, D.E., Leeks, G.J.L., (1998). Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. Earth Surface Processes and Landforms, 23(1), 31-52.

Collins, A.L., Zhang, Y., Walling, D.E., Grenfell, S.E., Smith, P., (2010). Tracing sediment loss from eroding farm tracks using a geochemical fingerprinting procedure combining local and genetic algorithm optimisation. Science of The Total Environment, 408(22), 5461-5471.

Douglas, G., Palmer, M., Caitcheon, G., (2003). The provenance of sediments in Moreton Bay, Australia: a synthesis of major, trace elmeent and Sr-Nd-Pb isotopic geochemistry, modelling and landscape analysis. Hydrobiologia, 494, 145-152.

Hatfield, R.G., Maher, B.A., (2009). Fingerprinting upland sediment sources: particle size-specific magnetic linkages between soils, lake sediments and suspended sediments. Earth Surface Processes and Landforms, 34(10), 1359-1373.

Hardy, F., Bariteau, L., Lorrain, S., Theriault, I., Gagnon, G., Messier, D., Rougerie, J.F., (2010). Geochemical tracing and spatial evolution of the sediment bed load of the Romaine River, Quebec, Canada. CATENA, 81(1), 66-76.

Hughes, A.O., Olley, J.M., Croke, J.C., McKergow, L.A., 2009. Sediment source changes over the last 250 years in a dry-tropical catchment, central Queensland, Australia. Geomorphology, 104(3-4), 262-275.

Frankel E., (1974). Recent sedimentation in the Princess Charlotte Bay area, Great Barrier Reef province. In: Proceedings of the Second International Coral Reef Symposium, Brisbane, December 1974, pp. 355-369.

Krause, A.K., Franks, S.W., Kalma, J.D., Loughran, R.J., Rowan, J.S., (2003). Multi-parameter fingerprinting of sediment deposition in a small gullied catchment in SE Australia. CATENA, 53(4), 327-348.

Laceby P., Olley, J., (in prep). A new aprroach using geochemistry to trace the source of sediments incorporting distributions and element correlations.

Mathews, E.J., Heap, A.D., Woods, M., (2007). Inter-reefal seabed sediments and geomorphology of the Great Barrier Reef, a spatial analysis. Geoscience Australia Record 2007/09, 140pp.

Phillips, J.M., Russell, M.A., Walling, D.E., 2000. Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments. Hydrological Processes, 14(14), 2589-2602.

Pietsch, T.J., Brooks, A.P., Spencer, J., Olley, J.M., Borombovits, D. K., (in prep.). Age, distribution and significance within a sediment budget of in-channel benches in the Normanby River, Queensland, Australia. Geomorphology

Prosser, I.P., Rustomji, P., Young, W.J., Moran, C.J. and Hughes, A.O., (2001). Constructing River Basin Sediment Budgets for the National Land and Water Resources Audit. CSIRO Land and Water, Technical Report 15/01.

Olley, J.M. and Caitcheon, G.G., (2000) The major element chemistry of sediments from the Darling-Barwon River and its tributaries: Implications for sediment and phosphorus sources, Hydrological Processes, 14, 1159-1175

Olley, J.M., Caitcheon, G.G., Hancock, G., Wallbrink, P.J., (2001). Tracing and dating techniques for sediment and associated substances, CSIRO Land and Water, Canberra.

Olley, J.M., Brooks, A., Spencer, J.S., Pietsch, T., Borombovits, D.K., (submitted). The dominant erosion process supplying sediment to rivers draining into Princess Charlotte Bay, Australia. Geomorphology

Sahl L.EE., and Marsden, M.A.H., (1987). Shelf sediment dispersal during the dry season, Princess Charlotte Bay, Great Barrier Reef, Australia. Continental Shelf Research, Vol. 7, No. 10, pp. 113-159.

Torgersen, T., Chivas, A.R., Chapman, A., (1983). Chemical and Isotopic characterisation and sedimentation rates in Princess Charlotte Bay Queensland. BMR Journal of Australian Geology and Geophysics 8, 191-200.

Walling, D.E., Collins, A.L., Stroud, R.W., (2008). Tracing suspended sediment and particulate phosphorus sources in catchments. Journal of Hydrology, 350(3-4), 274-289.

Weltje, G.J., Brommer, M.B., (2010). Sediment-budget modelling of multi-sourced basin fills: application to recent deposits of the western Adriatic mud wedge (Italy). Basin Research, 23(3), 291-308.

Wilkinson, S.N., Hancock, G.J., Bartley, R., Hawdon, A.A., Keen, R.M., (2012). Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin, Australia. Agriculture, Ecosystems and Environment. doi:10.1016/j.agee.2012.02.002.

Wolanski, E., Gibbs, R.J., Mazda, Y., Mehta, A., King, B., (1992).The role of turbulence in the settling of mud flocs. J. CoastalRes. 8, 35-46.

Table1: Correlation coefficients for elements measured on surficial sediment samples collected from PCB and its estuaries.

Element	SiO_2	Al_2O_3	CaO
SiO_2	1.00	−0.21	−0.84
TiO_2	−0.09	0.94	−0.44
Al_2O_3	−0.21	1.00	−0.34
Fe_2O_3	−0.23	0.98	−0.32
MgO	−0.86	0.38	0.59
Na_2O	−0.49	0.57	0.12
CaO	−0.84	−0.34	1.00
K_2O	0.05	0.90	−0.55
P_2O_5	−0.85	0.50	0.54
Zn	−0.04	0.80	−0.37
As	0.00	0.49	−0.24
Ba	0.13	0.42	−0.33
Ce	0.07	0.44	−0.28
Co	−0.08	0.78	−0.33
Cr	−0.24	0.82	−0.22
Dy	0.01	0.85	−0.47
Er	0.01	0.79	−0.45
Eu	−0.04	0.80	−0.38
Gd	−0.05	0.76	−0.35
Ho	−0.01	0.84	−0.45
La	0.00	0.59	−0.28
Lu	0.08	0.64	−0.44
Mn	0.01	0.59	−0.34
Nd	0.00	0.64	−0.31
Pr	0.01	0.63	−0.31
Sm	0.01	0.73	−0.38
Sr	−0.78	−0.36	0.95
Tb	−0.04	0.82	−0.40
Th	−0.07	0.86	−0.41
Tm	0.03	0.75	−0.45
U	−0.45	0.44	0.21
V	−0.22	0.96	−0.33
Y	−0.04	0.80	−0.39
b	0.04	0.74	−0.45

Table 2: Kruskal-Wallis H-test and linear discriminant analysis results for elemental concentrations from the source end members used to determine the provenance of sediment in PCB and its estuaries.

	Kruskal-Wallis H-test		*Percent (%) correctly classified*	
	H-value	*P*-Value	*Individual*	*Cumulative*
Suite of elements providing the best discrimination between sources				
V	31.9	<0.001	55.3	55.3
TiO_2	33.2	0.001	53.2	70.2
CaO	24.2	0.002	40.4	76.6
K_2O	25.7	<0.001	51.1	91.5
Yb	24.0	0.002	44.7	93.6
U	29.1	<0.001	46.8	97.9
Th	18.2	0.020	38.3	97.9
Pr	17.3	0.030	36.2	100
SiO_2	22.8	0.004	34.0	100
La	18.0	0.021	40.4	100
Other elements which passed the Kruskal-Wallis H-test				
Al_2O_3	23.1	0.003	34.0	
Fe_2O_3	28.8	<0.001	42.6	
MgO	29.0	<0.001	42.6	
P_2O_5	20.2	0.009	25.8	
Y	17.4	0.026	31.9	
Ce	16.0	0.042	40.4	
Nd	17.3	0.023	31.9	
Eu	25.0	0.001	25.5	
Dy	18.5	0.018	25.5	
Ho	19.3	0.013	34.0	
Er	22.7	0.003	42.6	
Tm	24.7	0.002	40.4	
Lu	23.1	0.003	31.9	
Elements failing the Kruskal-Wallis H-test				
Sm	15.0	0.060	27.7	
Gd	14.3	0.073	31.9	
Tb	13.6	0.092	27.7	

Table 3: The mean contribution, standard deviation and standard error of each source end members to surficial samples collected from PCB and the associated Ktonnes per year based on Torgensen et al., (1983) minimum and maximum sedimentation rates of 2.3 to 6.1 mm year

	Annie	Bizant	North Kennedy	Hann	Morehead	Normanby	Saltwater	Stewart	Coastal plain	Sand	Marine
Mean	0.012	0.239	0.002	0.012	0.009	0.039	0.002	0.011	0.138	0.260	0.276
Std Deviation	0.019	0.141	0.007	0.069	0.031	0.062	0.009	0.022	0.150	0.222	0.171
Std error	0.003	0.021	0.001	0.010	0.005	0.009	0.001	0.003	0.022	0.033	0.026
Deposition rates	Ktonnes per year derived from each source										
6.1 mm/yr	189	3839	27	195	143	633	27	185	2207	4172	4432
2.3 mm/yr	71	1448	10	74	54	239	10	70	832	1573	1671

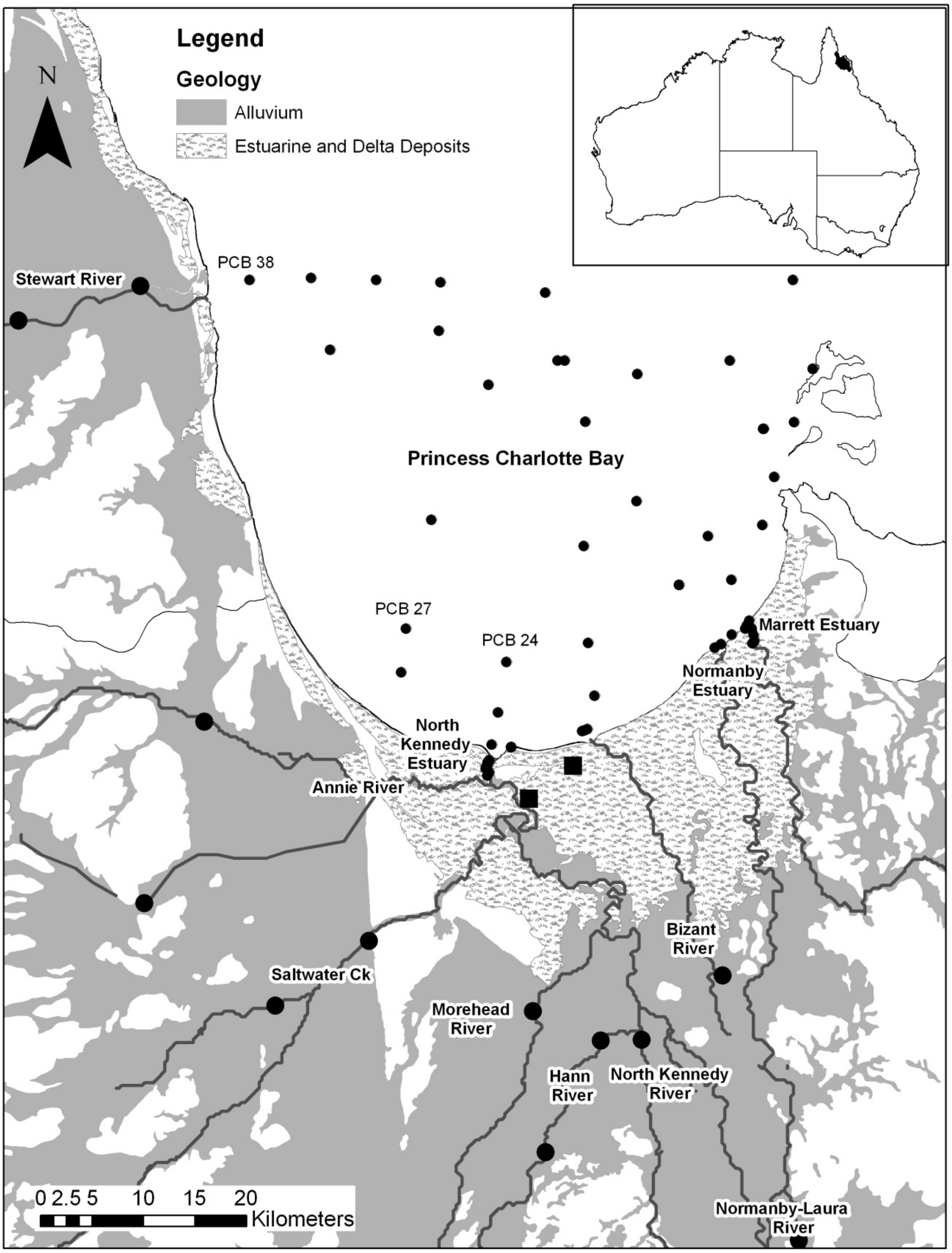

Figure 1: Map of the Princess Charlotte Bay showing the location of the river (large circles), coastal plain (closed squares) and Bay (small circles) sampling sites. The map also shows the major areas of alluvium, coastal deltaic and estuarine deposits, the major rivers (thick grey lines).

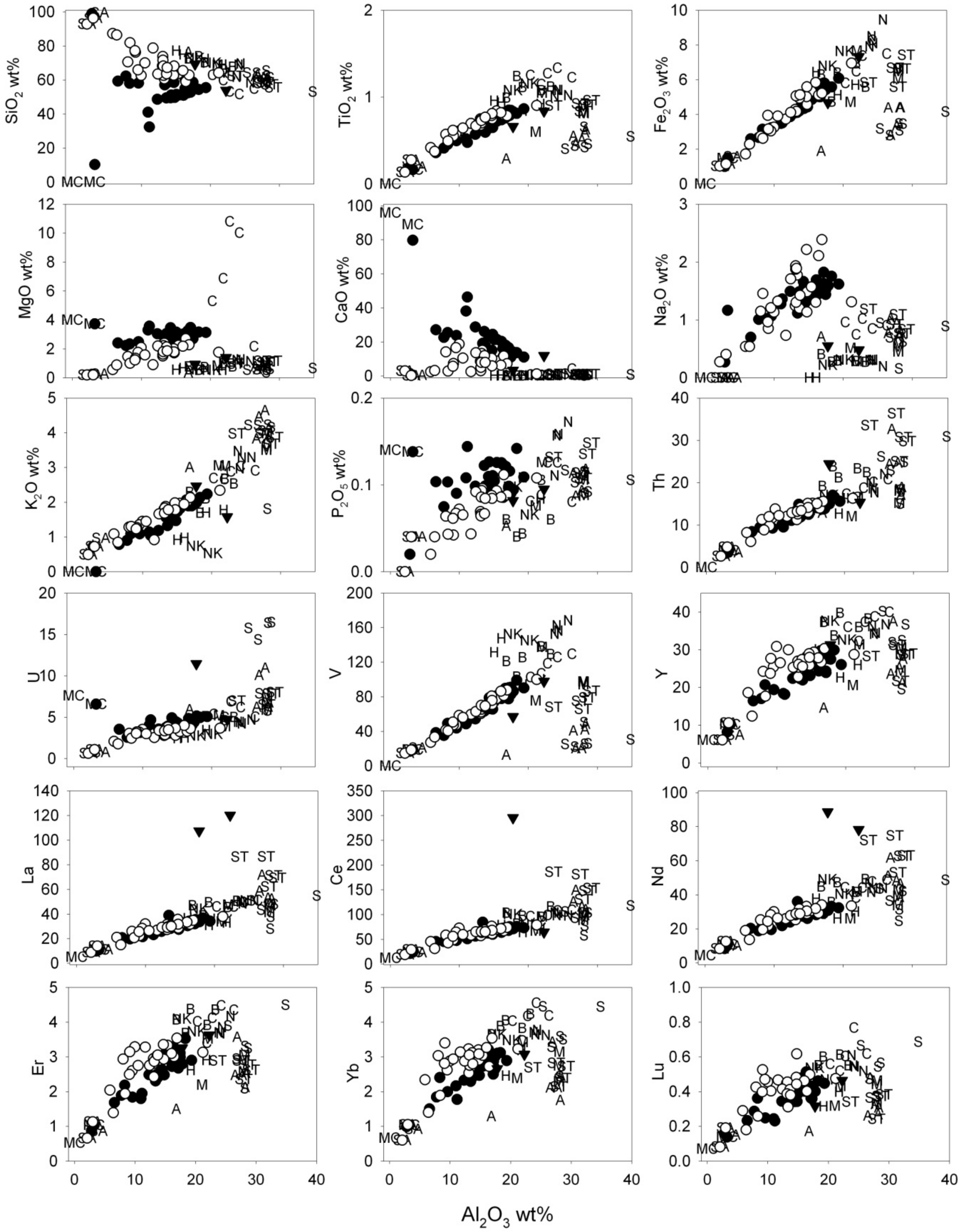

Figure 2: Concentrations of selected elements in the surface sediment samples collected PCB (closed circles), its major estuaries (open circles) and in samples collected to characterise the source end members (SA=Quartz silt sand, MC =Marine Carbonate, ST= Stewart, A= Annie, C= Coastal Plain, NK=North Kennedy, H=Hann, B=Bizant, N=Normanby, S=Saltwater, M=Morehead). Elements are plotted against Al_2O_3 (wt%). Trace and rare earth element concentrations are in ppm. Data from the basal samples from cores PCB27 and PCB38 (closed triangles) are also shown.

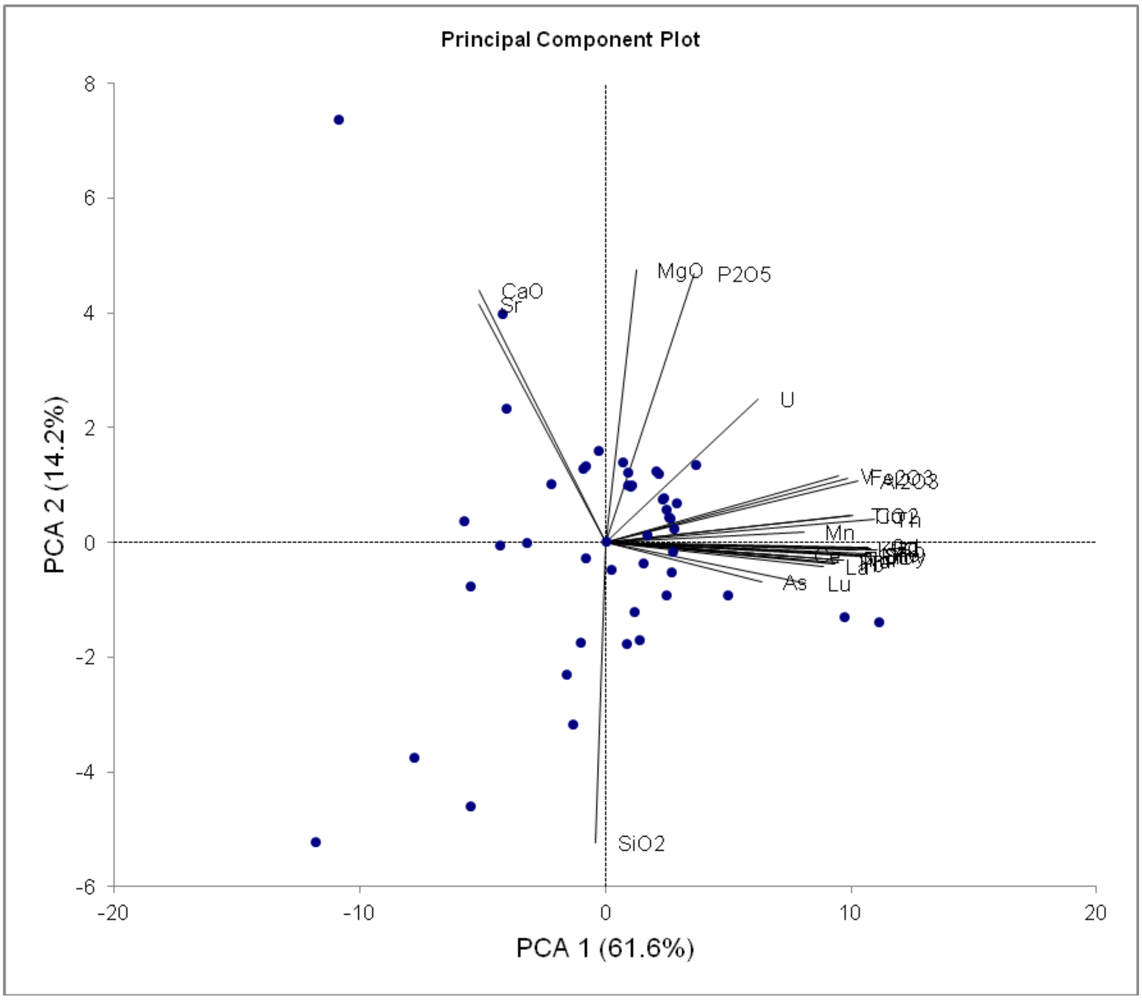

Figure 3: The first two principle components of the geochemistry (34 elements) of sediment samples collected from Princess Charlotte Bay and its estuaries. Principle component 1 which explains 61.6% of the variance is primarily related to the marine carbonate associated elements (CaO and Sr; Table 1) and the clay associated elements (those strongly correlated with Al_2O_3; Table 1). Principle component 2 is primarily related to the marine carbonate associated elements and SiO_2 which is associated with quartz silt sand.

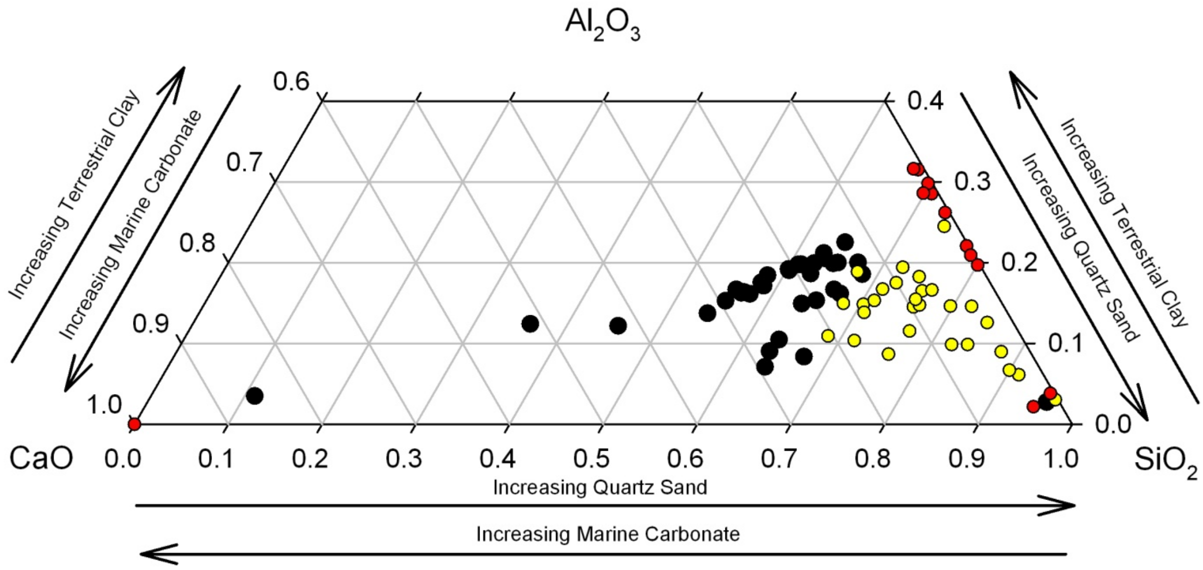

Figure 4: Ternary plot Al_2O_3–CaO–SiO_2 of sediment samples collected from PCB (black circles) and its the major estuaries (yellow circles). The end members used in the mixing model are shown (red circles).

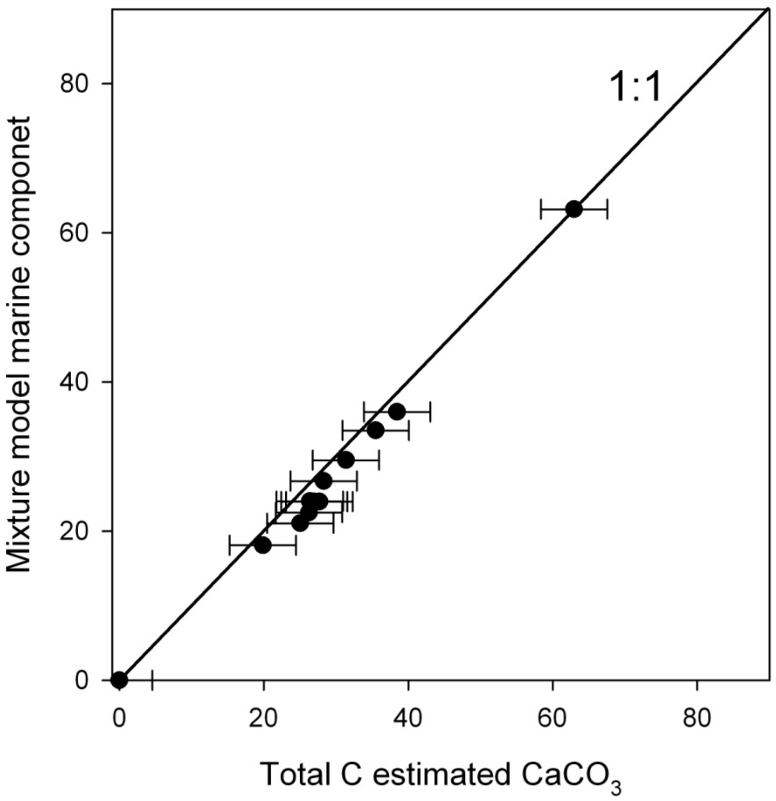

Figure 5: A comparison of the marine carbonate component estimated from the geochemical mixing model with estimates based on the total carbon content of 12 samples from PCB. Error bars are based on analytical uncertainties and are equivalent to one standard error on the mean. The results are in good agreement with all of the data consistent with the 1:1 line at 1 σ.

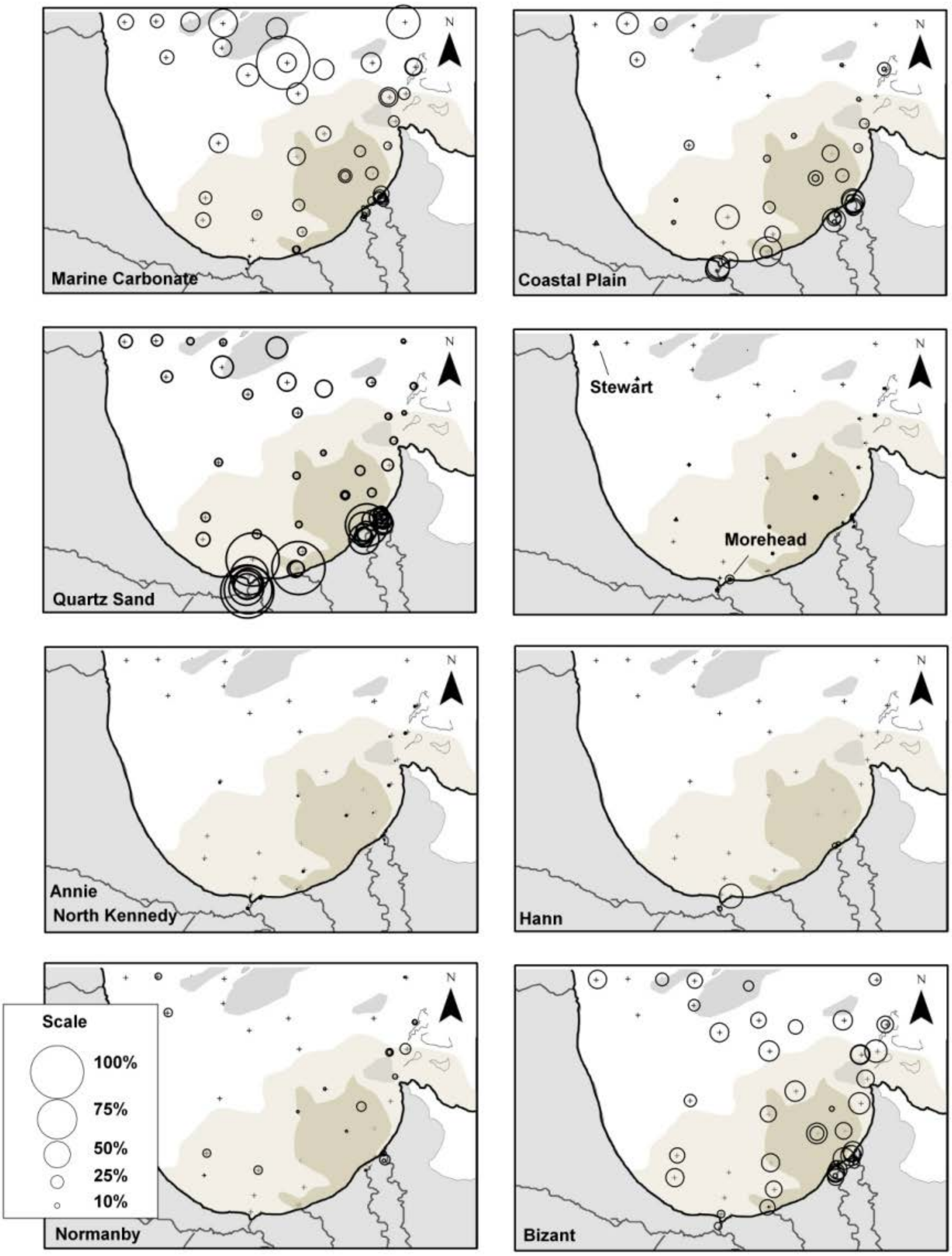

Figure 6: The relative contribution of each of the source end members to the surface sediment samples collected from PCB and its estuaries. The shading in the bay indicates the mud distribution (dark grey –100–80% mud, and light grey – 80–60% mud) as reported by Mathews et al., (2007). The circles within circles occur when sampling sites were closely located.

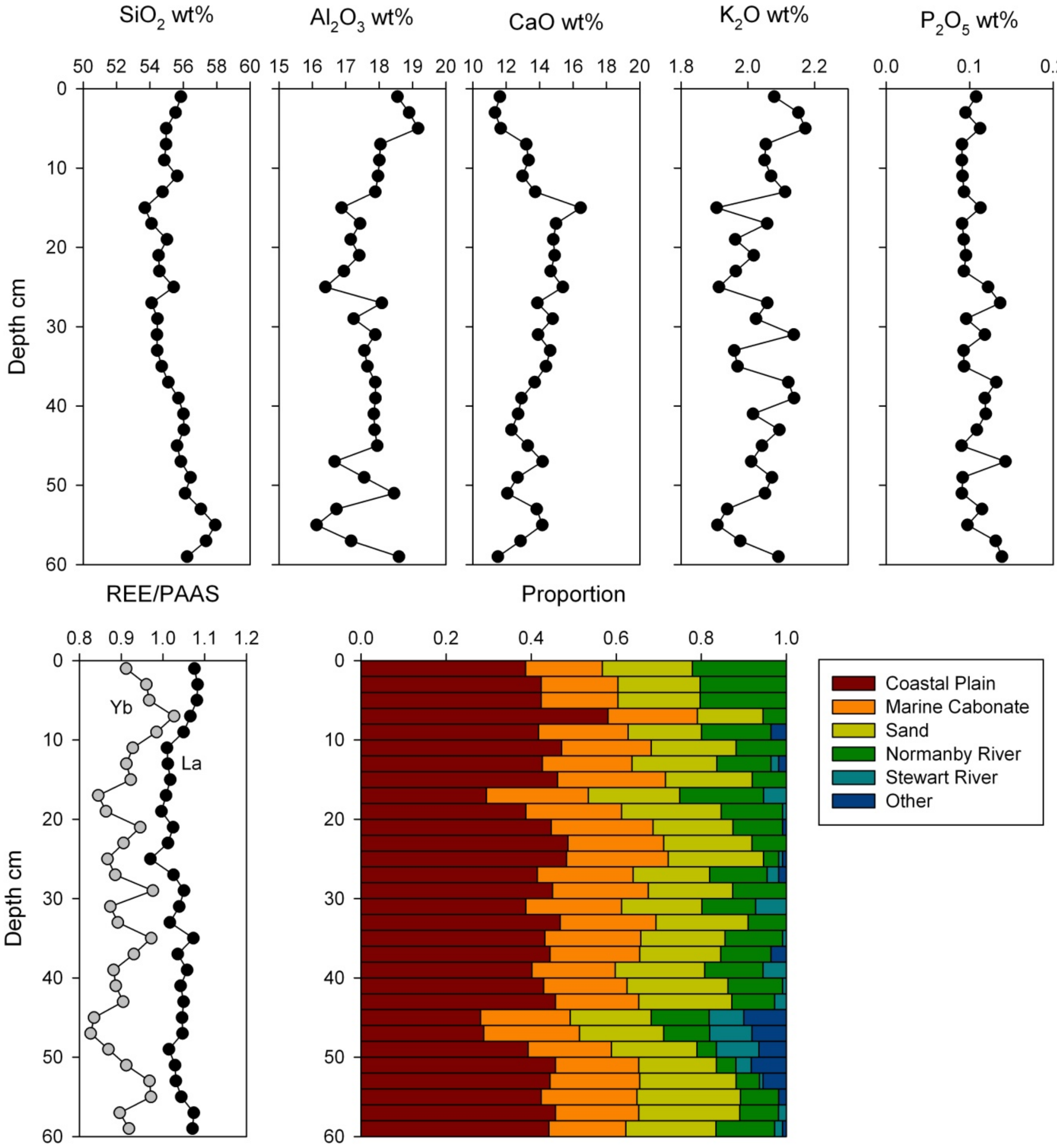

Figure 7: Down-core variation in selected elements from samples collected from site PCB24 Princess Charlotte Bay, together with the predicted relative contribution of each of the source end members to the sampled sediments.

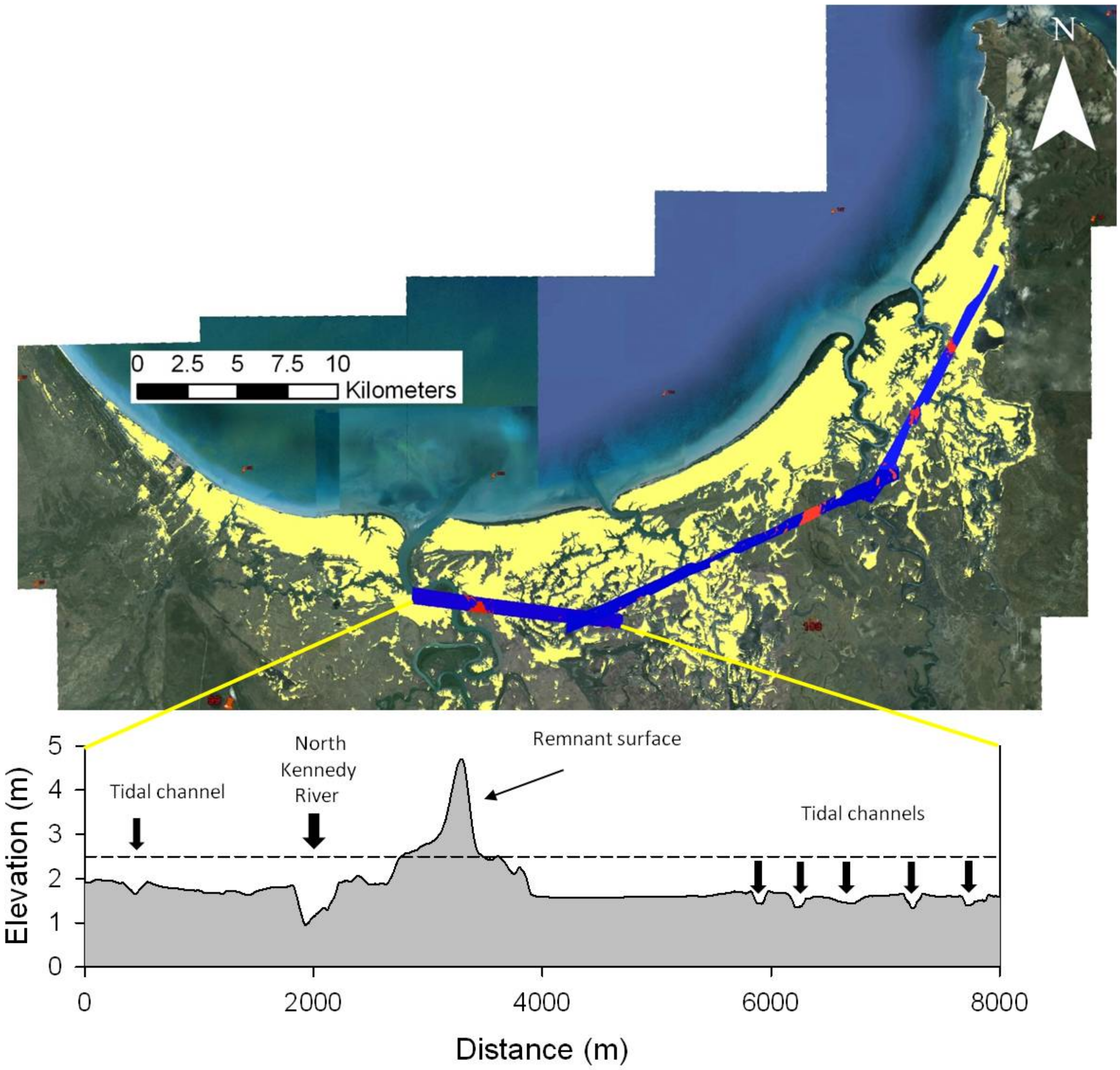

Figure 8: Top: Classified digital elevation data (blue < 2.5m < red) based on Light Detection and Ranging data (LiDAR) of a 22.4 km[2] of the coastal plain flown in September 2011 overlain on Google™Earth imagery (2012) of the coastal plain. The yellow polygons show the areas associated with highly reflective non-vegetated surfaces, which we have interpreted as representing areas of eroded coastal plain. Bottom: A cross-section along LiDAR strip showing an example of the remnant surface, the main channel of the North Kennedy and the tidal channels which dissect the coastal plain.