

**Depositional characteristics of recent and late  
Holocene overwash sandsheets in coastal  
embayments from southeast Australia.**

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## **CERTIFICATION**

**I, Adam D. Switzer, declare that this thesis, submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy, in the School of earth and Environmental Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.**

**Adam D. Switzer**

**16 February 2005**

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### **Abstract**

Sedimentary evidence for large-scale washover deposition along the Australian southeast coast is found as sandsheets in estuaries and anomalous boulder accumulations on rocky ramps and headlands. Large imbricated allochthonous boulders found elevated up to 33m above present sea-level indicate high energy deposition on sheltered rock ramps and coastal headlands and attest to very high wave energy in the past. Analysis of the sedimentary structures within the boulders can in places be related to ramp lithology and identify significant transport distances where the original position of the boulder is identified. The most striking boulder deposits are found in the ambient location of a large bay and have been transported more than 30 m horizontally along a boulder ramp and elevated to a height of more than 7 m above present sea-level. Although this evidence is striking, it is impossible to identify if the boulders were moved in one movement or have been moved by several events over time.

This study presents sedimentological evidence for a tsunami event(s) found in the upper fill of several embayments along the coast. Laterally extensive marine sandsheets are identified in back-barrier lagoons and elevated shell-rich sands are found on the margin of a large drowned river valley. These deposits exist up to 3km from the influence of modern coastal processes. The back-barrier sandsheets contrast with the finer confining sediments of the coastal lagoon and barrier estuary.

Interpretation of the depositional history of the deposits is conducted with reference to a global review of overwash deposition and a modern analog from the southeast Australian coast. In the absence of any geological evidence for known tsunami events on this coast, the deposits are compared to two modern sandsheets that were deposited during two large storms in 2001. This study therefore allows direct comparison of the deposits of unknown source to the storm deposited sediments found Abrahams Bosom Beach.

A large sandsheet is identified at Killalea Lagoon is composed of mixed marine sediment dominated by dune and beach sand but also containing platy heavy mineral assemblages indicative of nearshore to inner shelf sediments. This marine sediment is mixed with clumps of coastal vegetation and rip-up clasts of soil and lagoonal muds and clays.

The marginal drowned river valley material in a small embayment at Batemans Bay includes a coarse shell-unit containing large, often articulated, bivalve shells and oysters, along with cobbles of mixed lithology in a matrix of marine sand suggesting deposition of predominantly seaward tidal channel material.

The advantage of the sandy deposits lies in the analysis of their internal sedimentology and the presence of datable peat and shelly sands that confine the sand sheets and coarse shell-rich deposit respectively. The internal sedimentology of the deposit yields little structure and sediments consist of a series of massive, laminated and graded beds that often incorporate organic debris. These deposits contrast with storm washover deposits investigated at Abrahams Bosom Beach from the same coast that consist of thin graded beds of beach face and dune sediment only. These latter beds are a few centimeters thick and can be traced throughout the deposit. The storm deposits are the result of numerous wave-generated landward pulses while the larger more chaotic deposit is the result of several very large pulses capable of eroding and transporting shelf, nearshore, dune and terrestrial sediments landward followed by partial reworking by back flow. These characteristics are indicative of the chaotic reworking of such deposits by short-lived high-energy events attributed to tsunamis.

Dating of the Batemans Bay sequence was problematic and the shell-rich unit can only be confined to an age of around 1000 yrs. At Killalea Lagoon optically stimulated luminescence (OSL) dating of quartz sediments from the sandsheets supplemented dating of the confining peat deposits by AMS radiocarbon. Although affected by groundwater contamination, dates from the Killalea Lagoon site suggest that the depositional event is attributed to a large-scale inundation event around 1500AD adding to a considerable bank of published dates that cluster around this period. Possible tsunami sources include sediment slides off the continental slope of Australia or New Zealand, seismic events in New Zealand and the Macquarie Ridge and bolide impacts in the Tasman Sea or southwest Pacific.

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## **Chapter 1.**

### **Introduction**

#### **1. Study Overview**

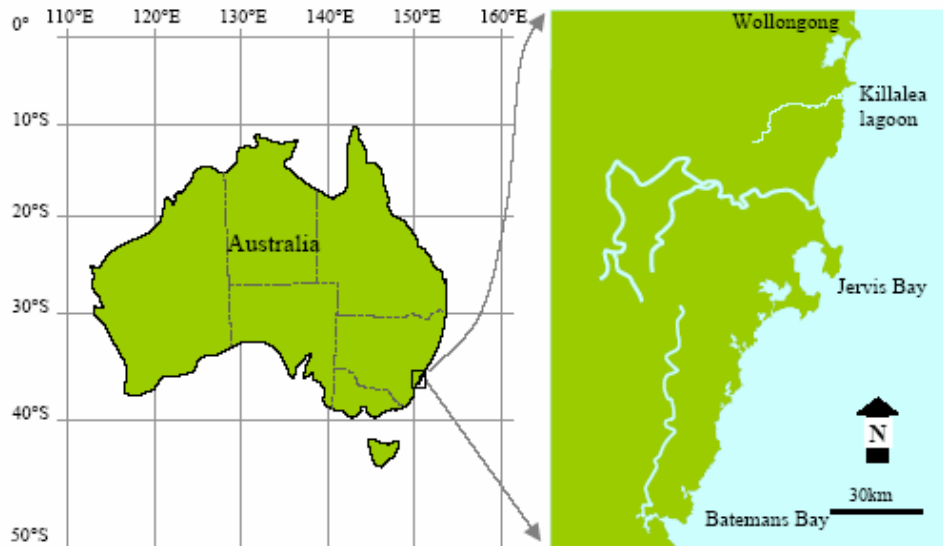
The sedimentology of extensive sandsheets, elevated shell-rich deposits and boulder accumulations found in coastal embayments and rocky headlands are investigated with the aim of defining the depositional mechanism of each deposit. All study sites for this project are located on the southeast coast of New South Wales, Australia (Figure 1.1). Depositional hypotheses are put forward and tested for each deposit before several dating techniques are used to investigate the chronology of the deposits.

#### **1.1 Aims of thesis and purpose of the study**

This thesis has seven main scientific aims.

- Provide criteria for the sedimentological differentiation of depositional units attributed to sea level change and large-scale washover using stratigraphic and sedimentological characteristics from fine-grained sandy deposits. These criteria are developed using examples derived from modern analogs sampled from different deposits of known depositional origin.
- Review, investigate and critically assess the evidence for tsunami from the southeast Australian coast with particular focus on the allochthonous boulder deposits of the Jervis Bay region.
- Investigate two deposits emplaced by large storms in 2001 at Abrahams Bosom Beach with the aim of using them as a modern analog for comparing the depositional signature of storm and tsunami deposits.
- To define and characterise the internal sedimentology of a large, raised laterally extensive sand sheet found in the upper fill of Killalea Lagoon on the southeast Australian coast.
- Characterise the depositional mechanism of a coarse-grained, raised shell-rich deposit found at Batemans Bay on the southeast Australian coast.
- Use ground penetrating radar to investigate an erosional signature for large scale reworking by washover in the dune system of Killalea lagoon.
- Attempt to define the depositional chronology of large-scale prehistoric washover deposits using Optically Stimulated Luminescence (OSL),

radiocarbon and amino acid racemisation (AAR) techniques on sediments, organic material and shelly fauna derived from fine sediment deposits.



*Figure 1.1 Location map of eastern Australia. The tectonically stable region lies on the southwestern Pacific margin. The micro-tidal coast is wave dominated and open to ocean swells generated in the Tasman Sea and southwest Pacific Ocean*

## 1.2 Background to the study

Investigations of palaeotsunami activity along the southeast coast of Australia have primarily been geomorphic and are summarised in Bryant and Nott (2001) and Bryant (2001). Collectively these studies (reviewed and critiqued in chapter 4) have identified a series of depositional and erosional signatures found along the southeast coast of Australia that are attributed to the action of tsunami (Figure 1.2).

The dominant geomorphic focus of previous investigations has led to a significant absence of knowledge regarding the sedimentary record of palaeotsunami in the coastal zone of New South Wales. Considerable debate exists worldwide over the analysis and differentiation of washover deposits attributed to tsunami and storms and recent works in this area suggest that contentious debate will continue (Felton and Crook, 2003). The present status of this debate is best encapsulated by Chague-Goff and Goff (1999) who stated “while it is easy enough to identify the difference between (the deposits of) a



large well documented tsunami and a small, well documented cyclone, there is a significant grey area in the middle”

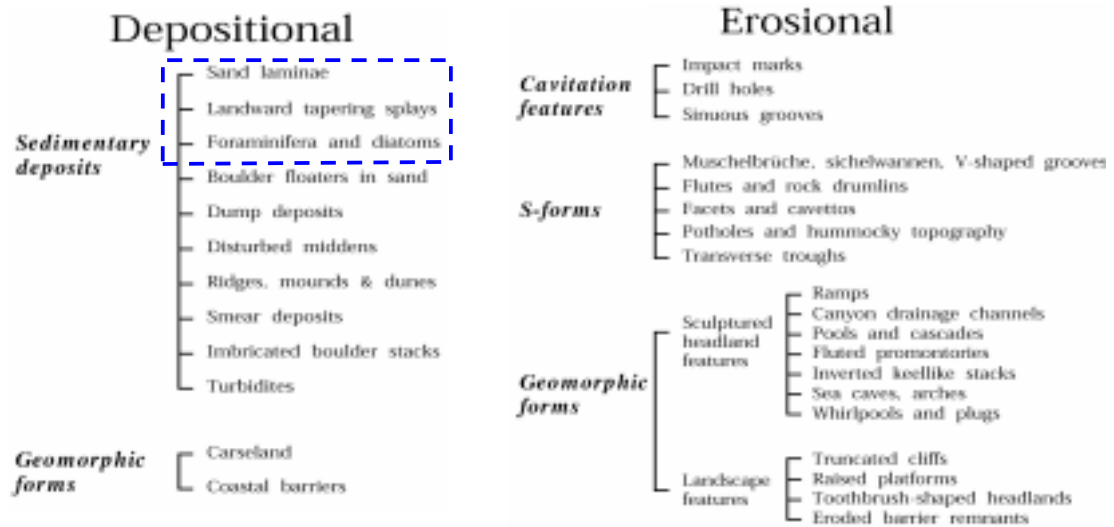


Figure 1.2 Summary of depositional and erosional signatures of tsunami found on the southeast coast of Australia (Bryant 2001). This research reviews analysis of imbricated boulders and then centres on the first three depositional signatures (stippled boxes) and provides an in-depth sedimentological study of these features found in the upper fill of two coastal embayments and provides a detailed description of the analytical sedimentology of the deposits and the apparent chronology of their deposition.

The likelihood of attributing the thin sand deposits in back barrier environments to sea level change, in particular higher Holocene sea levels, is disproven on both sedimentological and geographical grounds, as indicated below. Numerous studies of geomorphological evolution of estuaries along this coastline have led to a well-developed model for Quaternary estuarine evolution (Roy *et al.*, 1980; Roy and Boyd, 1996; Roy *et al.*, 2001). Transgressive sand sheets or sandy deposits attributed to the action of sea-level rise are observed in the majority of embayments along the eastern seaboard. The internal sedimentology of these deposits relates directly to the degree to which the environment is open to oceanic influences. Generally transgressive sand deposits consist of structureless quartz sand in the open parts of an embayment that fine landward to a shell-rich muddy sand found in sheltered parts of the embayment (Roy *et al.*, 1980; Switzer *et al.*, in press; Sloss *et al.*, in press) and although both contain considerable marine sand, they exhibit little internal lithological similarity with the

sandy back-barrier deposits from this study. All of the sand deposits investigated in this study exhibit very subtle lateral changes in sedimentology and are all essentially quartz sand, with one deposit containing considerable shelly fauna. The second characteristic of the sandy back barrier deposits that preclude sea level change is related to geographical extent. Extensive field surveys of numerous embayments, along with a review of geomorphological and geological studies from the study area, suggest that these large elevated overwash deposits only lie in embayments that face southeast. No similar deposits are found in embayments orientated to the east or northeast suggesting a single or multiple short-lived depositional event(s) from the southeast.

The definition and characteristics of washover are discussed in detail in Chapter 3. Washover sandsheets are often found in low-lying coastal embayments (Sedgwick and Davis, 2003). Washover deposition of marine sand is usually attributed to storm activity or tsunami and the distinction between these agents is often contentious especially in geological sequences that date beyond historical records. Landward tapering sandsheets found in the sedimentary record of coastal embayments are the most common tsunami signature worldwide (Dawson, 1999; Bryant, 2001) although rocky outcrops with allochthonous boulders have been subject to recent investigation and review (Nott, 1997; 2003; Scheffers, 2002; Radtke *et al.*, 2003). The current study applies many of the sedimentological techniques developed from studies over the last decade for the differentiation and identification of palaeotsunami deposits to two sites along the southeast coast of Australia. These sites consist of a fine back-barrier sand sheet and an elevated shell-rich deposit that are found in the upper fill of two coastal embayments.

Preliminary investigations identified a number of sand deposits in back-barrier environments in the Dunmore embayment (Switzer, 1999; Pucillo, 2000; Switzer *et al.* 2003, *in press*) that show characteristic sedimentological signatures of two extensive washover sandsheets attributed to late-Holocene tsunami activity. These deposits, along with those of this study, are all found in the upper fill of geomorphically diverse coastal embayments. They are compared with the characteristics observed in known tsunami deposits from the events in Nicaragua (1992), Indonesia (1992 and 1994), Japan (1993) and the Papua New Guinea (1998), plus recent (late 2004) photographic evidence from

the Indian Ocean tsunami. Key information for analysis of palaeoverwash is provided by comparative studies of storm and tsunami deposited sediments from the same stretch of coast. Four such studies from New Zealand, Japan, Portugal and the northeastern United States are reviewed here.

As suggested above, it is often hard to differentiate between washover deposits attributed to storm and tsunami (Dawson, 1999). As a modern storm deposited analog, this study also presents an analysis of washover deposition from storms observed during March and July 2001. The modern washover study was undertaken to assist in developing criteria for differentiation of back barrier sandsheet deposits using modern analogs of global tsunami and storm washover directly applicable to this coast.

The elevated and imbricated boulder deposits of the Jervis Bay region have been the focus of considerable research in the past with Young *et al.* (1996) and Bryant *et al.* (1996) suggesting that these deposits have been deposited by a large (mega) tsunami. Although compelling evidence for high-energy events, analysis of these boulder accumulations is problematic. These deposits are reviewed in light of recent research into facies relationships on rocky shorelines. Felton and Crook, (2002) suggested that the analysis of such deposits can only be undertaken if well-defined facies relationships are proven using modern analogs derived from known event. A difficult task as the processes on rocky shorelines remain poorly understood (Felton 2002; Felton and Crook, 2003).

Depositional models are developed for the sandsheet deposits at Abrahams Bosom Beach, Batemans Bay and Killalea using criteria developed from a detailed review of global research into washover deposits from storm and tsunami.

## Chapter 2

### Southeast Australian Coast: Regional setting and physical environment

#### 2. The southeast Australian coast

The southeast Australian coast (Figure 2.1) is a microtidal (<2 m), temperate continental margin that experiences a dominance of high-energy ocean waves often exceeding 2 m in amplitude. Superimposed on this wave-dominated environment are periodic storm events that cause swells in excess of 5 m high with waves often in excess of 10 m (Roy and Boyd, 1996). The coastline is an embayed coast where Holocene sandy barriers occupy the outer margins of coastal basins enclosed by rocky headlands. These barrier systems are a manifestation of long-term tectonic stability and sea-level fluctuations throughout the Quaternary (Roy *et al.*, 2001).

Climate is temperate to sub-tropical with dominant northeast sea-breezes in summer and stronger southwest to southerly winds in winter. Oceanic swell conditions are strongly dependent on low-pressure systems that form off the coast, but the coast is best described as wave-dominated due to a persistent background swell (Short and Trenaman, 1992). Dominant low-pressure systems from the south produce frequent high-energy pulses of swell to the coast. Periodic cyclones and locally produced east coast lows can generate swell from the north to east but are generally much less frequent (Short, 1993).

The Quaternary coastal geology onlaps a bedrock basement that can be broadly divided into an Ordovician to Silurian fold belt and a broad shallow Permo-Triassic sedimentary basin sequence. The continental margin is considered as a tectonically stable, wave-dominated, sediment-deficient margin with an embayed coast and narrow shelf (Roy and Boyd, 1996).

The oceanography south of Sydney consists of a narrow continental shelf ~30 km wide that appears to limit the action of storm surge and is dominated by seasonal currents and a dominant south to north littoral drift (Davies, 1979; Bryant, 1991). The steep continental slope is heavily dissected with numerous submarine canyons that steeply descend to depths in excess of 2000 m (Jenkins and Keene, 1992).

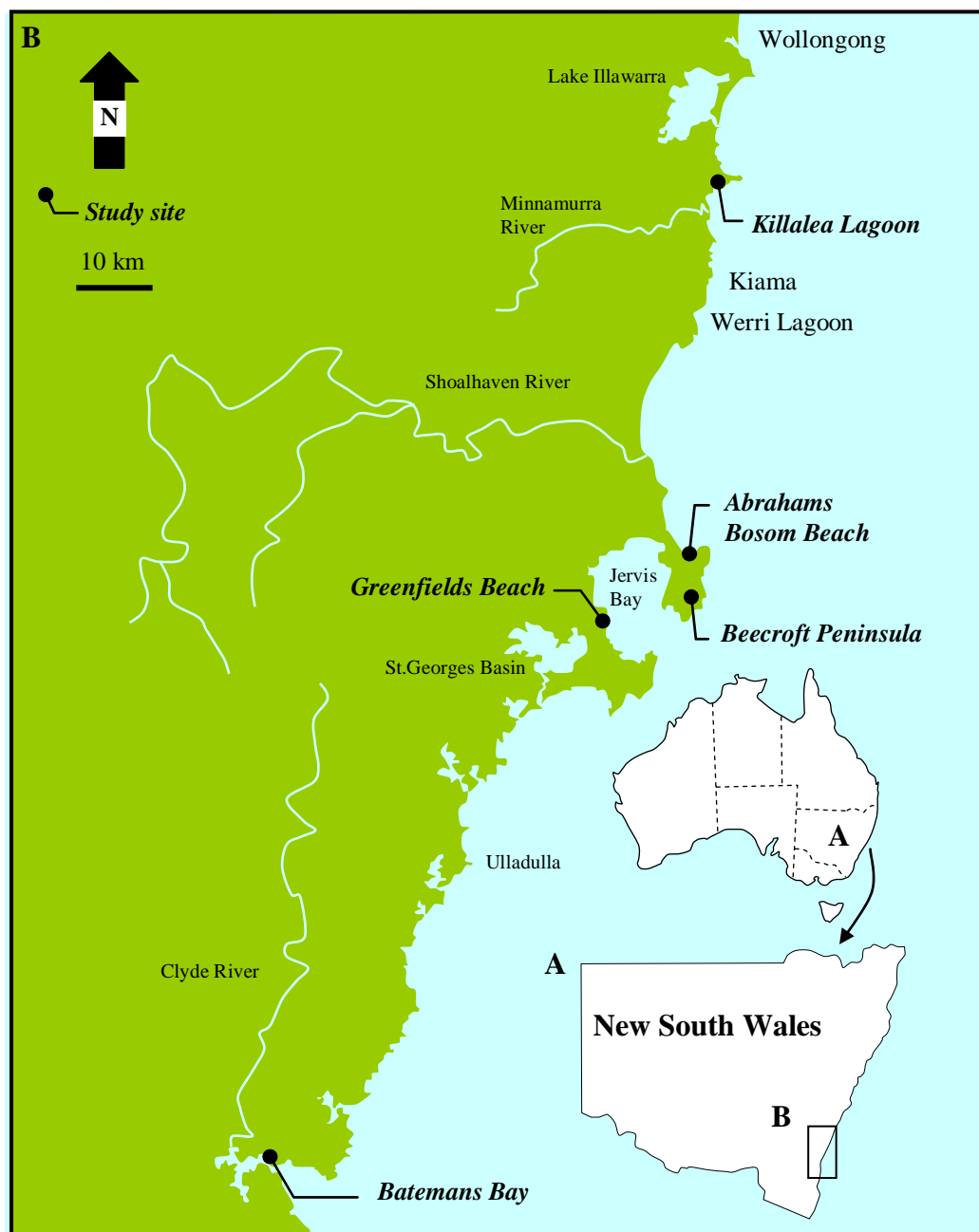


Figure 2.1 Map showing the location of the study sites on the southeast Australian coast along with other sites mentioned in the preceding text.

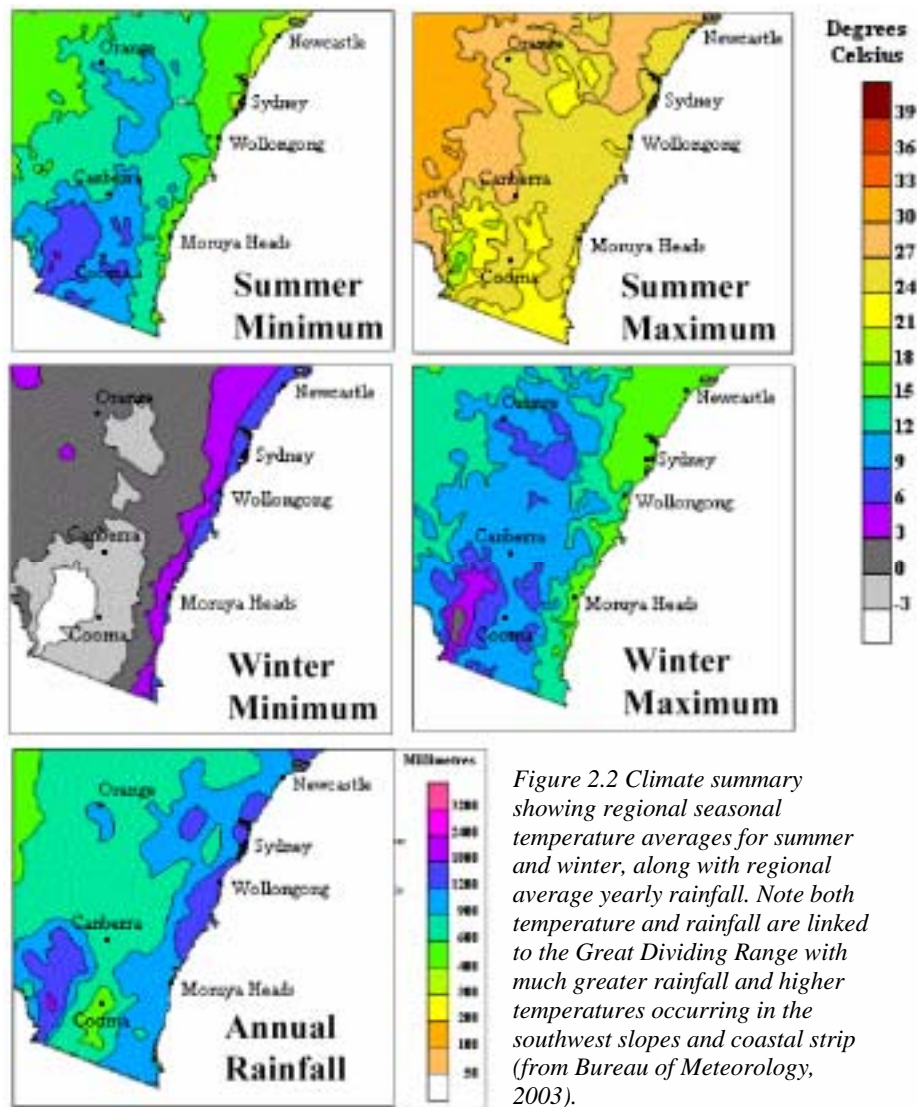
The geomorphic expression of the present coastline is the product of the post-glacial marine transgression and subsequent highstand superimposed on earlier lowstand erosional episodes. The estuaries of the coast are classified on the basis of maturity using geomorphic and geological models for estuarine evolution (Roy, 1984; Roy *et al.*, 2001).

A variety of depositional landforms exist from mega-clast (boulder) accumulations on rock ramps to fine-muds in the sheltered backwaters of barrier estuaries. Identification of modern processes, sedimentary facies and associated landforms allows the interpretation of older geological sequences under the principles of uniformitarianism.

## **2.1. Climate**

Southeastern Australia experiences a temperate to subtropical climate, which is generally mild and free from extreme periods of heat and cold. Mean daily maximum temperatures ( $>25^{\circ}\text{C}$ ) occur between December and March with mean daily minimum ( $<10^{\circ}\text{C}$ ) between June and August (Bureau of Meteorology, 2003). The Great Dividing Range, running approximately north to south in the east of New South Wales, has a large impact on the climate, creating four distinct climate zones; the narrow coastal strip, the highlands, the western slopes and the flatter country to the west (Figure 2.2).

Rainfall in coastal New South Wales has two distinct and seasonal sources. In summer, most rainfall occurs from tropical and east coast lows. In winter, rainfall occurs from southerly cold fronts and mid-latitude low-pressure systems. The climate of the coastal strip is influenced by the waters of the Tasman Sea that in general, moderates the climate and provides moisture to increase rainfall, which ranges from about 750 mm in the south to 2000 mm in the north. The highlands abruptly rise from the coastal strip (Figure 2.3). Summer experiences coastal sea breezes and intermittent southerly changes. In contrast, the winter wind regime is dominated by strong southwest to southerly winds associated with low-pressure systems that move across the southern part of Australia.



## 2.2 Regional Geology

The basement geology of eastern Australia is broadly composed of the Tasman Fold Belt, a Cambrian to Carboniferous orogenic system. The Tasman Fold Belt, which is now partially covered, by younger sedimentary basins including the Sydney (Permian-Triassic) and Murray (Quaternary) Basins can be divided into the younger New England Fold Belt to the north and the Lachlan Fold Belt to the south and west (Scheibner *et al.*, 1999; Figure 2.3) The Sydney Basin lies to the east of the Lachlan Fold Belt system and is most likely the product of a back-arc environment. This latter sequence expresses a general trend of sediment accumulation from the Permian to Triassic with depositional environments from shallow marine to terrestrial. Many of



the study sites mentioned in the text are located in the Permian-Triassic Sydney basin (such as Killalea Lagoon, Jervis Bay, Abrahams Bosom Beach) with another site (Batemans Bay) just to the south, which lies in the eastern Lachlan Fold Belt (Figure 2.3).

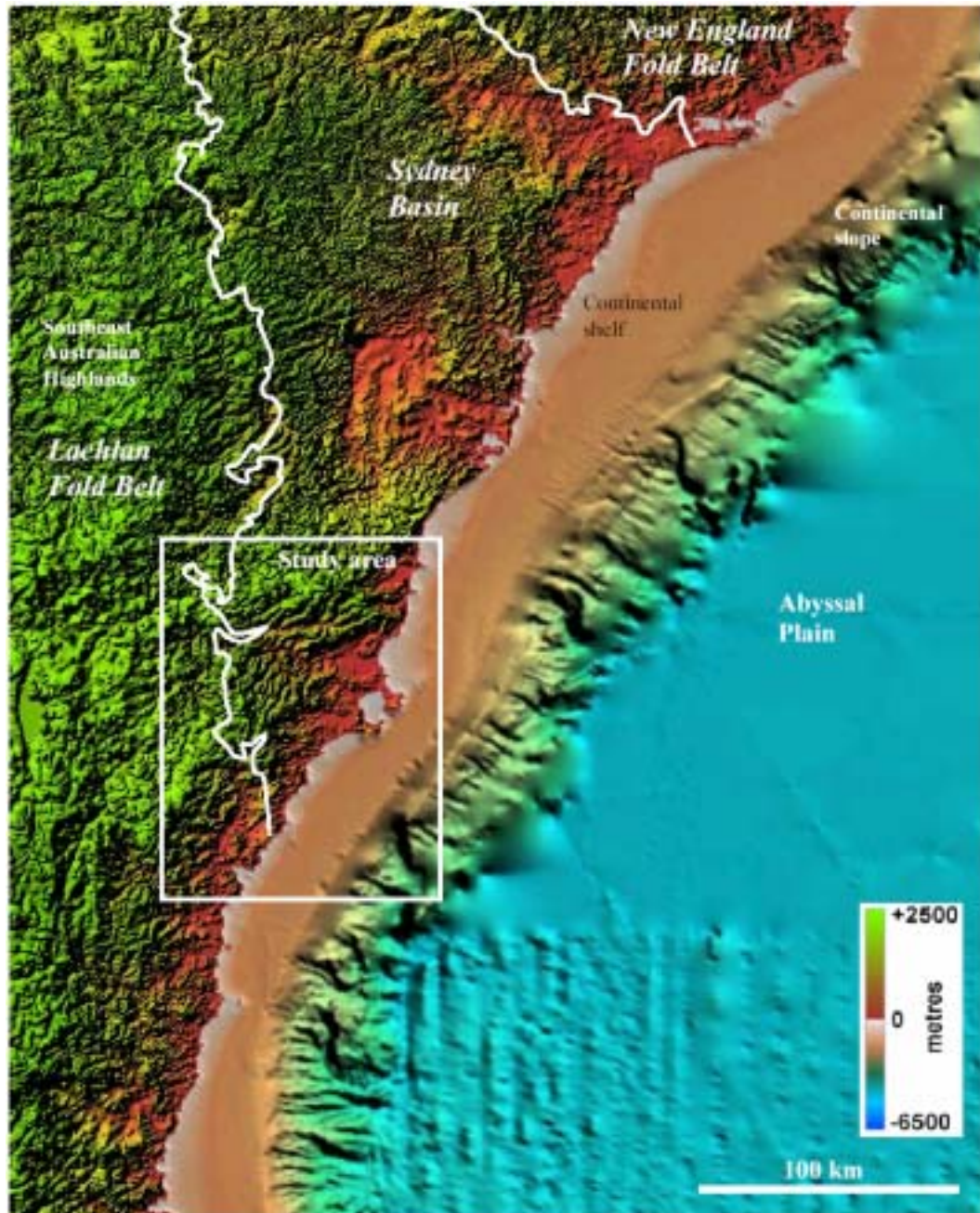


Figure 2.3 Topographic and bathymetric image of the southeast Australian coast. The study sites are located on a narrow coastal plain to the east of the southeast Australian ranges. Regional geology is dominated by two fold belts (Lachlan and New England) and a younger sedimentary basin (Sydney Basin). Submarine topography is dominated by a narrow relatively flat continental shelf and steep heavily dissected continental slope (Image from Geoscience Australia 2002, geology after Scheibner *et al.*, 1999).



### 2.3 Oceanography

An understanding of the bathymetry and oceanic processes on the east Australian coast forms an important basis for parts of this study. The continental shelf of the east Australian coast is relatively narrow (>50 km) and deep, with depth increasing to 200 m within 25 km of the coast before increasing rapidly to more than 3000 m (Middleton *et al.*, 1996). Yassini and Jones (1995) suggested that roughly 80% of the shelf is greater than 50 m deep. Sediment partitioning is essentially shore parallel and consists of a tripartite distribution of sand and mud relative to depth (Matthai and Birch, 2001). The steep continental slope and narrow continental shelf limits the attenuation of ocean waves and minimises the likelihood of storm surges (Bryant, 1991). The oceanographic regime of the Australian east coast is complex, and is influenced by coastal-trapped waves, local winds, internal waves, estuaries and the East Australian Current and its associated eddies that all affect shelf sedimentation and circulation (Middleton *et al.*, 1996). Of importance to this study is the generation of large waves of any kind that may strike the coast and present a potential source of large-scale washover sedimentation. These agents are discussed in Chapter 4, whilst the general wave climate of the southeast coast is outlined below.

### 2.4. Seasonal variation in climate related to winds, wave generation and rainfall.

Wave climate on the southeast coast is generally associated with ocean swells generated by high-pressure cells, mid-latitude lows, east coast lows and tropical lows in the Tasman Sea and southwest Pacific Ocean (Short, 1993; Figure 2.4). High-pressure cells migrate in an easterly direction across the Australian continent approximately every ten days. Seasonal changes cause the tracks of these systems to migrate latitudinally between 36°S in summer and 30°S in winter. These high-pressure systems are dominated by light winds, clear skies, warmer temperatures and low nearshore seas, allowing background swell to dominate the wave regime. Low pressure systems to the south produce southwest to southeast winds that pass up the east coast throughout the year, but the seasonal migration of these systems to a more southerly track means that in summer their effect is weaker and the moderate northeasterly sea breezes dominate.

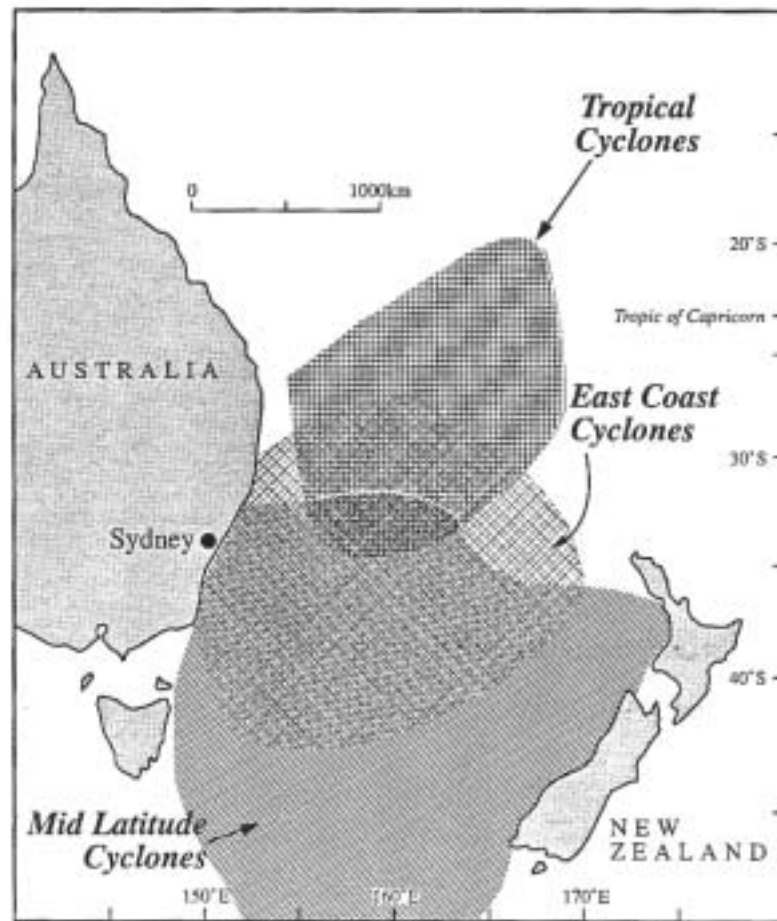


Figure 2.4 the direction and sources of waves influencing the New South Wales coast are dominated by three different weather systems. The shaded areas show where tropical cyclones, east coast lows and mid latitude lows occur (after Short 1993, p24).

The winter wave climate is dominated by mid-latitude cyclones. These systems are subpolar low-pressure systems that migrate from west to east across the continent every three to four days, producing strong southwest to southeasterly winds often accompanied by rainfall (Figure 2.5a). East coast lows can occur at any time of the year, but particularly in early to mid winter. These last four to five days and form large swells, strong winds and heavy rain (Bryant, 1991; Figure 2.5b). Tropical cyclones form between five and ten degrees north and south latitude between November and March. Those that form in the Coral Sea may impact the New South Wales coast if they travel past 25°S, producing strong winds, heavy rainfall and large swell (Figure 2.5c).

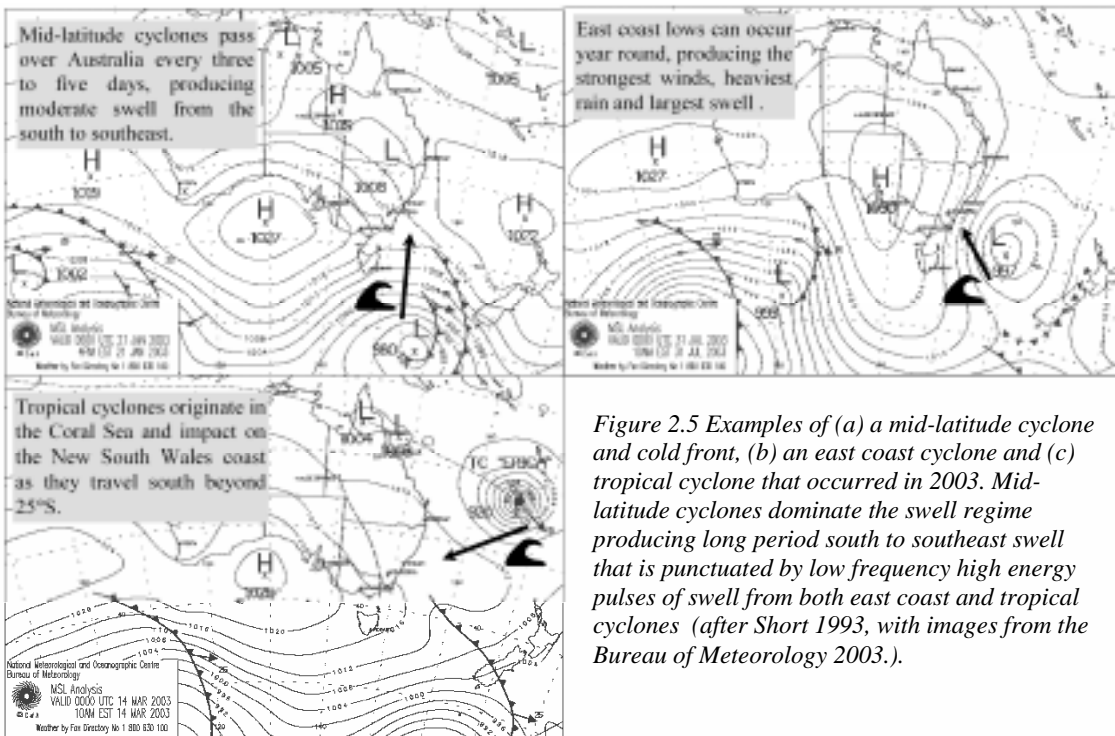


Figure 2.5 Examples of (a) a mid-latitude cyclone and cold front, (b) an east coast cyclone and (c) tropical cyclone that occurred in 2003. Mid-latitude cyclones dominate the swell regime producing long period south to southeast swell that is punctuated by low frequency high energy pulses of swell from both east coast and tropical cyclones (after Short 1993, with images from the Bureau of Meteorology 2003.).

### 2.4.1 Wave Regime

Southeast Australia has a high-energy ocean wave environment that is superimposed upon by a highly variable wind wave climate (Lawson and Abernethy, 1975). Since the continental shelf off the New South Wales coast is narrow (<50 km wide), the nearshore wave energy is reduced by only five percent from the deepwater wave energy as a result of friction (Wright, 1976).

General patterns of wave energy for the New South Wales coast suggest that approximately 18 percent of waves arrive from the northeast, 41 percent from the east and 40 percent from the southeast (Short and Wright, 1981). The remaining 1% have no discernable direction. The sources of these waves are the weather systems described above. In summarising the wave climate, Short and Wright (1981) suggested that 95 % of waves over 2.5 m high are the result of low-pressure systems with mid-latitude cyclones producing 200 days of southeast waves per year that average 2.3 m in height and have periods of ten to twelve seconds. Larger waves often result from three to four east coast lows per year. These events usually last four to five days and produce waves averaging 2.8 m in height with ten to twelve second periods. Short and Wright (1981) suggested tropical cyclones may periodically affect

wave conditions on the southeast coast and occur approximately 16.5 days per year particularly in February and March. These events cause waves averaging 2.7 m in height with nine to ten second periods that strike the coast from the east to northeast. Waves produced by high-pressure conditions average less than 1.5 m in height with periods of nine to ten seconds. These small high-pressure systems generate small waves from any direction forming a localised wave regime of 0.5 to 1.0 metres in height with short periods (6-8 seconds) generated by northeast sea breezes that are more prevalent in summer than in winter. Figure 2.6 is taken from Short and Wright (1981) and summarises the annual wave climate for the Sydney coast located to the north of the study area.

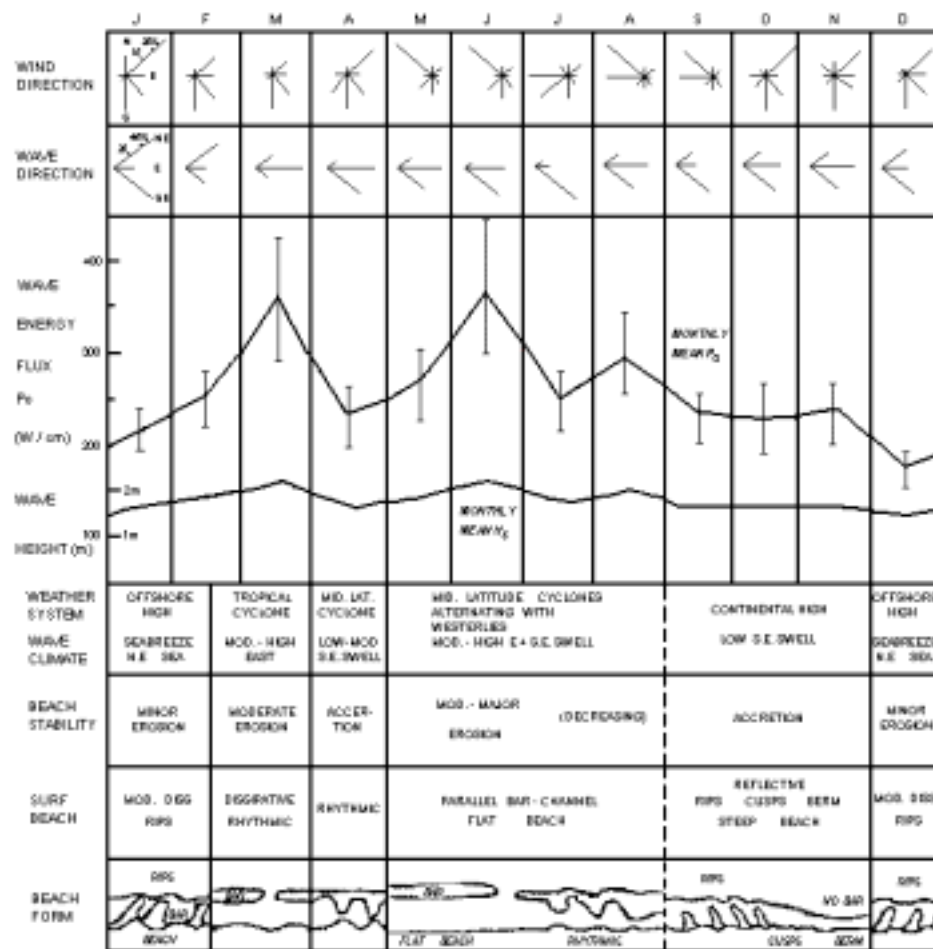


Figure 2.6 Wave climate for the Sydney coast over an annual cycle (Short and Wright, 1981, p.13) this summary diagram shows the relationship between weather systems and beach forms for this coast. Note that wave energy is high year round and beaches vary from transverse bars and rips in summer to the more dissipative rhythmic bar and beach state in autumn. The winter beach state is dominated by erosion and beaches become dissipative. While spring is considered an accretionary period causing beaches to become more reflective.

## 2.5. Quaternary sea level change

Many studies of both onshore and offshore evidence have been used to interpret sea-level changes. Pirazzoli (1991) suggested a complete picture may be only achieved by combining geomorphological and stratigraphical evidence. Quaternary sea levels can often be reconstructed using these techniques.

This section will review the study of sea-level variation throughout the late Quaternary on a regional scale. A sea-level envelope is constructed from detailed studies listed and summarised in Table 2.1. The derived sea-level envelope (Figure 2.8) summarises Holocene sea-levels with particular emphasis on late Holocene sea-levels and the associated relative highstand identified by Flood and Frankel (1989), Baker and Haworth (2000a,b) and Baker *et al.* (2003).

### 2.5.1 Quaternary sea-level studies

Far-field sites such as Australia are removed from former ice-sheets (Lambeck, 1993; Pirazzoli, 1996), and have subdued isostatic signals, only in the order of a few metres. This isostatic stability results in differences in sea-level change at far-field sites being attributed to regional hydro-isostatic or local tectonic land-level changes (Belperio, *et al.* 2002). In Australia, relative sea-level rise predominates during the deglaciation period; a period often followed by a slight relative sea-level fall of hydro-isostatic origin during the late Holocene (Pirazzoli, 1996).

The Australian coastline exhibits relative tectonic stability (Cann *et al.*, 1988; Young *et al.*, 1993), due to its remoteness from plate boundaries. Regions of Australia farther from the centre of the Australian plate, such as Tasmania, experience increased regional tectonic deformation (Bryant, 1992). Parts of the Australian coast exhibit relative tectonic stability, these include some of the South Australian coastline between Adelaide and southwestern Victoria, the New South Wales coastline north of Wollongong, and the Western Australian coastline between Onslow and the western Great Australian Bight (Bryant, 1992). Nakada and Lambeck (1989) produced a model indicating that Holocene sea level increased northward around Australia resulting from deformation of the crust. Meltwater loading of the ocean crust caused continental tilting that decreased in amplitude seaward from the present shoreline, and produced a regional variation in the time the post-glacial marine transgression

peak was attained, suggesting that southern Australia experienced a highstand first, while island sites trailed by as much as 2,000 years behind (Nakada and Lambeck, 1989).

References	Summary
<b>Quaternary Curve</b>	
Chappell, <i>et al.</i> , (1996)	Sea level curve for the Quaternary derived from surveyed coral terraces in the tectonically uplifted Huon Peninsula Papua New Guinea.
Shackelton, (1987)	Sea-level curve for the past 140 ka based on $\delta^{18}\text{O}$ values for benthic foraminifera.
<b>Holocene Curve</b>	
Ota and Chappell, (1999)	Sea level for postglacial marine transgression derived from surveyed coral terraces in the tectonically uplifted Huon Peninsula, Papua New Guinea.
Baker & Haworth, (2000a,b)	An oscillating sea-level curve determined from fixed biological indicators suggests a highstand of 1-2 m during 5-3 ka.
Bryant <i>et al.</i> , (1992)	Holocene highstand 1-2 m above present sea-level based on radiocarbon dating of shells from coastal barriers and estuaries.
Thom and Roy (1983)	Sealevel envelop developed from radiocarbon dating. <i>In situ</i> tree stumps near present mean sea-level and high water mark indicating little to no Holocene highstand.
Flood and Frankel (1989)	Intertidal calcareous worm tubes indicating a Holocene highstand of >1 m up to 3.42 ka BP.
Belperio, <i>et al.</i> , (2002).	Time-depth plots from South Australia generating a broad sea-level envelope indicating transgression from 10 ka-6 ka, followed by a more or less consistent level to the present. Selection, separation and regionalisation of the data suggest a very rapid sea-level rise in the early Holocene reaching present levels at 6.4 ka This was followed by regionally variable regression and emergence of the land 1-3 m, a process that continues to the present.

*Table 2.1 Key references for Quaternary and Holocene sea level pertaining to the southeast Australian coast. Several key curves are included in Figure 2.7 and this thesis is based on an envelope (Figure 2.8) that incorporates an assumed Holocene highstand of up to 2 m before 3 ka and a relative possibly stepped regression to present.*

Bryant (1992), however, suggested that field evidence from Nakada and Lambeck (1989), Hopley (1983) and Woodroffe *et al.* (1989) shows a trend of Holocene sea level peaking higher towards the southeast of Australia. Bryant's (1992) explanation for variation across Australia for the Holocene sea-level peak pertains to continuing tectonic processes active since the last interglacial. Also, he suggested the Holocene sea-level curve is difficult to interpret due to Holocene sea-levels being dominated by local variations reflecting regional loading of the shelf by water during the transgression.

The tectonically stable Southeast Australian coast has a narrow shelf and microtidal wave-dominated regime that is likely to provide straightforward associations between dating and fossil markers of sea-level change. One generally accepted Holocene sea level curve for the southeast coast is the sea level envelope of Thom and Roy (1983);

a sea-level envelope modified from the sea-level curve of Thom *et al.* (1969) to include acknowledgement of error bars associated with the dating of molluscs from which it was derived. For this study the Holocene sea-level envelope of Thom and Roy (1983) will be accepted as a relative indicator of sea level change throughout the post-glacial transgression as it corresponds with that of Ota and Chappell (1999) and incorporates a mid-Holocene highstand.

As the deposits studied in this project are of mid- to late-Holocene age, an understanding of sea levels of this period is intrinsic to the development of depositional hypotheses. Some authors have noted a highstand in the order of ~2 m during the mid Holocene (Flood and Frankel, 1989; Young *et al.* 1993; Baker and Haworth, 1997). In summary, general agreement exists on the transgressive record with minor conflict on sea-level since 6 ka. Most suggest a maximum level of +1-2 m sometime between 6-3 ka. A relative fall to present level since 3 ka is also apparent in most studies. It is uncertain whether this is a hydrostatic crustal response or a genuine sea-level change related to global ice volumes. Several key Quaternary and early Holocene curves are included in Figure 2.7 and this thesis is based on these curves along with the regional mid- to late-Holocene sea level curves by Baker *et al.* (2003) as presented in Figure 2.8. These late-Holocene curves incorporate an assumed highstand of up to 2 m before 3 ka, and a relative, possibly stepped, regression to present. Figure 2.9 summarises these data sets into a key diagram upon which post-glacial sea-levels for the study site are based.

## **2.6. Coastal sedimentation and Quaternary evolution of southeastern Australian estuaries**

The east coast of Australia is best considered a siliclastic shoreline dominated by clastic sediment transported from the coastal plain and escarpment. Beaches, barrier islands, lagoons, tidal inlets, cheniers, tidal flats, and estuaries are all examples of the diverse environments that are produced on clastic coasts. Currents, tidal processes, waves, sediment supply, climate, tectonic setting and relative sea-level history all contribute to the geomorphic expression of a coastline. Roy (1994) suggested that substrate gradient inherently affects coastal geomorphology and considered two end members on coasts with different substrate gradients.

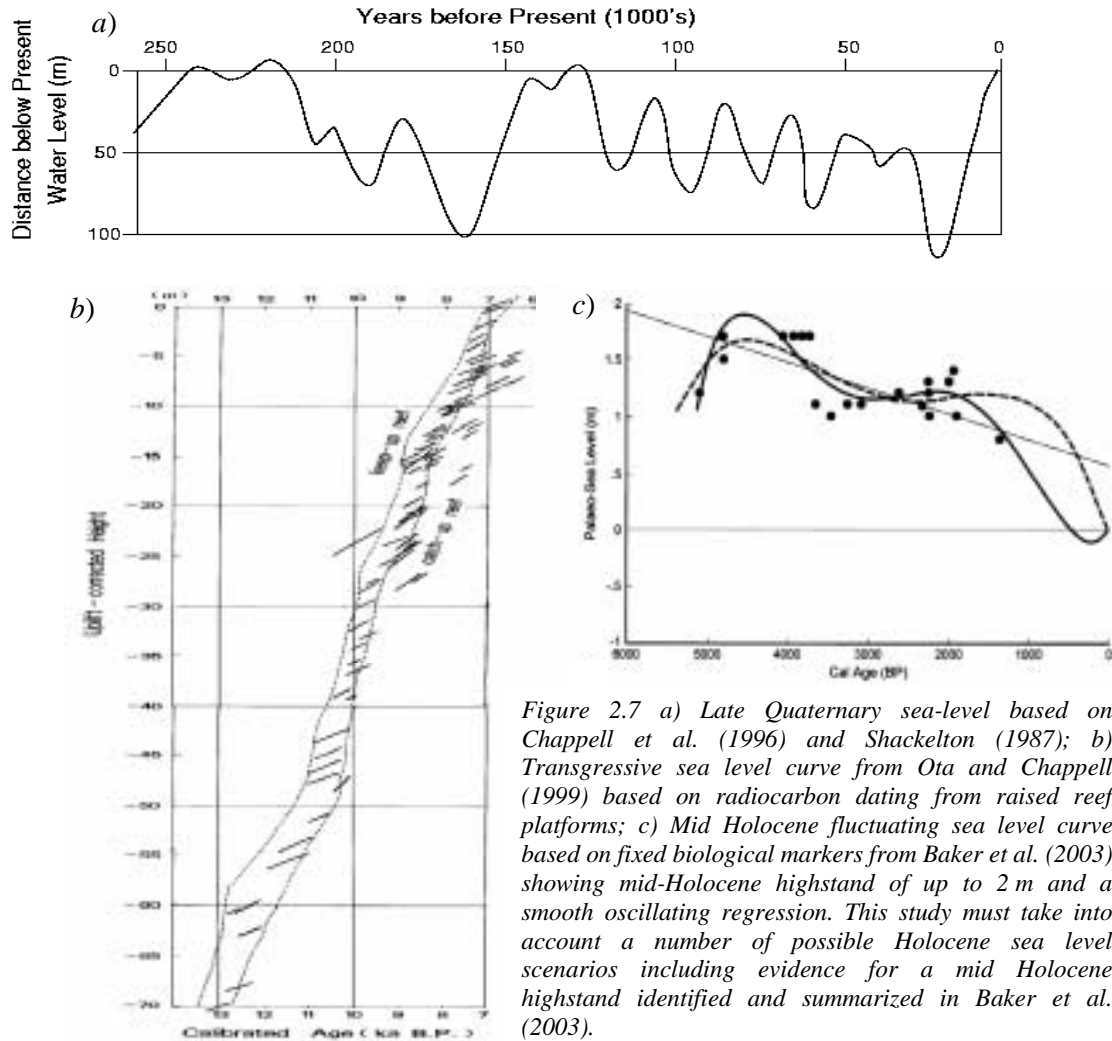


Figure 2.7 a) Late Quaternary sea-level based on Chappell et al. (1996) and Shackleton (1987); b) Transgressive sea level curve from Ota and Chappell (1999) based on radiocarbon dating from raised reef platforms; c) Mid Holocene fluctuating sea level curve based on fixed biological markers from Baker et al. (2003) showing mid-Holocene highstand of up to 2 m and a smooth oscillating regression. This study must take into account a number of possible Holocene sea level highstand scenarios including evidence for a mid Holocene highstand identified and summarized in Baker et al. (2003).

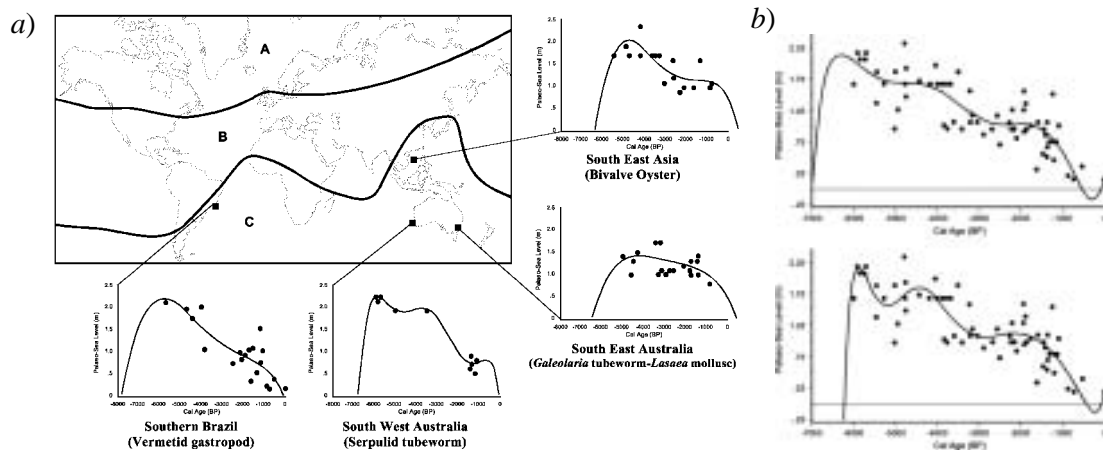


Figure 2.8 a). Mid- to late-Holocene sea level curves from the southern hemisphere and southeast Asia using fixed biological indicators (FBI's). Map divisions A, B and C are based on Bird (2000). All curves were constructed using 4th or 6th order polynomials and show a mid-Holocene highstand of around 2m. b) 7th and 9th order polynomial regressions of aggregated data in Figure 2.8a showing the smooth or oscillating lines of best fit for the FBI samples in Region C. Both figures from Baker et al. (2003, p93 and 96).



At one extreme, low-gradient, open coasts such as those of the United States east coast produce a morphology of barrier islands and wide lagoons. As substrates progressively steepen the lagoon becomes narrower. At the steep-gradient extreme the special case of a mainland beach with negligible backbarrier morphologies can result. Since an exhaustive global review of coastal and estuarine dynamics is deemed outside the objectives of this study, the following section will review regional studies of gradual and episodic coastal change with emphasis on the southeastern coast of Australia.

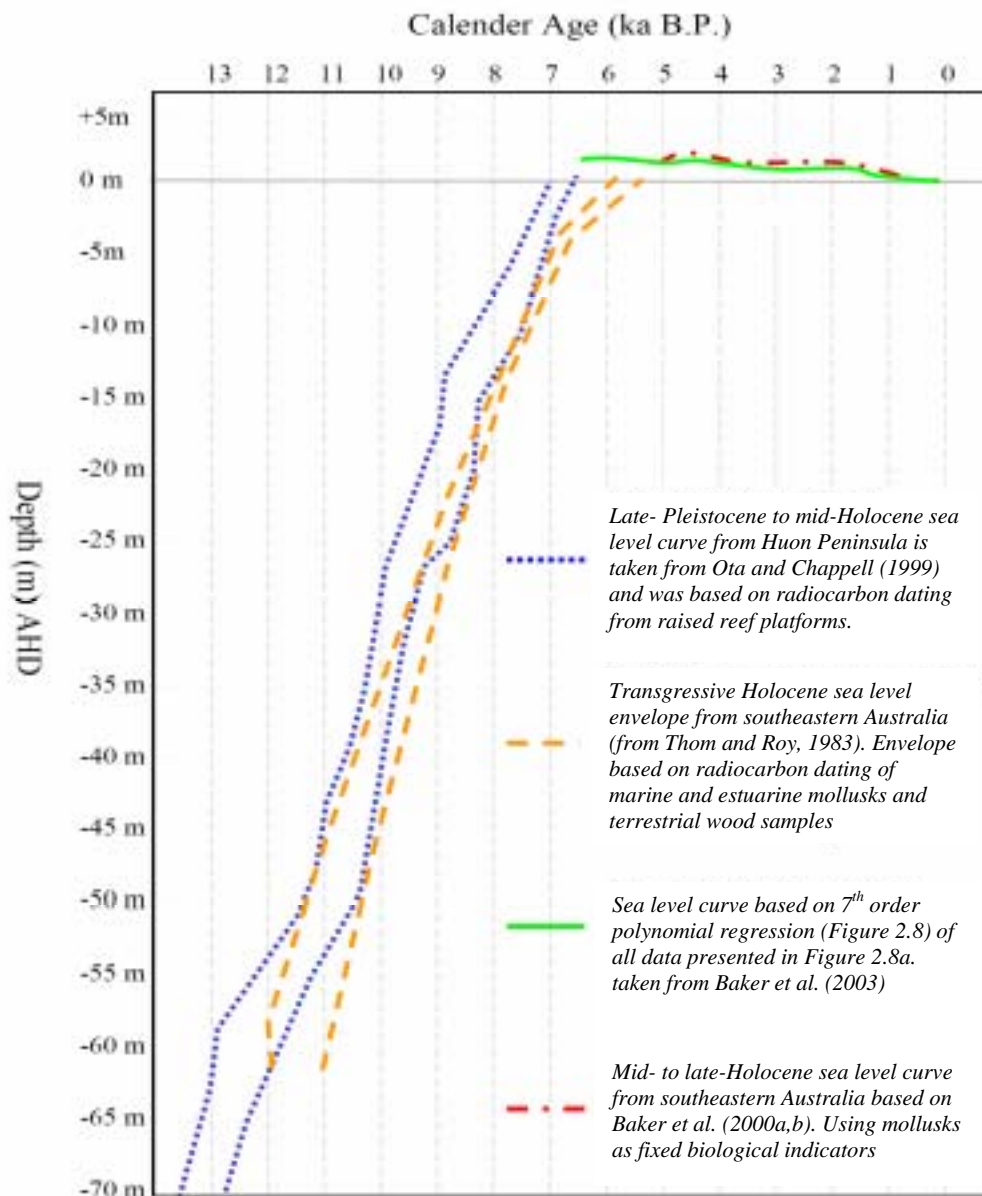


Figure 2.9 Graphic summary of relevant sea-level curves for the east Australian coast. A rapid transgression is evident until 7-6 ka followed by a relative highstand from 6-3 ka. This highstand is followed by a relative (possibly stepped) regression to present.

### **2.6.1 Coastal sedimentation in southeastern Australia**

The embayed coast of southeastern Australia can be divided into three general morphological categories described Roy *et al.* (2001): (1) a rugged coast where the immediate hinterland is hilly and small river valleys at the coast are occupied by bay barriers; (2) a subdued coast where relief is low, embayments are broad with composite bay barriers and where headlands are less prominent (Langford-Smith and Thom, 1969); and (3) a barrier island coast characterised by large barriers with wide strand plains located some distance from the bedrock hinterland.

The latter is typical of the Australian east coast south of Newcastle (Langford-Smith and Thom, 1969). The nature of barriers and estuarine water bodies contained in coastal embayments is controlled by the gross bedrock morphology (Roy, 1998) and is a product of inherited geology. Along the east coast of Australia estuaries and barriers developed in the deep, steeply incised valleys associated with resistant sandstone strata of the Sydney Basin and metasediments of the coastal Lachlan Fold Belt are morphologically different to those formed in a more easily eroded rock units found in the New England Fold Belt to the north.

The drowned embayed coast of southeastern Australia is characterised by beach compartments where valleys cut into bedrock during low stands of sea-level and separated by rocky headlands, are partially in-filled by sandy bay barriers, tidal flats, lagoons and deltaic plains (Roy *et al.*, 1980). The bedrock framework of these incised valleys has evolved since the formation of the Tasman Sea (Bishop and Goldrick, 1997), and has since under gone multiple cycles of erosion and infilling (Roy and Thom, 1981). These coastal embayments vary in size and are exposed to high-energy wave action most commonly from the south-southeast. Off the coast, the continental shelf is narrow (80% > 50 km wide), and consists of two zones. The outer shelf plain is described as accretional, whereas the inner shelf zone is steeper, narrower and has a thin cover of sediment (Roy *et al.*, 1980).

### **2.6.2 Coastal and shelf sediment types**

Sediments from coastal embayments of southeastern Australia, can be divided into two general facies groups, marine facies and fluvial facies (Roy and Crawford, 1977; Roy *et al.*, 1980). They are characterised and defined on the basis of sediment

characteristics including mineralogy and particle roundness and can often be directly related to the their original source sediments.

The marine sediments are generally dominated by well-rounded, quartz-rich sand, which usually contains less than 10% rock and feldspar grains (Chapman *et al.*, 1982). They represent a product of marine processes acting on terrigenous sediments, contributed to the inner continental shelf over long periods of time. Termed ‘marine’ sand by Roy and Crawford (1977), other definitive characteristics include biogenic carbonate and a mature heavy mineral assemblage. The maturity of these sediments is most likely the result of marine/aeolian reworking on the continental shelf during more than one eustatic cycle (Roy *et al.*, 1980). This is supported by the dominance of marine sediment in coastal sand barriers of southeastern Australia suggesting a large accumulation of offshore sediment and a slow supply rate of fluvial sediment to this coast (Roy *et al.*, 1980; Roy and Thom, 1981).

In contrast to the marine sand of the barriers and shelf, Roy *et al.* (1980) reported that the less mature ‘fluvial sand’ population is composed of angular lithic grains of mixed mineralogy and is usually deposited in coastal river valleys and estuaries, rarely reaching the coast or shelf. There are four main environments of deposition on the southeastern coast of Australia, each relating to different lithofacies (Roy *et al.*, 1980, 2001). These consist of fluvial, estuarine, barrier and continental shelf deposits and are identified by characteristic sediment types (Roy, 1998).

## **2.7. Quaternary estuarine and barrier evolution**

Roy *et al.* (1980) and Roy (1994) suggested three general phases that control the evolution of coastal sequences in southeastern Australia. This phase concept is presented in Table 2.2 and summarises the basic principles of coastal evolution during a highstand that were used to define the model presented in Figures 2.10 and 2.11. Considerable research since the 1980’s has provided two general models for the evolution of estuaries (Roy, 1994, 1998; Roy *et al.* 1980, 2001), coastal barriers and other sand bodies (Langford-Smith and Thom, 1969; Thom, 1984; Roy, 1994). Figure 2.12 (from Roy, 1994) shows a generalised distribution of estuarine and coastal lithofacies on the New South Wales coast and demonstrates the relationship between the various lithofacies and their occurrence relative to the coast.

Phase	Post-transgression stillstand characteristics
Phase 1	The first phase is the initiation of barrier and tidal delta development towards the end of the post-glacial marine transgression (ca. 6000 yrs ago). Coastal deposits of 'marine sand' accreted rapidly in the form of extensive barriers from 6000 – 3000 yrs BP. As offshore sand resources became depleted and growth decayed and eventually ceased.
Phase 2	Coastal valleys were drowned towards the end of the marine transgression and estuaries were formed. These estuaries, now located behind the barriers of phase 1, trapped sediment from the hinterland and were progressively infilled with fluvio-deltaic sands and pro-delta muds.
Phase 3	The final phase suggested by Roy <i>et al.</i> (1980) is an erosive stillstand phase affecting the near-shore beach and dune deposits of the coastal barriers. Erosion was initiated once offshore reserves of marine sand were depleted approximately 3000 years ago. This erosion is characteristic of coastal processes since the Holocene 'stillstand', up to and including the present day. Roy <i>et al.</i> (1980) recognised three mechanisms for the net loss of barrier sand. They are: littoral drifting towards the north, aeolian transport of barrier sand onto transgressive dunes, and the offshore transport of sand by seaward flowing, storm surge-induced currents.

Table 2.2 Stillstand evolutionary phases identified by Roy *et al.* (1980, 2001).

### 2.7.1 Models for estuarine evolution

As sea level along this coast rose to its present sea-level 7500 – 6000 yrs BP (Jones *et al.*, 1979; Roy and Boyd, 1996; Roy *et al.*, 2001), sediment on the continental shelf was reworked landwards and accumulated in coastal valleys cut into the landscape during the low stands in sea-level. These valleys provide the inherited framework for the present high-stand coastal morphology. Estuaries were formed in many embayments and accumulated sedimentary fill from both the land and the sea. The coast experiences a broadly uniform micro-tidal high-energy wave-dominated regime suggesting local factors such as river discharge and catchment geology are responsible for the diversity of estuary types along this coast (Roy, 1998). Considerable research on estuarine stratigraphy, morphology, and present-day hydrology led Roy (1984) to the hypothesis that estuary type is directly related to entrance conditions at the initiation of estuary formation. Roy (1984) suggested that entrance conditions control the style of subsequent sedimentation, the salinity regime, and water circulation in the estuary. Using entrance condition as a basis, Roy (1984) classified New South Wales estuaries into three basic types and developed a model based on the infilling of estuaries from marine and fluvial sources under stable sea-level conditions. This classification follows estuarine evolution of the three basic estuary types, (1) drowned river valley estuaries; (2) barrier estuaries; and (3) saline coastal lakes as they progress from youth to maturity. The characteristics of each type of estuary are presented in Table 2.3 and the progression from youth to maturity is summarised schematically in Figure 2.11.

Estuary type	Estuary characteristics
Drowned river valley estuaries	Drowned river valley estuaries have characteristic open mouths with sub-aqueous tidal deltas and full tidal ranges throughout (Roy <i>et al.</i> 1980). They develop in deep palaeo-valleys with steep rocky sides. In their youthful stage of development these estuaries contain extensive, deep mud basins, which form behind shallow tidal deltas. Growth of fluvial and marine deltas decreases the size of the mud basin as the system gradually infills. Figure 2.10b models the evolution of a drowned river valley toward an infilled system dominated by fluvial sedimentation as a river estuary with tidal influence.
Barrier estuaries	Barrier estuaries are embayments in which lagoons or estuaries, impounded by coastal sand barriers, occupy drowned valleys (Chapman <i>et al.</i> , 1982). These estuaries are characterised by narrow, elongated entrance channels within broad tidal delta and back-barrier sand flats (Roy, 1984). These estuaries are typically flat bottomed and may follow the shape of the drowned bedrock valley, or may be more oval. Relict back-barrier deposits, both aerial and sub-aqueous, are usually well developed and belong to the transgressive phase of barrier building (Roy, 1984; Roy <i>et al.</i> 2001). These estuaries occupy a shallower, broader palaeo-valley geometry than that of drowned river valley estuaries and sediment thicknesses for these estuaries are thinner (> 30m). Figure 2.10c models the progression of a barrier estuary from youth to maturity. the tidal regime also changes from weakly tidal in youth to relatively high in maturity when the estuary is characterised by sinuous channels and smooth levee banks (Roy, 1984).
Saline coastal lakes	In the youthful stage of evolution, saline coastal lakes are morphologically similar to immature barrier estuaries but are usually smaller and have less marine sand input. In larger examples, saline conditions are maintained for long periods due to small fluvial influences. Also muddy and shelly deposits accumulate in the low energy basin and deltaic environments (Roy, 1984; Roy <i>et al.</i> 2001). Salinity variations increase as the basin infills and fresh to brackish conditions are prolonged. This results in sea grasses being progressively replaced with more freshwater-tolerant species. Figure 2.10d models the evolution to maturity of a saline-coastal lake that eventually becomes infilled by swampy floodplains intersected by narrow channels.

Table 2.3 Summary table of estuary types identified by Roy (1984), Roy *et al* (1980, 2001)

### 2.7.2. Coastal sand deposits and the barrier development model

Many types of coastal sand deposits are present along the southeast coast of N.S.W. and this section provides a brief overview of barrier genesis and development models for this coast.

Barrier genesis along the wave-dominated coast of southeastern Australia is controlled by three main factors: (1) changing sea-levels; (2) the contemporary sand budget; and (3) the pre-existing substrate morphology (Roy, 1994). Once sea-level stabilised in the Holocene (c. 7,500 – 6000 yrs BP) a new set of factors controlling sediment movement along the coast emerged. This sea-level stability allowed shoreline profiles to achieve an equilibrium configuration where sediment budgets for coastal embayments were balanced and barrier development involved the reworking of current barriers by coastal forces including waves, currents and tides on a framework derived from shelf slope, sediment budget, sea-level and tidal range. The estuary or lagoon, often present in back-barrier environments, is intrinsically related to the type of coastal barrier that develops as a product of these factors.

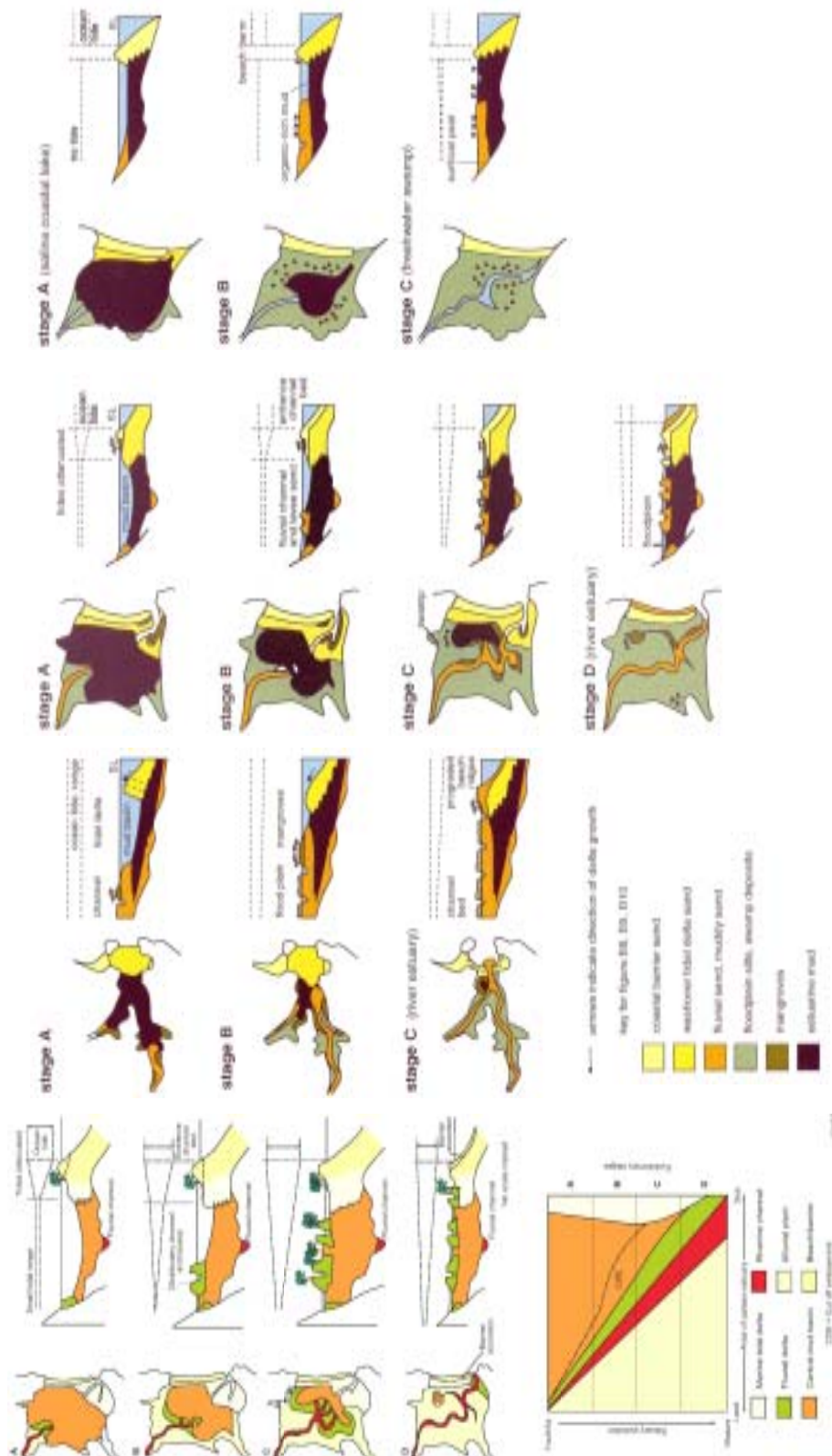


Figure 2.10 a) Schematic of Roy's model from Roy et al., (2000). Models for the evolution of a (b) drowned river valley (c) barrier estuary (d) saline coastal lake based on Roy (1984) and taken from New South Wales Department of Land Water Conservation (now Infrastructure Planning and Natural Resources) Website 2001.

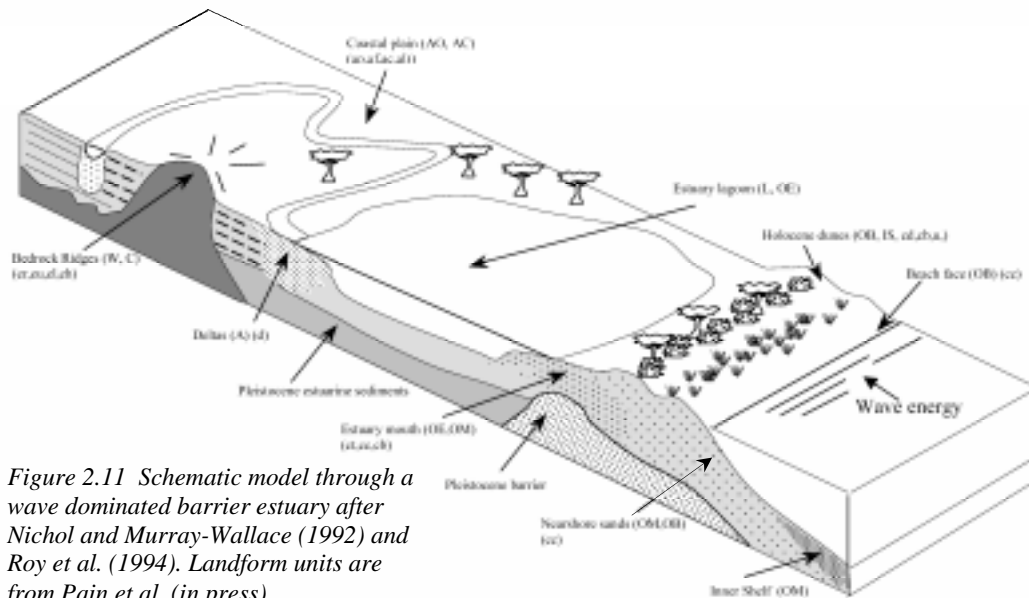


Figure 2.11 Schematic model through a wave dominated barrier estuary after Nichol and Murray-Wallace (1992) and Roy et al. (1994). Landform units are from Pain et al. (in press).

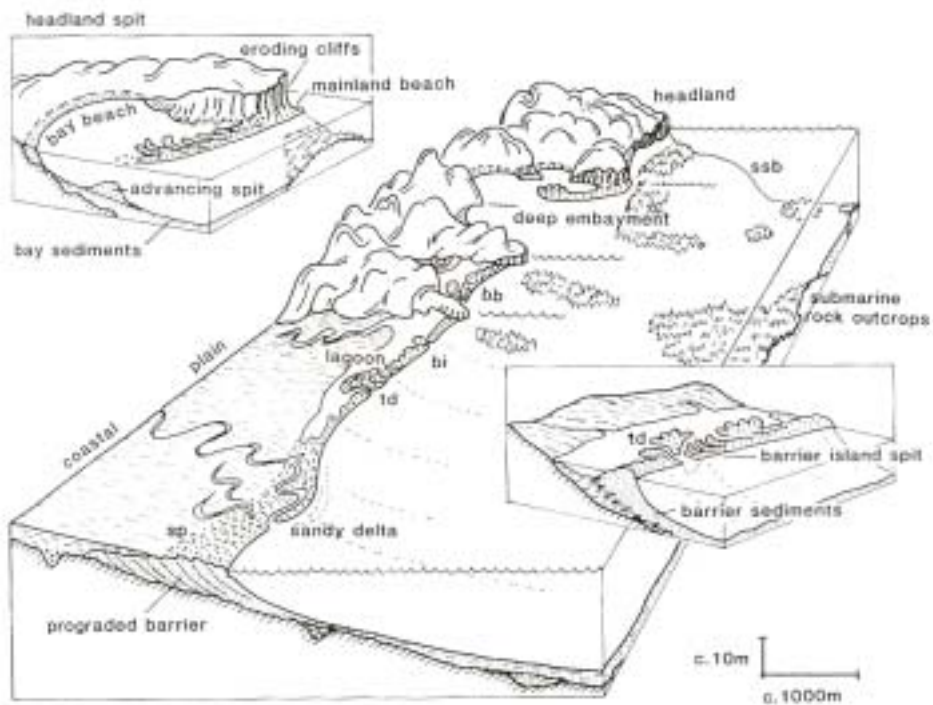


Figure 2.12 Typical geomorphic units of a wave dominated coast showing cliffed sections and coastal embayments (ssb=shelf sand body; bb= bay barrier; bi=barrier island; td=tidal delta; sp=strand plain (Roy et al. 1994)

Early work by Langford-Smith and Thom (1969) suggested that lagoon or estuary development in many coastal valleys occurred in response to partial or complete enclosure by marine sand barriers, defined as detrital sediment, which rises above

present sea-level and blocks off or impounds drainage from the hinterland (Thom, 1984). Over the last glacial cycle, previous marine highstand deposits along the New South Wales coast were temporarily stored during the lowstand on the shore and inner shelf. This occurred until the most recent post-glacial marine transgression moved sand landward into the incised coastal embayments (Chapman *et al.*, 1982). Figure 2.12 provides a summary of models for barrier development through the onshore movement of sand during the post-glacial transgression.

## **2.8. Systematic geomorphology and sedimentary facies**

This dissertation requires repeated reference to many geomorphic landforms and sedimentary facies. As such the geomorphic landforms of the southeast Australian coast are introduced, discussed and coded here in an attempt to simplify their use. Landform codes for this dissertation are derived from Pain *et al.* (in press) a landform association scheme used for regolith mapping. Although limited by its broad scope, this scheme (Figure 2.13) allows simple landform, process and facies relationships to be identified and eliminates the particular complexity of defining nomenclature and classification of the sedimentary facies that make up many of these landforms. The remainder of this dissertation will then refer to the geomorphic units and sedimentary facies presented in the following section. As washover sediments and boulder deposits are the focus of this project they are discussed in detail in the succeeding chapter.

### **2.8.1. Landforms types**

This section outlines the systematic geomorphic units, which make up the coastal plains of southeastern New South Wales. Coastal embayments occur between bedrock ridges and contain several types of Quaternary depositional landforms, which are the product of a variety of interrelated processes (Roy, 1984). Bedrock headlands found at the coast separate drowned river valleys, and back-barrier estuarine and barrier environments of varied maturity (Figure 2.12). The maturity and fill of the coastal embayments is dependent on the geomorphic framework that is broadly dependent on the inherited geology and drainage (Roy *et al.* 2001). Broad shallow basins like the Shoalhaven system drain large catchments and are now infilled and carry sediment to the coast. Such system are in direct contrast to deeply incised narrow valleys, such as Batemans Bay and Port Hacking, that continue to accommodate extensive drowned river valleys.

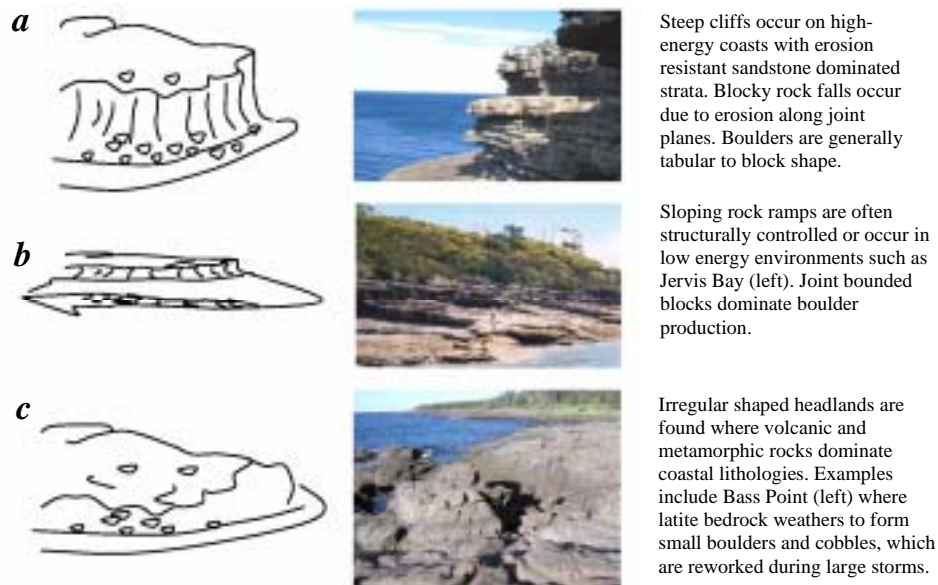


REGOLITH-LANDFORM UNIT (RLU) MAPPING CODES – Pain et al (in press)	
REGOLITH TYPES	LANDFORMS
<b>TRANSPORTED REGOLITH</b>	
A Alluvial sediments	a Alluvial landforms
AC Channel deposits	ap alluvial plain
AD Overbank deposits	af flood plain
	aa anastomatic plain
I Aeolian sediments	ab bar plain
IS Aeolian sand	ac covered plain
IL Loess	am meander plain
IP Pama	ao floodout
	at alluvial terrace
C Colluvial sediments	as stagnant alluvial plain
CM Mass movement	ai terraced land
CH Sheet flow deposit	aw alluvial swamp
CF Conglomerate	
	u dunefield
E Evaporite	ul longitudinal dunefield
EH Halite	
EG Gypsum	f fan
	fa alluvial fan
L Lacustrine sediments	fc colluvial fan
	fs sheet-flood fan
G Glacial sediments	p plain
V Volcanic sediments	pd depositional plain
VT Tephra	pl lacustrine plain
	pp playa plain
F Fill	ps sandplain
O Coastal sediments	g glacial landforms
OB Beach sediments	gd depositional glacial landforms
OE Estuarine sediments	ga erosional glacial landforms
OC Coral	
OM Marine sediments	d delta
<b>IN-SITU REGOLITH</b>	
W Weathered bedrock	c coastal lands
	cb beach ridge plain
R Residual material	cc chenier plain
	cr coral reef
S Saprolite	om marine plain
SC Completely weathered bedrock	ct tidal flat
SV Very highly weathered bedrock	cd coastal dunes
SH Highly weathered bedrock	cp coastal plain
SM Moderately weathered bedrock	oc beach
SS Slightly weathered bedrock	
	e erosional landforms
	ep erosional plain
	el pediment
	ea pediplain
	en peneplain
	ec etchplain
	er rises
	eu residual rises
	el low hills
	eh hills
	am mountains
	ee escarpment
	eb badlands
	ed drainage depression
	k karst
	l plateau
	v volcanic landform
	vc caldera
	vv cone
	vl lava plain
	va ash plain
	vf lava flow
	vp lava plateau
	m made land
	t meteor crater

Figure 2.13 Regolith landform unit (RLU) mapping codes from Pain et al. (in press). This scheme provides a landform-lithofacies relationship for the systematic study of sedimentary successions in coastal embayments on the southeast Australian coast.

### 2.8.1.1. Bedrock headlands and ramps.

All headlands within the study area are generally cliffed to some extent. This is particularly the case in the erosion resistant sandstone strata of the upper and lower Sydney Basin sequence, which forms prominent cliffs around Sydney, Jervis Bay and Pebbly Beach to the south. Headlands that are eroded into strata such as the basaltic rocks of the Kiama-Shellharbour region generally have a more irregular appearance, as do the rocky headlands around Batemans Bay, which are composed of folded metasediments of the Lachlan Fold Belt. Three basic types of headland are identified along this coast and a general schematic of headlands from the southeast coast is provided in Figure 2.14 along with photos of a large cliffed headland at Little Beecroft Peninsula, a small irregular headland at Bass Point, and a sheltered rock ramp at Greenfields Beach, Jervis Bay. Note that most headlands have a cliffed section and rock shelf that accommodates numerous boulders. These boulders are the product of the blocky nature of cliff erosion along the coast that is generally associated with the extensive shallow dipping sedimentary rock units of the Sydney Basin. Of particular interest to this study is the reworking of these deposits by large-scale washover activity.



*Figure 2.14 Three examples of rocky morphologies identified on the southeast Australian coast. a) Steep cliffed shorelines of Little Beecroft Peninsula near Jervis Bay. The cliffs are characteristic of many of the cliffs along this predominantly sandstone coast that are usually associated with areas of high wave energy. b) A gently sloping rock ramp found at Greenfields Beach in Jervis Bay. This ramp occurs in shallow dipping sandstones of Permian age. c) Irregular shaped bedrock headlands such as this one at Bass Point are often found in volcanic rocks around Kiama and metamorphic rocks around Bateman Bay. Variation in rock mineralogy, along with the presence of numerous dykes, often leads to the formation of sea caves and blowholes.*

The sedimentology of these boulder accumulations is discussed in detail in Chapter 4 as an integral part of the review of previous boulder based studies from this coast. In many cases boulder accumulations have been used to indicate large-scale washover activity attributed to tsunami (Young *et al.*, 1996; Bryant, 2001). The small study outlined in Chapter 4 re-examines several boulders accumulations from the Jervis Bay region.

#### **2.8.1.2. Drowned River Valleys; an incised landform.**

Drowned river valleys have formed where fluvial activity during lowstands, including the last glacial, have incised deep, steep sided valleys that are now accumulating sediment during the Holocene highstand of sea level. Figure 2.15 shows part of the Batemans Bay system and outlines specific landforms within the estuary. Fluvial deltas prograde into deep muddy basins and are composed of immature fluvial sands. Fine muddy sediments accumulate in mud basins, tidal flats and mangrove forests, whilst pocket beaches on the seaward margins of the estuary contain coarser sandy muds that are often overlapped by a muddy tidal flat deposit. Often, as is the case with Batemans Bay, a large tidal delta sand body rests at the entrance to the estuary and confines a small channel through which open tidal exchange occurs. Seaward of the tidal delta higher wave energy results in sandy beaches between bedrock headlands.

#### **2.8.1.3. Landforms found in barrier estuaries**

Landforms that comprise barrier estuaries can be divided into finer, often muddy back-barrier sequences and coarse sandy barriers. Barriers dominate the landform of much of the coast and all these systems share some simple landform characteristics as outlined in Figure 2.16. In these systems fine sediment either accumulates in mud basins and floodplains or is transported offshore. Coarser sediments are found in channels, fluvial and tidal deltas and barriers, with sediments showing increasing maturity in a seaward direction. These depositional environments result in a diverse range of channels, mud basins, tidal mud flats and prograding deltas. Often the sand-dominated barrier sequence is deposited on or overlies an older sandy barrier sequence. In many places the contemporary sandy barriers on the coast overlie older Pleistocene barrier sequences behind which lie accumulations of older back-barrier deposits. The nature of this cyclical development means that accommodation space in estuaries such as Killalea Lagoon was often very limited and was infilled rapidly during the Holocene transgression and subsequent highstand.

Code	Landform unit	Description of dominant sediment types
A	Beach face and nearshore zone	Sandy beaches dominated by mature quartz sand material with some pebbles and cobbles. Shell content dominated by beach face shells and shell hash. Sediment are indicative of high but variable wave energy.
B	Sheltered and pocket beaches	Fine quartz with abundant shell dominated by <i>Norospisula</i> sp. Some mud in more sheltered locations. Pocket beach to west of bridge appears to be mid-Holocene and is now a receding system.
C	Tidal delta	Large deltaic sand body that reduces wave energy and confines a small channel (E) that is often partially exposed at low tide. Sediments are medium- to coarse-grained sand with variable amounts of shell.
D	Small deltas	Small coastal creeks that enter into the bay drain small catchments. Small mud basins exist behind prograded chenier plains or beach ridges. Delta sediments consist of muddy sands that are reworked as they enter the higher energy of the bay.
E	Tidal Channel	A deep confined channel that contains abundant shell material, pebbles and debris. High and variable energy results in quartz sandy sediments with a minor lithic component. Shells include robust species including <i>Anadara trapezia</i> , <i>Norospisula</i> sp. and abundant gastropods.
F	Estuarine mud basin	Deep estuarine valley with muddy sediments. Abundant shelly macrofauna with numerous species of bivalves and gastropods. The muddy sediments also support populations of foraminifers and ostracods.
G	Tidal flats, salt marshes and mangroves	Tidal and periodically flooded mud flats. Muddy sediments that often support seagrasses, salt marshes or mangroves. Occuring on the fringes of estuarine lagoons these muddy sequences are often exposed at low tide or during periods of low rainfall.
H	Outer bay	Open embayment up to 40-m deep. Open to ocean swell from the southeast to northeast. Sediments are dominated by silty sands with abundant microfauna, sponge spicules and shell hash.



Figure 2.15 Geomorphological units of Batemans Bay a drowned river valley at the southern limit of the study area. The labelled units form the basic geomorphic components of the system (from Pain et al., in press). Sedimentation is inherently tied to the geomorphic units and energy regimes responsible for each. The study site at this location is highlighted with a stippled rectangle. It is also important that all parts of the system are considered as large-scale washover may incorporate and mix sediments derived from many parts of the coastal system. Large-scale overwash in this system would be likely to incorporate material from A,B,C,E and possibly H. (photo from the Department of Infrastructure, Planning and Natural Resources, 2001)

Code	Landform unit	Description of dominant sediment types
A	Beach face and nearshore zone	Sandy beaches dominated by mature quartz sand material with some pebbles and cobbles. Shell content dominated by beach face shells and shell hash. Sediment are indicative of high but variable wave energy.
B	Aeolian dunes	Fine quartz sand blown from beach that usually overrules coarser barrier sands of the prograded barrier system (C). Often topped with vegetation such as <i>Acacia</i> sp. and grasses such as <i>Spinifex</i> .
C	Barrier sands	Medium- to coarse-grained sands with varied shell content formed during progradation of the beach system (A). Older (Pleistocene) systems appear as more mottled modified units.
D	Estuary channel	Sandy sediments often with significant shell content. Varied mud content is dependent on hydraulics of the channel and is directly related to the size of the estuary and the action of tides.
E	Estuarine lagoon	Much finer sediments than the channel facies. Faunal components include many estuarine bivalves and gastropods who live in and on the muddy sediments. Often seagrasses grow on sander banks.
F	Estuarine mud flats	Tidal and periodically flooded mud flats. Muddy sediments that often support seagrasses, salt marshes or mangroves. Occuring on the fringes of estuarine lagoons these muddy sequences are often exposed at low tide or during periods of low rainfall.
G	Fluvial deltas	Sandy sequences of immature (often muddy) sands composed of the eroded remnants of the catchment geology. Sand material is deposited on active deltas with finer material carried to the estuarine lagoon.
H	Coastal floodplains	Over bank sequences of immature muds and sands vertically increased during flood events in the upper catchment. Usually composed of silt to fine grained sand with variable organic matter and little carbonate.

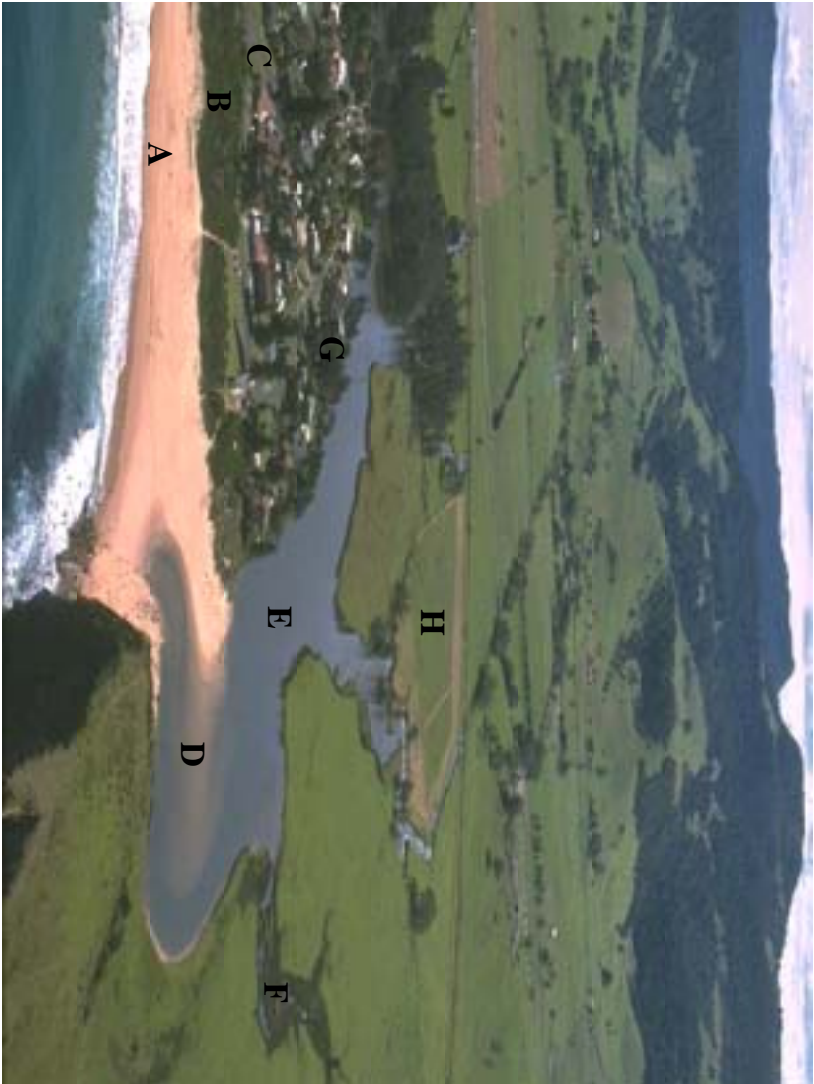


Figure 2.16 Geomorphological units of Werri Lagoon, a barrier estuary located in the study area. The labelled landform units form the basic geomorphic components of the system. Sedimentation is inherently tied to the geomorphic units and energy regimes responsible for each. It is also important that all parts of the system are considered as large-scale washover may incorporate and mix sediments derived from many parts of the coastal system. Such overwash in this system would be likely to incorporate material from A,B,C,D,E and F. (photo from the Department of Infrastructure, Planning and Natural Resources, 2001)

#### **2.8.1.4. Saline coastal lakes and freshwater-brackish lagoons.**

Saline coastal lakes lack tidal influence and are intermittently or permanently closed from marine influences. Examples include Lake Wollumbula (coastal lake) and Killalea Lagoon (freshwater-brackish lagoon, Figure 2.17). Generally these environments are characterised by low energy and the accumulation of large amounts of fine material and organic matter as the low energy environment provides a habitat for colonising sea grasses and algae. Sea grasses are found in the saline to brackish systems whereas algae dominate the freshwater systems such as Killalea Lagoon. As Killalea Lagoon is a major part of this project the landforms of this embayment are discussed in detail in Chapter 7.

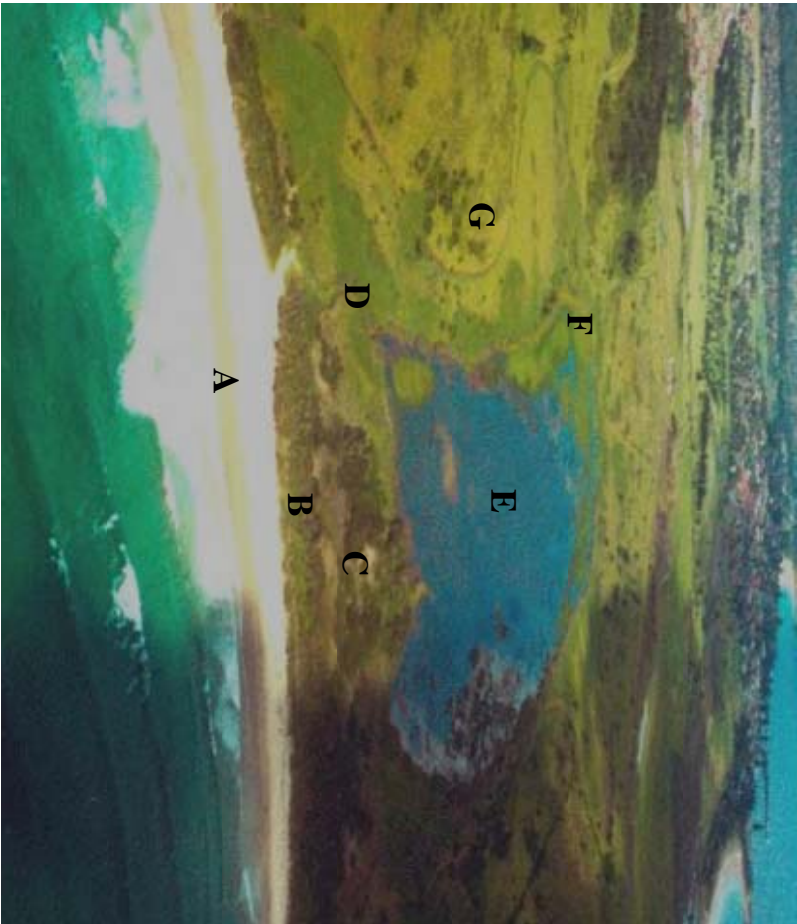
#### **2.8.1.5. Pocket embayments**

Several small pocket embayments exist on the open coast, where small beach systems generally rest directly on weathered bedrock or Pleistocene sediments. In most cases these systems lack a barrier structure and drainage is via sheetwash and transmission through the sandy barrier system as groundwater flow. Although large-scale washover may be found in these embayments none of these systems were investigated in this study.

### **2.9. Sedimentary facies associations**

Facies models developed from the analysis of modern processes allow direct comparison with the depositional record of the past under the principles of uniformitarianism. Middleton (1978) noted that “facies definition is quite objective” and suggested that “the key to interpretation of facies is to combine observations made on their spatial relations and internal characteristics...with comparative information from other well-studied stratigraphic units, and particularly from studies of modern sedimentary environments”. This study uses broad facies descriptions for key geomorphic and sedimentological units where facies are initially divided into fine (<2 mm) facies and coarse (>2 mm) facies before focusing on the internal sandy facies of overwash sandsheets. The internal sedimentology of the sandsheets requires further subdivision into a series of sandy facies.





Code	Landform Unit	Description of landform and sediment types
A	Beachface and nearshore	Sandy beaches dominated by mature quartz sand material with some pebbles and cobbles. Shell content dominated by beach face shells and shell hash. Sediment are indicative of high but variable wave energy.
B	Foredune	Fine quartz sand blown from beach that usually overlies coarser barrier sands of the prograded barrier system (C). Often topped with vegetation such as <i>Acacia</i> sp. and grasses such as <i>spthifex</i> .
C	Aeolian dunes	Prograded barrier sands are topped by a large accumulation of fine aeolian sand with a contemporary surface expression of a series of small well-vegetated transgressive dunes. The irregular shaped dunes have poorly developed soils and coastal vegetation a such as <i>spthifex</i> and <i>acacia</i> sp.
D	Rarely breached channel	Marsh environment with reeds. Storm events rarely breach the system depositing thin sheets of sand. High lagoon levels associated with heavy rainfall are recorded as wet organic-rich clays and peat.
E	Lagoon floor	Organic-rich lagoon floor with minor aeolian sand. Major organic components are reed fragments including <i>Juncus</i> sp. and <i>Triglochin striata</i> . Sediment consists of silty clay with small amounts of aeolian sand.
F	Lagoon margin	Organic-rich clays and peats with soil development during low lagoon levels. Sheetwash processes introduce debris and soil clasts from the hillslopes intermittently during flooding.
G	Bedrock ridges	Skeletal soils exist over bedrock ridges. The bedrock of the small Killalea catchment consists of the Bunbarra Lignite member a basaltic rock of Permian age. Erosion of these ridges is by sheetwash flow.

Figure 2.17 Systematic geomorphic units of Killalea lagoon. The lagoon catchment would have been well vegetated before clearing for farmland in the late 1800's. The dune system remains comparatively unmodified when compared to the catchment. This study focuses on investigating a sandsheet in the upper fill of the embayment. The main focus area is the western margin of the lagoon.

### **2.9.1 Fine-grained facies and associated structures**

Fine-grained siliclastic sediments (<2 mm) are found in most depositional environments along the southeast Australian coast. Generally coastal dune sequences and pocket embayments consist of sandy facies dominated by quartz sands, with muddy facies confined to estuaries, the continental shelf and overbank deposits on floodplains (Figures 2.15-2.17). In places remnant (Pleistocene) facies, including mottled dune sands and mottled clays exposed during low sea levels, are present. The Pleistocene sediments are often found in sedimentary sequences underlying recent Holocene fill. Sedimentary structures observed in fine-grained facies include internal bedding, graded sequences and clasts of foreign lithologies or debris.

### **2.9.2 Rocky coastal outcrops and coarse-grained (gravel) facies.**

Erosion of bedrock headlands produces a variety of rock debris including gravels and mega-clast accumulations. Mega-clasts (large-boulders) are found in many headlands along the southeast Australian coast. Boulder and gravel facies on rocky shorelines has been the subject of significant recent debate (Felton, 2002; Felton and Crook 2003).

The main issues of contention highlighted by Felton (2002) include a lack of sedimentary facies models for rocky shoreline environments, with which to compare such deposits, and inadequate methodologies for describing and characterizing coarse gravel deposits generally. Felton (2002), referring to debate over the depositional hypotheses forwarded for the Hulopoe gravel on Lanai in the Hawaiian Islands (Felton *et al.*, 2000; Rubin *et al.*, 2000; Keating and Helsley, 2002 suggested that resolution of these debates will only be possible through the development of facies-based “new methodologies that focus on vertical and lateral variations in petro-, litho- and biofacies, facies architecture, contact relationships, geomorphic settings and stratal geometries”. Such methodologies (models) will only be useful when compared to a range of examples from modern and well-described ancient rocky shorelines. A lack of well-defined facies models has implications for the study of boulders on the rocky outcrops on this coast. This is discussed in Chapter 4 with particular reference to the tsunami hypothesis forwarded by Bryant *et al.* (1996); Bryant and Nott, (2001) and Young *et al.* (1996) and criticism of this hypothesis by Felton and Crook (2003) and Switzer *et al.* (2004a,b).



## **2.10 Synthesis**

The southeast Australian coast has a temperate climate and a coastline characterised by a micro-tidal regime and high wave energy. This wave energy (>2 m) is associated with low-pressure systems in the Tasman Sea and southwest Pacific Ocean. The study site for this project stretches for 260 km from Bass Point in the north to Batemans Bay in the south. All sites except for the Batemans Bay site lie in the Sydney Basin system, a back-arc sedimentary basin of Permo-Triassic age. Batemans Bay is a drowned river valley cut into the metasediments of the underlying Lachlan Fold Belt system. Quaternary sediments have infilled dissected embayments to varied degrees dependent on local bedrock geology, drainage, inherited geology and to some extent the influence of man. This high-energy coast provides an excellent study site to explore the role of large waves on coastal sedimentation. The later part of this review has outlined the key geomorphic units found along this coast using some of the study sites as examples. These geomorphic units were tabled along with the facies associations of each system. This review outlines the varied coastal processes operating on this coast and provides a platform to investigate the role of large-scale washover in the late Holocene and possible depositional signatures for such events.

## **2.11 Conclusions**

- The southeast Australian coast is a microtidal (<2 m), temperate margin that experiences a dominance of high-energy ocean waves that often exceed 2 m and periodic storm events that can cause swells in excess of 3 m. Climate is temperate with dominant sea-breezes in summer and stronger southwest winds in winter.
- Along the tectonically stable, embayed coast Holocene sandy barriers occupy coastal basins separated by rocky headlands. The coastline onlaps a geology that can broadly be divided into an Ordovician to Silurian fold belt and a broad shallow Permo-Triassic sedimentary basin sequence. The geomorphic expression of the present coastline is the product of the post-glacial transgression and subsequent highstand as embayments have evolved over numerous glacial cycles and now contain large accumulations of post-glacial estuarine to marine sediments.

- Oceanic swell conditions are strongly dependent on low-pressure systems that form off the coast the majority of which come from the south and produce frequent high-energy pulses of southeast swell to the coast. These events are more frequent than the periodic cyclones and locally produced east coast lows that generate swell from the north to east.
- The study area has a wide and varied geomorphic framework including rocky headlands and numerous barrier systems that are infilled to different stages of maturity. These systems contain a variety of fine- and coarse-grained facies that inherently represent differing energy regimes during deposition and in some instances can record periodic fluctuations in energy associated with short-lived depositional events.

### **Chapter 3**

#### **Large-scale washover deposition by storms and tsunami: a review of the sedimentological characteristics using modern analogs and recent literature**

##### **Introduction**

This chapter describes the characteristics of large-scale washover sedimentation with the assistance of regional reviews of relevant literature along with case studies of modern analogs for the deposition of washover sandsheets and boulders in coastal environments. In all cases the deposits are attributed to large waves, storm surges or tsunami (Table 3.1).

In broad terms the mechanics of large-scale washover deposition are simple and modern processes provide valuable insights into the nature of deposition and the impact of such events on coastal environments. Complexity is encountered when considering older deposits without known origins, where analysis often becomes problematic as large waves, storm surge and tsunami share many characteristics in hydraulic potential and depositional processes.

##### **3.1 Washover events, flood tide deltas and sea level change**

Differentiating between transgressive sand deposits that are the result of sea level rise and washover that is short-lived or event based is often not possible from a single depositional unit or core sample. Further complication lies in the differentiation between washover sand deposits and flood tide deltas as these features share many characteristics (Sedgwick and Davis, 2003). Transgressive deposits are generally regional in their nature and accumulate during the landward movement of a coastline (Cattaneo and Steel, 2003). In most cases this requires a rise in relative sea level, although exceptions occur in unusual situations such as subsidence or significant erosion of the coast at a time of slow sea level fall and minimal sediment input (Curry, 1964). Transgressive deposits associated with Holocene sea level rise are identified in many embayments from the southeast Australian coast (Roy *et al.*, 2001; Sloss *et al.*, in press).

Such analysis requires a regional overview of the spatial variability and detailed analysis of sediment characteristics, sedimentary structures and geomorphic variability.

A sea-level review from the east coast of NSW was provided in Section 2.5.1. It is important to reiterate here that the deposits discussed in this thesis are not the result of sea level change. The likelihood of attributing these deposits to sea level change, in particular higher mid-Holocene sea levels is disproven on both sedimentological and geographical grounds. Numerous studies of the geomorphological evolution of estuaries along this coastline have lead to a well-developed model for Quaternary estuarine evolution (Roy, 1994; Roy *et al.*, 1980, 2001). The sandsheets lack evidence of beach structures or wave scour and are sedimentologically and spatially unique. The sand-sized fraction consists of well-sorted, fine- to medium-grained quartz sand with traces of fine-grained heavy minerals. Textural analysis indicated that the sand grains incorporated in the sandsheets were rounded to sub-rounded, a description that closely fits that for eastern Australian marine sand by Roy and Crawford (1977) and Roy *et al.* (1980).

Event type	Locations of vulnerability	Likely return periodicity	Critical tide level
Severe waves	Coasts exposed to significant oversea wind fetch	Storm-related; months to year (often seasonal).	High or super-elevated due to piling of water against the coast
Storm surge	Areas prone to intense storms attributed to cyclones, hurricanes, and typhoons.	Storm-related; months to year (often seasonal).	High or super-elevated due to piling of water against the coast
Tsunami	Exposed coasts and critical inlets exposed to far-field and localised events	Years to centuries.	High (although damage can occur at any tide dependent on run-up)

Table 3.1 Vulnerability, return periodicity and critical tide levels for three washover sources. Attributing washover deposits in coastal sequences to either of these, or a combination of both, require modern analogs. In the case of tsunami, where return periods often exceed decades, this becomes more difficult as these events are rare.

Furthermore all of the deposits in the study area are concentrated in a particular orientation suggesting a depositional event from the southeast to east. No such sandsheets are found in the upper fill of any embayments that are orientated to the northeast. The occurrence of marine quartz sand in sheltered parts of embayments orientated southeast and not in those orientated northeast cannot be explained by the models of coastal evolution for southeastern Australia proposed by Roy (1984) and Roy *et al.* (2001), and cannot be attributed to sea-level change.

On siliclastic coasts flood-tidal deltas are found to be genetically and stratigraphically similar to washovers (Pierce, 1970). Furthermore washover deposits show consistent internal heterogeneity that inhibits the production of a unified stratigraphic model for these deposits (Leatherman and Williams, 1977). Of particular pertinence to this study are the effects of regional differences in geology and the inherent differences between estuary types, sources of sediments, and the preservation potential of washover deposits. These factors cause differences among washover deposits and are often caused by variations in sediment composition, height of storm surge, height of the barrier, and the resultant duration of overwash (Leatherman, 1977). Despite these difficulties, there are common attributes to all washover deposits that result from common flow conditions during genesis of the deposit (Schwartz, 1982). On some coastlines differentiating between washover and tidal delta deposits is difficult, although Sedgwick and Davis (2003) suggested the distinction between washover facies and flood-tidal delta facies can be made by looking for evidence of tidal signatures and the presence of tidal inlet channel deposits. No evidence for flood-tide delta facies associations are found in the sandsheets and they bear little resemblance to flood-tide delta facies identified in the study area.

Sedimentation in flood tide deltas from southeast Australian estuaries was described by Roy (1984) as sites where marine sands in active delta fronts are observed to retrograde over estuarine muds. When intercepted, the flood-tide delta sequences often exhibit an apparent upward coarsening of mean particle size that is most likely the result of the flood-tide delta retrograding over the estuarine muds, with the sand becoming cleaner and coarser as water depth decreased and energy levels increased with delta growth (Roy, 1984). The sandy back barrier deposit at Killalea Lagoon that are the focus of this project do not show evidence of retrograde delta activity and exist as lenses of thin (usually less than 1m thick) graded, massive and organic- and clast-bearing sands suggesting that short lived washover deposition is the most likely agent of deposition.

### **3.2 Mechanics of washover deposition**

For the purpose of this study large-scale washover sedimentation is considered to be an order of magnitude above episodic events such as small coastal storms or seasonal tidal fluctuations and will be broadly defined as; short-lived, high-energy depositional events

that transport significant volumes of sediment (of any size) from the littoral or near shore zone and deposit the material in an area not usually affected by active coastal processes such as tides or waves. This definition is based on Kumar and Sanders (1976) definition of the littoral zone as stretching from the landward limit of wave action to water depths of 10-20 m at low tide. Large-scale washover should also be considered an order of magnitude greater than that described by Leatherman (1977) who defined washover as “the continuation of the swash uprush over the crest of the most landward berm, during high-energy conditions”. A model for the mechanism of washover sedimentation is presented in Figure 3.1 and provides a schematic overview of the definition used for this study.

### **3.3 The concept of disequilibrium state**

Many oceanic variables can result in washover; the key factor in determining washover potential is the concept of coastal equilibrium. For example, coastlines such as the east and gulf coasts of the United States are dominated by a micro-tidal regime and offshore winds with characteristically low wave energy and a shallow gently sloping coastal shelf (Figure 3.2), conditions that lead to the formation extensive low-lying barrier islands. Periodic seasonal extreme events associated with hurricanes in the Gulf of Mexico are not in equilibrium with the ambient setting and often result in significant coastal modification including frequent storm-dominated washover events (Sedgwick and Davis, 2003). An event significantly greater in energy than the environmental equilibrium of a coastline may result in large-scale washover. This study aims to identify the high-energy disequilibrium events that resulted in the onshore movement of large boulder accumulations and deposited a series of washover sand sheet deposits in the upper fill of three coastal embayments from the NSW coast.

### **3.4 Washover deposits and the geological record**

The disequilibrium concept above suggests that all coasts are susceptible to washover deposition if a high-energy event of significant magnitude occurs. However any geological record of such events requires deposition of material and, furthermore, requires preservation of that material in a recognizable state. The most common geological record of washover occurs as boulders on rocky shorelines and marine sand sheets in coastal sequences.

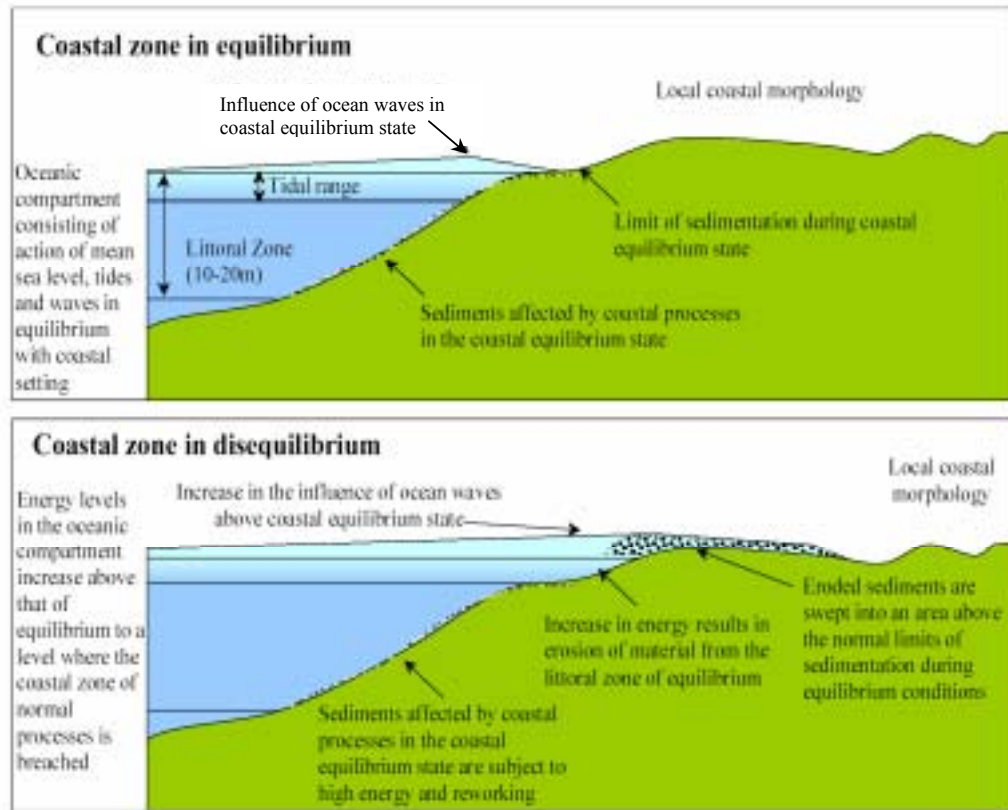


Figure 3.1 Schematic representation of overwash events and the concept of equilibrium threshold where overwash represents short lived depositional events that transport sediment from the littoral zone and deposit the material in an area not usually affected by active coastal processes such as tides or waves.

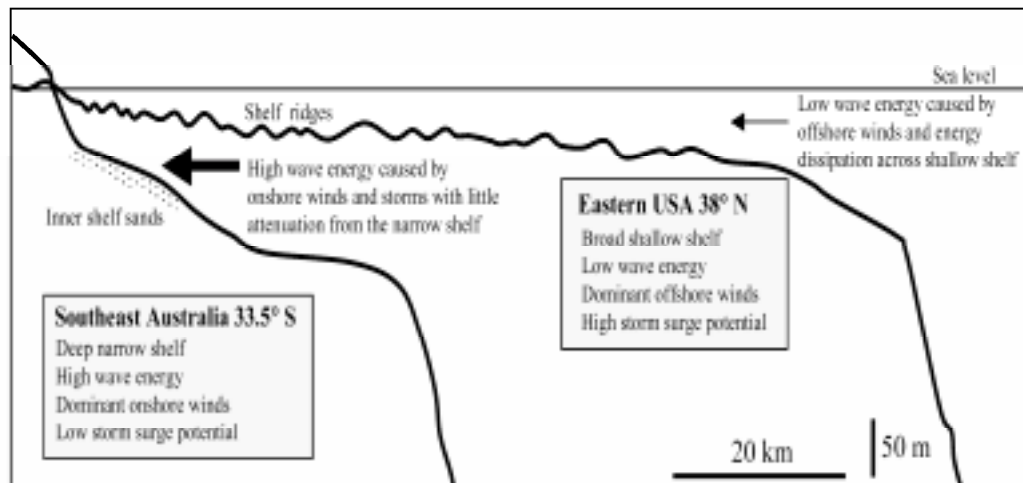


Figure 3.2 Comparison of the continental shelf morphologies of southeastern Australia and eastern USA coastlines (after Cowell et al., 1994).

#### **3.4.1 Repeated misinterpretation of an early study of high-energy deposition**

Bourrouilh-Le Jan and Talandier (1985) studied the coastline of Rangiroa, Taumotu Tahitian islands in the south Pacific. The authors identified large boulders on reef platforms and sandsheets in back-reef lagoons that they attributed to the action of large-scale washover by storm or tsunami. It is important to note that this extensive study was unable to differentiate between storm and tsunami. It is also interesting to note that many articles on storm and tsunami produced in recent times have misquoted the work of Bourrouilh-Le Jan and Talandier (1985) and used the study as evidence for the action of either storms or tsunami when they in fact could not attribute the deposits and geomorphic forms to either or a combination of the processes. For example Hearty (1997) quoted Bourrouilh-Le Jan and Talandier (1985) as “describing ‘cyclopean blocks’ (15 x 10 x 5 m) in Polynesia that were deposited by ‘tidal waves’ during the Holocene”. This quote suggests the deposits are the result of a tsunami, incorrectly termed a ‘tidal wave’ - a term not used by Bourrouilh-Le Jan and Talandier (1985) that had not been determined as the cause of sediment movement. Further incidences include Luque *et al.* (2002) and Bryant (2001; Figure 4.6) who recreated a vital diagram from the Bourrouilh-Le Jan and Talandier (1985) paper but used it to model tsunami impacts on a coral atoll.

#### **3.4.2 Boulders and gravel**

On rocky shorelines washover deposits are usually identified as elevated boulder or gravel deposits. The problematic nature of boulder and gravel deposits on rocky shorelines will be discussed briefly in this chapter and in more detail in Chapter 4 where particular reference is made to boulder accumulations identified on the Australian southeast coast.

#### **3.4.3 Sandsheets**

With regard to internal fabric, the sedimentology of washover sandsheets is inherently dependent on the nature of the source sediments but generally they can be defined as “horizontally bedded, alternating layers of terrigenous sand, shell fragments and heavy minerals that reflect changing hydraulic competence and tidal variations during (storm) surge” (Kochel and Dolan, 1986, p. 902). Although this definition is directly related to storm surge, the same definition can also be applied to tsunami inundation and both will be considered here. All washover deposits, regardless of their sediment source are only



recognizable if preserved and such preservation depends on many factors including rate of reworking due to post depositional factors such as bioturbation, and further overwash events. Also pertinent is the frequency of overwash events and their potential to rework previous records, the thickness of the units, and the magnitude and rate of sea-level change (Sedgwick and Davis, 2003).

### **3.5 Storms as agents of washover deposition.**

Most coastlines are affected by storms with variable recurrence intervals that are often seasonally controlled (Bryant, 1991; Nott, 2003). Tropical coasts such as those in northern Australia, the Caribbean and Pacific islands such as Fiji are frequently struck by tropical cyclones or hurricanes. Such events can cause significant damage and often result in large storm waves and possible storm surge. Nott (2003) noted that tropical cyclones in northern Australia can deposit subaerial sediments in the form of ridges (Figure 3.3) composed of tropical carbonate sediments including coral rubble, pumice, shelly carbonate sand or splays and sheets of sand incorporating shells. Lithic clasts and coral rubble may be found incorporated in the sand sheets confined by otherwise finer muds in back-barrier lagoons. It must be noted that during high winds associated with tropical cyclones such material may also be transported by wind and Nott (2003) noted that differentiating between deposits attributed to waves and/or storm surge from deposits caused by high winds may be difficult. One way to eliminate this variable is the study of marine deposition or reworking of marine sediments by storms. Examples include the investigation of coarse sandy shell layers in fine-grained sediments found in shallow marine environments that can be attributed to large storm events (Nott 2003; Huang, 2000; Huang and Yim, 2001).

The Australian southeast and southern coasts are high-energy wave dominated coasts that are frequently impacted by high-energy ocean swells (Figure 3.4). An outline of swell conditions for the coast was provided in Section 2.4. The impact of such swell events can be exacerbated by the occurrence of storm surges where super-elevation of sea level for periods of up to several hours can increase the risk of overwash into coastal embayments.

### 3.5.1 Storm surges

A combination of wind stress and falling atmospheric pressure during a severe storm can cause a storm surge (McInness and Hubbert, 2001) - a temporary local super-elevation in sea level above the expected tide level that accompanies intense low-pressure systems.

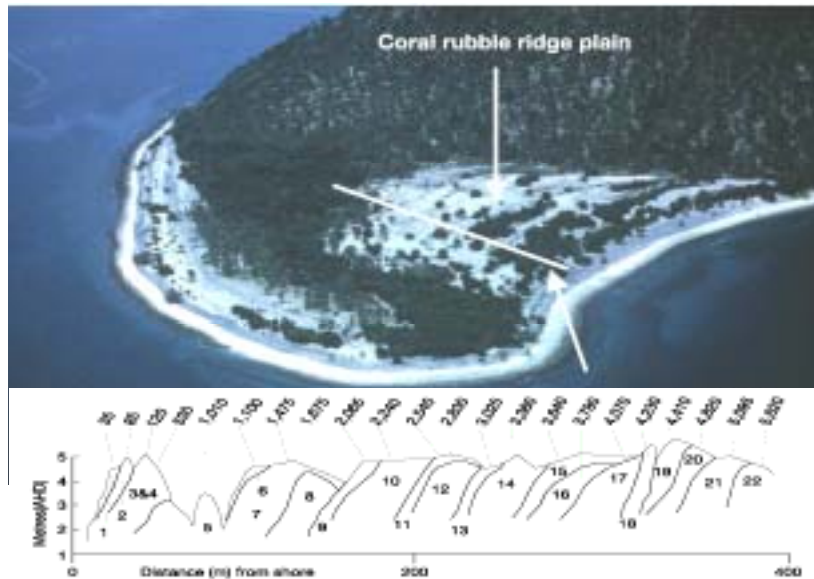


Figure 3.3 a) Storm deposits, forming a coral rubble ridge plain on Curaco Island, Great Barrier Reef, Australia. b) A schematic of the stepped accretionary chronology obtained from radiocarbon dating of debris (Nott, 2003).

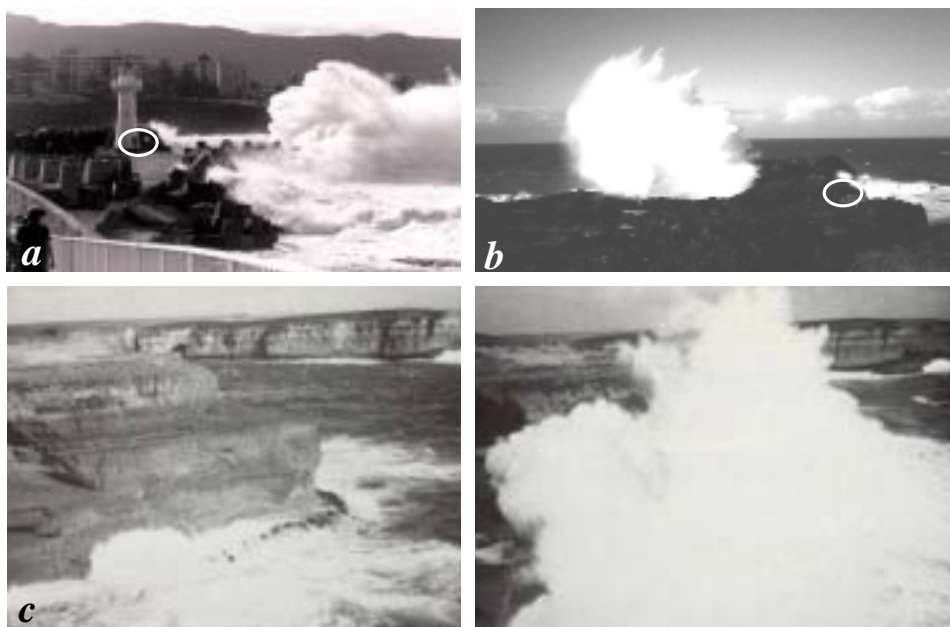


Figure 3.4 Storm waves strike a) a breakwall ~5 m high at Wollongong (note people circled) on the southeast Australian coast (Bryant 1991); b) near Kiama (note people circled); c) at Broken Head near Port Campbell in Victoria, Australia (after Baker, 1943, cited in Hills, 1971). The cliff at Broken Head is 33 m high.

Chapman *et al.* (1982) described storm surge as a low frequency rise in mean water level which is generated by strong winds and migrating low-pressure systems. The authors identified two general types of localized, temporary, storm related sea level rise (Figure 3.5). The first is a storm surge that is generated by the inverse relationship between water level and barometric pressure. The second is caused by the shoreward mass-transport of water in steep high waves, which results in the piling up of water against the coast. The National Oceanic and Atmospheric Administration (NOAA) described the key aspects of storm surge providing a general definition for storm surge magnitude that broadly states that a storm surge is an abnormal rise in sea level accompanying a hurricane or other intense storm. The storm surge is the difference between the observed level of the sea surface and the astronomical tide that would have occurred in the absence of the storm (NOAA, 2003). The low barometric pressure allows a hydrostatic rise in the water level of approximately 0.1 metre for each 10 hPa that the central pressure of the system is lower than the surrounding pressure. As a low-pressure system moves into shallow coastal waters, the nearshore seabed and coastline shape modify the surge and cause substantial amplification of its height.

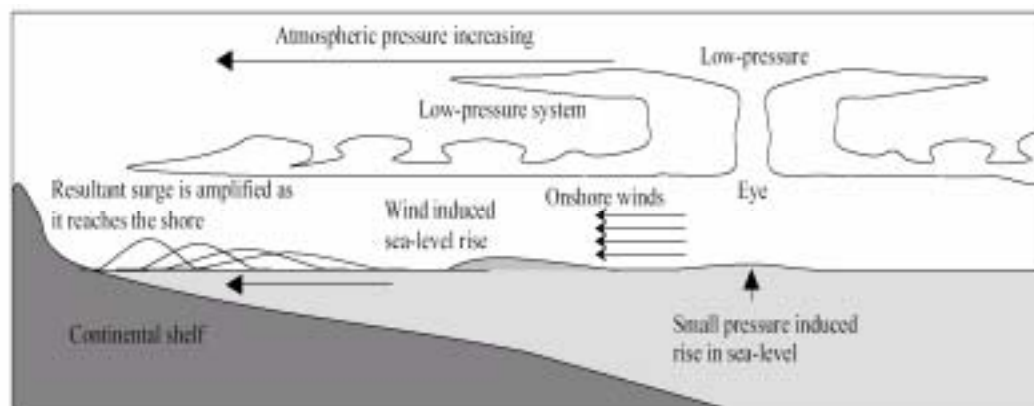


Figure 3.5 Atmospheric components of a storm surge. The drop in pressure in the center of the low pressure system causes a small 'bulge' or rise in sea-level in the ocean surface. A larger bulge may be formed by strong onshore winds piling water up against a coastline. As the system moves towards land the surge can be amplified by the continental slope and nearshore morphology.

Storm surges can persist for 24 hours and affect 300 kilometres of coastline. Storm surges increase the water level above the normal tide levels and the resultant water level, known as the storm tide level, may inundate low-lying coastal and estuarine communities and increase flood levels farther upstream.

### 3.5.2 Review of recent scientific literature on geological investigations of storm deposits

Significant studies of storm deposits from back-barrier environments on siliclastic coasts (Leatherman and Williams, 1977; Morton, 1979; Liu and Fearn, 1993; Ehlers *et al.*, 1993; FitzGerald *et al.*, 1994; Guillen *et al.*, 1994; Delaney and Devoy, 1995) and rocky shorelines (Hearty, 1997; Nott, 1997; Mastronuzzi and Sansò, 2000; Felton, 2002; 2003, Sommerville *et al.*, 2003; Williams and Hall, 2004) suggest that high-energy storm events can deposit sediments behind sandy barriers and on rocky shorelines when velocities of flood currents drop dramatically after breaching the focus area of the shoreface (Zong and Tooley, 1999). Other deposits attributed to storms have been recorded in the internal stratigraphy of coastal dune systems (Jelgersma *et al.*, 1995). This project uses the concept of facies models obtained from the analysis of modern analogs to develop a model for analysing ancient storm and tsunami deposits - a process that is often difficult on high-energy shorelines (Felton and Crook, 2003). Zong and Tooley (1999) suggested that reliable storm-surge signatures can only be developed by using appropriate analytical techniques, such as determining the particle-size distribution of the storm layers and comparing them to associated biogenic non-storm sequences (Delaney and Devoy, 1995). Also the examination of lateral textural grading of washover deposits within horizontal laminations (Leatherman and Williams, 1977) and the identification of sand layers in lagoon cores (Liu and Fearn, 1993) can define storm washover deposits. Commenting on fine-grained samples, Zong and Tooley (1999) suggested that methods are best conducted on sediment samples extracted from locations with high preservation potential. Although particularly useful for fine-grained sediments, the same can be said for coarse debris such as boulders.

Studies from the Netherlands (Jelgersma *et al.*, 1995), Long Island New York (Tuttle *et al.* 2004), the Gulf of Mexico and United States east coast (Sedgwick and Davis, 2003, and references therein.) provide data about modern fine-grained washover deposits from back-barrier environments (Table 3.2), whilst studies from Ireland (Hansom 2001, Williams and Hall, 2004), Italy (Mastronuzzi, and Sansò 2000, 2004), Australia (Felton and Crook, 2002) and Hawaii (Noormets *et al.*, 2002) provide examples of modern storm-deposited coarse debris or boulder accumulations (Table 3.3). In contrast to facies analysis of fine-grained coastal sequences, the study of boulder or cobble deposits is complicated by a lack of facies models unequivocally relating deposits to

modern processes, suggesting that analysis without such direct process models can only infer past events (Felton and Crook, 2002).

### 3.5.3 Modern Storm deposits

Studying storm deposition in the coastal zone is not a new branch of the science. Sussmilch (1912) noted boulder accumulations near Sydney, Australia, and attributed them to a large coastal storm (Figure 3.6). However a relatively new endeavour concerns the field of palaeotempestology, defined by Nott (2003, p.15) as the reconstruction of “past extreme events from sedimentary or erosional evidence left in the landscape as a result of storm surge and wave action”. This new field builds on the historical records of storms to include past events and act as a long term predictive measure for use by coastal engineers and managers in recurrence analysis. Palaeotempestological research, as with many new branches of science, is currently focused in a number key locations around the world, including areas of tropical cyclones in northern Australia (Chappell *et al.*, 1983; Chivas *et al.*, 1986; Hayne and Chappell, 2001), southern and eastern United States (Liu and Fearn, 1993, 2000; Collins *et al.*, 1999; Donnelly *et al.*, 2001) and to a lesser extent throughout the south Pacific islands (McKee, 1959; Baines and McLean, 1976; McLean, 1993) along with other coastlines dominated by low gradient shelves including southwest England (Zong and Tooley, 1999).

Storm deposits from the southeast coast of Australia have not been studied in detail. An understanding of storm formation and the presence of storm surge on the coast has been the focus of recent work by researchers at the Commonwealth Scientific and Industrial Research Organization (CSIRO) and others (Hopkins and Holland, 1997; McInnes and Hubbert, 2001). This research has increased the understanding of storm processes but still significant gaps in knowledge remain. These gaps center on the coastal processes of such events and their depositional and preservation potential in coastal sedimentary sequences. One of the supplementary aims of this thesis is to provide a detailed study of storm deposits from known storm events on the southeast coast. Incorporating information derived from this modern process study not only provides a modern analog for this thesis but also may enable older sequences to be identified in the future.



Figure 3.6 A large erratic block at Mermaid Rock, Ben Buckler, north Bondi, Sydney, Australia. This sandstone block measures 6.1x4.9x3.0 m and weighs approximately 235 tonnes. The block was emplaced by a large coastal storm in 1912 (Sussmilch, 1912) and appears inverted relative to its original orientation in the bed.

### 3.6 Coastal boulder deposits and the role of washover events

High-energy wave-dominated environments, such as those on the southeastern Australian coast, are by definition subject to swell and storm waves. These agents cause a variety of depositional and erosional processes (Figure 3.7) that not only erode and sculpture the bedrock of rocky headlands, but also generate coarse gravelly sediment. These coarse gravels, including boulders and blocks, are particularly poorly studied (Felton and Crook, 2002) and interpretation of these deposits even in modern situations is complicated by a general lack of consistency within the literature on coarse deposits.

#### Boulder deposition attributed to tsunami

Many studies over the last 30 years have attributed boulder deposits on rocky coasts to large-scale events such as tsunami, often with contentious results. Examples include Davies and Hughes (1983); Miyoshi *et al.* (1983); Moore and Moore (1984, 1988); Ota *et al.* (1985); Paskoff (1991); Bryant *et al.* (1992, 1996); Jones and Hunter (1992);

Jones (1992); Nakata and Kawana (1995); Shi *et al.* (1993, 1995); Moore *et al.* (1994); Nishimura and Miyaji (1995); Schubert (1994); Hearty (1997); Nott (1997, 2000); Mastronuzzi and Sanso (2000); Felton *et al.* (2000); Bryant (2001); Kelletat and Schellmann (2002); and Scheffers (2002). Large tsunami events are capable of transporting boulders along with sand and other fine materials more than 1 km inland. Extremely large tsunami or “mega-tsunami” are even purported as capable of boulder transport up to 30 km inland on Australia’s southeast and northwest coasts (Bryant and Nott, 2001).

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / storm signatures	Reference(s)
Southeastern USA	Various throughout late Holocene	Hurricanes in Gulf of Mexico and Atlantic Ocean	Up to 6 m+	Sandsheets in barrier estuaries and lagoons. The sandsheets are the result of washover due to intense hurricanes. They are generally identified as coarse sand lenses in marsh environments. Often considerable horizontal stratification is observed. See Text. Microfaunal analysis often identifies marine microfauna such as forams and diatoms. They are generally thin and extend less than 200 m inland.  Signatures; (Sedgwick and Davis, 2003) - Sandsheets in low energy environments - Marine microfauna - Confined by low energy deposits - Thin horizontal laminations	Hippensteel, 1999 Sedgwick and Davis, 2003 Keen <i>et al.</i> , 2004 Donnelly <i>et al.</i> , 2004 Buynevich <i>et al.</i> , 2004
Northwestern Australia	March 1999	Tropical cyclone Vance	~ 6 m	A sand barrier comprising parallel dunes approximately 4-6 m high was subject to washover. The back barrier sandsheet occurs as an extensive splay approximately 400-500 m wide and extends 200-250 m inland. This sandsheet decreases in thickness from 1.5 m to 0.75 m thick at its most inland extent, where it terminates as a steep fronted (~30° angle) toe slope as it enters a saltmarsh. Sediments within the splay were deposited as steep (~30°) tabular cross-beds. Medium- to coarse-grained sand occurred at the base of the unit, along with clasts of coral and shells, and graded upwards into medium- to fine-grained sand. Scour pits on the lee (inland) side of trees, imbricated gravels and small boulders of lithic rock within the splay also indicate large-scale overwash.  Signatures; (Nott, 2003, 2004) - deflated dune sequence - extensive sandsheet up to 250 m inland - tabular cross-bedding	Nott, 2003 Nott, 2004
Great Barrier Reef Australia	Various through Holocene	Tropical Cyclones	Up to 4 m	22 consecutive coral rubble ridges are found paralleling the shore (Figure 3.3) with individual ridges that extend for over 100 m along shore and rise to over 5 m above the mid-tide level (the tidal range ~3 m). Successive cyclones deposit new ridges seaward of the previously emplaced ridge. The age of the ridges increases progressively with distance inland. Signatures; (Nott, 2003) - Ridges of cobbles and coral - Marine material eroded from nearshore - Marine microfauna	Nott, 2003 Hayne and Chappell, 2001 Nott and Hayne, 2001
Morcambe Bay Midwestern England	Recent to mid-Holocene	Storm surge in the Irish Sea.	~5 m	Non-marine diatoms in back-barrier lagoon confine diatoms indicative of marine conditions. Interpreted as a consequence of marine floods during storm surge conditions. These flood events did not disrupt the vegetation and are invariably associated with reduced (LOI) values and small increase in clastic sediments. The core studied is located ~4 m above sea level and at the possible margin of run-up. It is possible that diatoms and a small amount of clastic sediments were transported by the floodwater while the majority of marine sediments, particularly the sand and silt fractions, were deposited immediately behind or on the back slope of the sand barrier.  Signatures; (Zong and Tooley, 1999) - Marine diatoms and small amounts of marine sand. - decrease in Loss On Ignition (LOI)	Zong and Tooley, 1999
Netherlands		Storm surges		Sequences of shell medium-sand deposits in coastal dunes that are believed to be the result of storm surge activity on the foreshore, both through swash or overwash action, and of subsequent preservation due to aeolian coverage. Signatures; (Jelergsma <i>et al.</i> , 1995) - Thin laminations - Shell beds raised in aeolian dunes	Jelergsma <i>et al.</i> , 1995

Table 3.2 – Examples of storm deposited sand lenses and cobble ridges. These deposits highlight a number of key criteria for storm deposited sand sheets including horizontal laminations, bedding, shell beds and landward distance.



Figure 3.7 Storm deposits can occur as a) coralline debris (Dawson, 1999), b) boulder accumulations, c) sandsheets (Nott, 2003) d) shelly lags in dune sequences (Jelgersma *et al.*, 1995). Often storm deposits are the result of both a surge component and wave activity that can lead to individual pulses of sediment being deposited by each wave.

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / storm signatures	Reference(s)
Sydney Australia	1912 storm	Strong low pressure system	Up to ~10 m	A large erratic block is found on a rock shelf at Ben Buckler Head. This sandstone block measures 6.1x4.9x3.0 m and weighs approximately 235 tonnes. The block was emplaced by a large coastal storm in 1912 (Sussmilch 1912) and appears inverted relative to its original orientation in the bed.  Signatures (Felton and Crook, 2002) - Large boulder detachment from jointed rock surface - Landward transport both laterally and vertically - Inversion (determined by sedimentary features)	Sussmilch, 1912 Felton and Crook 2003
Hawaii	Recent	Large ocean swells.	~5 m	Very large clasts (megaclasts) are found on a limestone rock platform on the north shore of Oahu, Hawaii. The clasts appear to have been removed from a submerged cliff area in front of the platform and transported onto the platform. Certain parts of the platform produce the largest numbers of clasts, most likely due repeated focused wave attack due to platform orientation and nearshore bathymetry. A variety of erosional processes form an irregular intersecting joints and cracks in the platform which bounds boulders and blocks of various sizes and is most prominent at the platform edge. Large storm waves detach joint bounded clasts and move them to the platform where they appear to undergo occasional reworking by subsequent events.  Signatures (Noormets <i>et al.</i> , 2002) - Joint bounded clasts - detachment dependent on platform orientation and nearshore bathymetry - reworking after initial detachment	Felton, 2000 Noormets <i>et al.</i> 2002 Felton and Crook 2003 Noormets <i>et al.</i> 2004
West coast of Ireland and Scotland	Holocene storms	Storms in the	~15 m	At several locations on the Shetland Islands, Scottish and Irish coasts large rock clasts (boulders) appear to have been quarried from the adjacent cliff-top edge, and transported landwards where they are deposited as cliff-top boulder ridges. In both Scotland and Ireland fresh rocks relatively unweathered boulders are found mixed with older lichen encrusted boulders, which indicates a reasonably recent event. The rocks exist up to 50 m above sea-level and can weigh in excess of 200 tonnes at ~15 m above sea level.  Signatures (Williams and Hall, 2004) - Joint bounded clasts - Imbricated deposits. - Boulders of mixed ages within the ridge.	Hansom 2001 Williams and Hall 2004

Table 3.3 – Examples of storm deposited boulders (mega-clasts). These deposits highlight a number of key criteria for storm deposited boulders including imbrication, the influence of offshore bathymetry and the importance of pre-existing joints and cracks in boulder formation.



### 3.8 Tsunami as agents of washover deposition

Evidence for washover by tsunami events found in coastal environments can be extremely difficult to detect (Scheffers and Kelletat, 2003). Wave-introduced sediments, such as marine sandsheets and accumulations of coarse debris and/or boulders, when located some distance inland, may suggest deposition by tsunami. Fine sediments in the form of sandsheets are, because of their mostly hidden nature, not easy to recognize and in most cases are bound to a stratigraphical context (Dawson, 1999; Dawson and Shi, 2000; Goff *et al.*, 2001). The analysis and chronology of fine sediments is relatively uncomplicated due to facies models and well-established methodologies for stratigraphy and dating of modern and Quaternary deposits. Their unambiguous relation to a tsunami-induced origin is difficult to determine as the sedimentary deposits could often be attributed to deposition by wind or storm waves (Dawson and Shi, 2000). In contrast to coarse debris such as boulders, fine sediments such as laterally extensive sheets of marine sand, are characteristic of washover deposition in coastal settings and in many cases their spatial distribution can be determined via systematic cross-sections constructed from drill cores. Therefore, often it is coincident that fine sediments are studied in order to demonstrate their tsunamigenic origin (Dawson *et al.*, 1991; Dawson 1994, 1996, 1999; Bondevik *et al.*, 1997a,b; Goff *et al.*, 2001).

Often an inductive approach, considering a tsunamigenic origin for unusual deposits or geomorphological features in coastal areas, seems to be more promising as most presently reliable known geological traces of tsunami events have been detected via inductive field research. A worldwide distribution of geological tsunami imprints based on this inductive approach is represented in Figure 3.8. Around the Atlantic Ocean evidence of tsunami in sedimentary records can be found in the Caribbean (Grand Cayman, Bahamas, Puerto Rico, Nicaragua, Curacao, Bonaire and Aruba, as well as in Venezuela), in Scotland and western Norway and along the southern coast of Portugal. In the Mediterranean, tsunami-deposited sediments are located at sites in southern Italy, the Aegean Sea and Cyprus. Sedimentary evidence for tsunami in the Indian Ocean is restricted so far to northwestern Australia (Nott, 2000; Bryant, 2001). The Pacific Ocean experiences the highest tsunami frequency due to the surrounding active plate boundaries. Here, besides field evidence in Indonesia, New Guinea, northern and

southeastern Australia and New Zealand, tsunami occur in particular in areas in the South Seas (Tuamotu), the Hawaiian Islands, the northwestern coast of the USA and British Columbia, Kamchatka, and especially Japan and the Kuriles Islands.

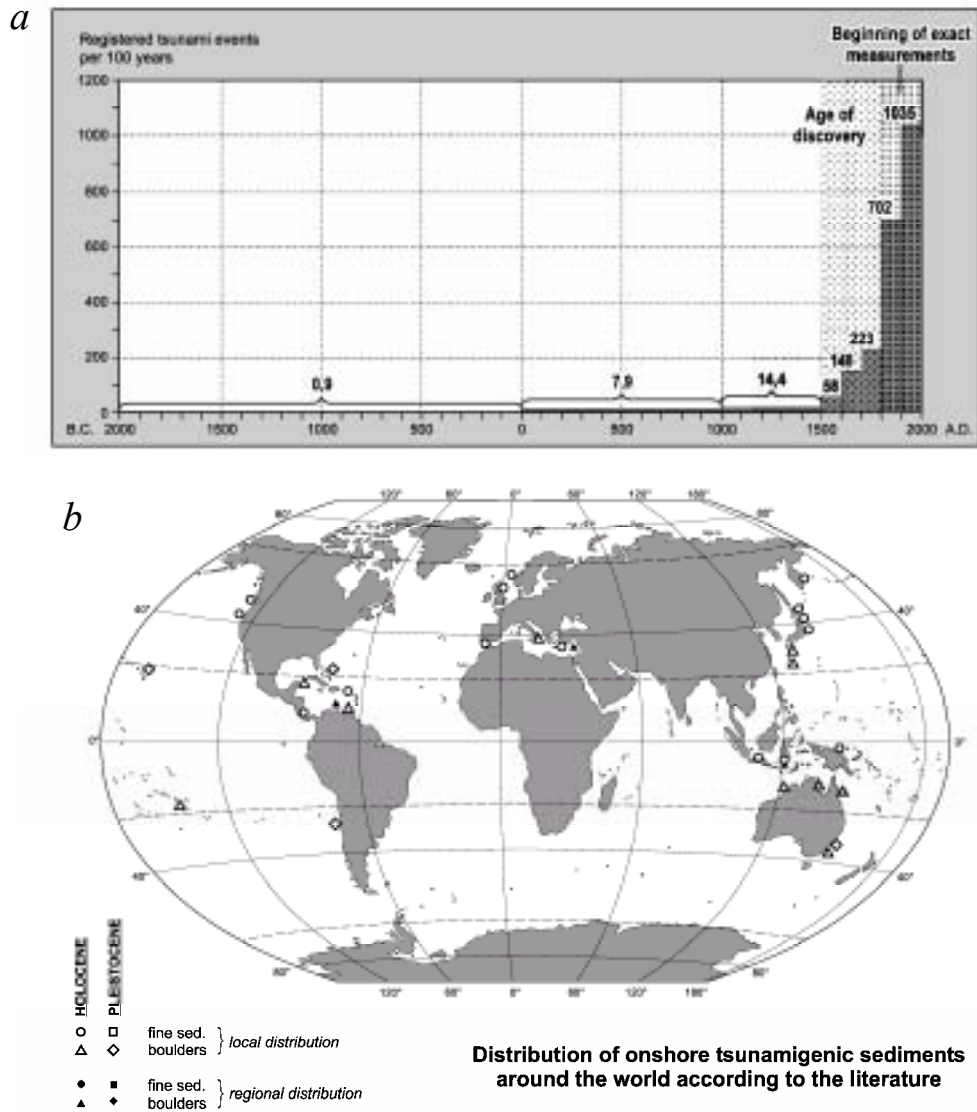


Figure 3.8 *a*) Frequency of tsunami over the last 400 years from National Geophysical Data Center (NGDC) and *b*) world map of tsunami deposits identified in recent scientific literature (from Scheffers and Kelletat, 2003).

### 3.8.1 Tsunami frequency

Although rare in human history, tsunami events when considered over geological timescales can be considered frequent. Such events can have extreme effects on sedimentary transport at the coast and can cause considerable alterations of the coastal morphology (Sheffers and Kelletat, 2003). Palaeotsunami studies require inevitable

sedimentological and geomorphological research, much of which is focused on sandsheet deposition in the coastal zone (Dawson, 1999). This research provides valuable insights into the geological record but it is important to note that field research concerning palaeotsunami is astonishingly rare within the scientific community and only 5% of the existing tsunami literature is related to this subject (Scheffers and Kelletat, 2003).

A review of worldwide tsunami catalogues by Scheffers and Kelletat (2003) including those of: Lander and Whiteside (1997); Tinti and Maramai (1996); Nakata and Kawana (1995), Iida et al. (1967a,b); Heck, (1947); Papadopoulos and Chalkis (1984); Zhou and Adams (1986); NGDC (1997, 2001), identified more than 2000 tsunami events during the past 4000 years (Figure 3.8a). These figures should however be treated with caution as they are skewed strongly toward recent times, and older events would only be recorded if destructive to civilization. They are not likely to be included if they were small or had struck uninhabited areas. It is, therefore, not unreasonable to assume that the actual number of large tsunami over the last 4000 years could actually be far higher.

### **3.8.2 Initial investigations of tsunami sandsheets**

Until the late 1980's the study of tsunami predominantly involved seismologists, numerical modellers, geophysicists and historians. In particular, historians played a valuable role by providing detailed documentary information on former tsunamis from around the world (Dawson and Shi, 2000). Often, historical accounts would provide estimates of frequency-magnitude relationships for past tsunami events and hence provide information on future tsunami risk for different areas. Geologists paid little attention to tsunami records in recent coastal stratigraphy until 1987 and 1988, when two papers were published one from the United States west coast (Atwater, 1987) and another from the Scottish coast (Dawson *et al.*, 1988). The paper by Atwater (1987) linked prehistoric earthquakes with geological evidence from the outer coast of Washington State, U.S.A. This evidence included sheets of marine sediment (Figure 3.9a) visible in coastal stratigraphic sequences that were interpreted as prehistoric (palaeo-) tsunami deposits. Around the same time Dawson *et al.* (1988) in a study of uplifted coastal sedimentary sequences in Scotland, described an unusual sand deposit (Figure 3.9b) which they linked to a prehistoric tsunami event. They hypothesized the event was the result of the Storegga slide, one of the world's largest submarine slides

that took place approximately 7100  $^{14}\text{C}$  years ago on the continental shelf edge west of Norway.

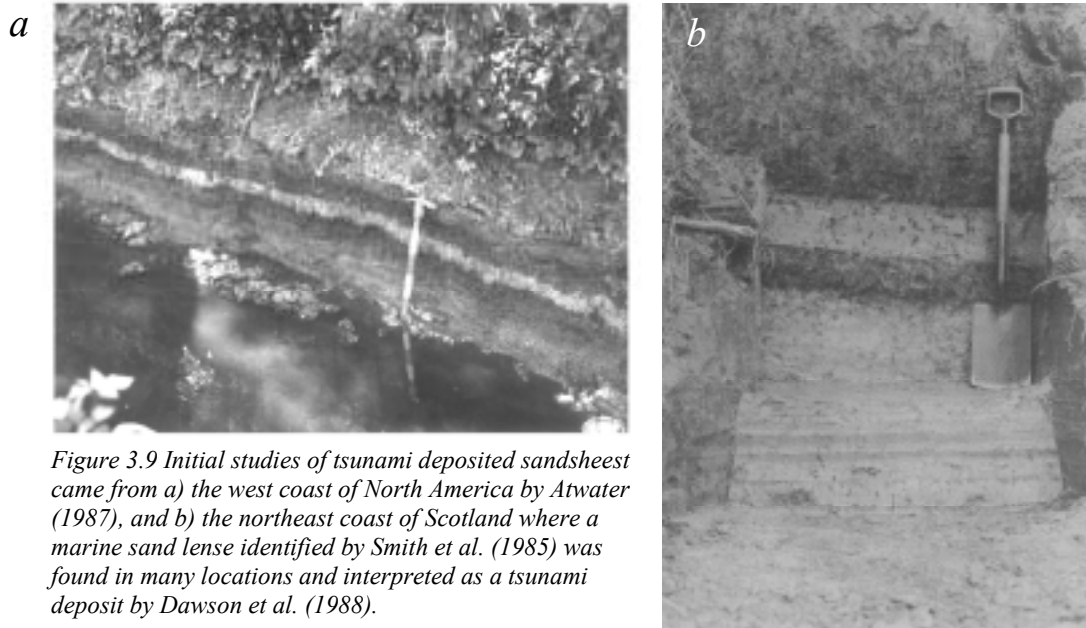


Figure 3.9 Initial studies of tsunami deposited sandsheets came from a) the west coast of North America by Atwater (1987), and b) the northeast coast of Scotland where a marine sand lense identified by Smith *et al.* (1985) was found in many locations and interpreted as a tsunami deposit by Dawson *et al.* (1988).

### 3.8.3 Tsunami sedimentation: advances in the last 15 years

Although geological investigations of former tsunami are a relatively new research area, the last fifteen years has seen a plethora of academic papers on the topic. A wide range of sedimentary evidence from different locations has been attributed to a series of former tsunami (see reviews by Dawson and Shi, 2000; Goff *et al.*, 2001; Bryant, 2001; Scheffers and Kelletat, 2003). Many authors have argued that tsunami are frequently associated with the deposition of continuous and discontinuous sediment sheets across large areas of the coastal zone, provided that there is an adequate sediment supply (e.g., Dawson, 1999; Hindson *et al.*, 1996; Goff *et al.*, 2001). Although tsunami deposits are mostly characterised by sheets of sediment, they are also frequently represented by boulder accumulations (Scheffers and Kelletat, 2003). In addition, microfossil assemblages of diatoms and foraminifera contained within tsunami-deposited sandsheets may provide additional information on the nature of onshore transport of sediment from deeper water (Dominey-Howes, 1996; Hemphill-Haley, 1996).

### **3.8.4 Tsunami dynamics**

The term tsunami is a collective noun, meaning that it may be used as singular or plural, that is derived from the Japanese word meaning harbour wave (Dawson, 1994; Bryant, 2001). Often originally called tidal waves, the phenomenon has little to do with tides and the term refers to waves which have a characteristically long wavelength. They can now be generally defined for the scientific literature as long period waves generated by a sudden displacement of the water surface (De Lange and Fraser, 1999). This general definition is sufficiently broad to cover all possible scenarios for the generation of tsunami. Tsunami generation is generally thought of as a product of seismic disturbances on the sea floor with sudden sea floor disturbances attributed to submarine earthquakes, subaerial or submarine mass flows (slides), volcanic explosions, sea floor collapse or bolide impacts in the ocean (Scheffers, 2002). Recently the risk of tsunami generated by gas hydrate release on continental shelves or submarine failures on continental slopes and at the head of large deltas (Locat and Lee, 2002) has become a new focus for tsunami researchers and suggests that localised tsunami risk may not be restricted to seismically active areas.

### **3.8.4 Tsunami waves in the ocean**

Many tsunamis are caused by sudden seismically induced displacements of the sea floor, which are often caused by large shallow submarine earthquakes occurring along dip-slip faults that exhibit predominantly vertical displacement (Kortekaas, 2002). Tsunami amplitude for events attributed to submarine earthquakes is dependent on the water depth at the epicentre, the fault geometry (orientation and displacement) and to a lesser extent, on the distance from the epicentre to the coast (Murty 1977).

If however, the tsunami is triggered by submarine landslides, gas hydrate release or seismic surface waves passing across the shallow continental shelf, determining the amplitude is often more complex. For example, the amplitude of tsunami waves triggered by a landslide will depend on the properties of the slide such as dimensions, density and flow velocity and on the water depth at the end of the landslide (Pelinovsky and Poplavsky 1996). A tsunami consists of a wave train or series of waves, each with periods ranging from 5 to 120 minutes (Bryant, 2001). They are characterised by a very long wavelength ( $\lambda$ ) of several hundred kilometres and very low amplitudes in the order of one metre when travelling in deep water (Murty 1977). Because of their low

amplitudes tsunamis often remain undetected in the open ocean although their long wavelengths mean that they can affect the whole water column from the surface to the sea floor. According to linear wave theory, the velocity of tsunami waves (celerity) depends on the water depth ( $d$ ): the deeper the ocean, the faster the tsunami. Assuming that  $d < 0.05 \lambda$ , the wave velocity ( $c$ ) can be expressed approximately by the following equation:

$$c = \sqrt{gd}$$

where  $g$  is the acceleration of gravity ( $g = 9.8 \text{ m/s}^2$ )

If, however, the water depth is between  $0.05 \lambda < d < 0.5 \lambda$ , the wave velocity would be dependent on the wave length ( $\lambda$ ) or wave period ( $T$ ) because  $c = \lambda/T$

$$c = \sqrt{\frac{g\lambda}{2\pi}} \quad \text{or} \quad c = \frac{g}{2\pi} (T)$$

Since the wavelength of a tsunami is very long, this is not normally the case and therefore the velocity of a tsunami wave is solely dependent on the depth of the water it is travelling through (Murty 1977).

### 3.8.5 Tsunami at the coast

When a tsunami approaches the coast and the water depth decreases, the waves slow down and the amplitude increases dramatically (Bryant, 2001). Depending on the fault displacement and direction of the wave propagation, the wave trough may reach the coast first, resulting in an initial withdrawal of the sea (Kortekaas, 2002). The maximum water level and the maximum runup of a tsunami wave may in some cases be the same measurements, but they often differ (IOC, 1998).

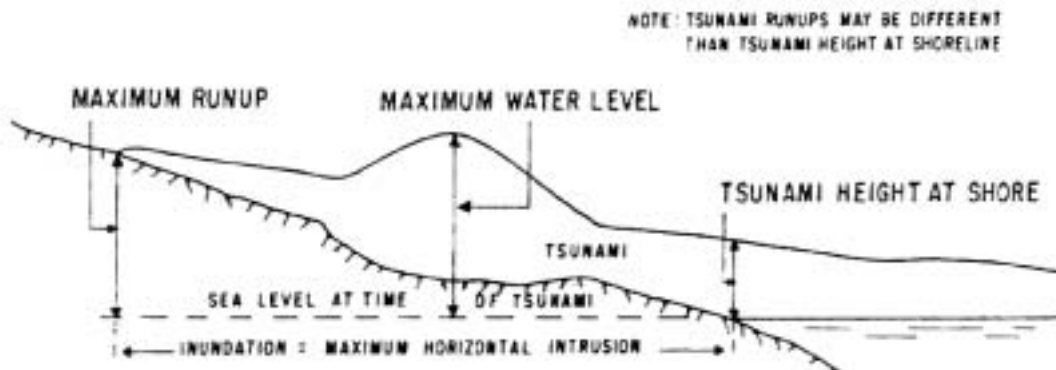


Figure 3.10 Schematic diagram from (IOC, 1998) showing concepts of maximum run-up, inundation, maximum water level and tsunami height at shore.

The maximum runup and water level of the tsunami at the coast, as well as the horizontal inundation distance (Figure 3.8) is not only dependent on the dimensions of the waves, but also on the bathymetry and topography of the coastal zone. Soloviev (1978) suggested that steep coasts will reflect most of the tsunami energy, resulting in a reduced runup and inundation distance. In contrast, submarine ridges can concentrate wave energy, causing higher waves where these ridges intersect the coast. The height of the waves may also increase in bays and gulfs, due to a funnelling effect as well as reflection of waves (Bryant *et al.*, 1992; Bryant, 2001). Soloviev (1978) also suggested that the presence of loose sea-bottom material will also affect inundation potential. He suggested that modelling experiments show that transportation of this material by the tsunami reduces the inundation distance by 20-30%.

Between the successive incoming waves of a tsunami wave train, pulses of seaward flow or ‘backwash’ currents occur. These can be equally or more intense and destructive than the landward currents (Kortekaas, 2002). In some cases the destructive effects of a tsunami are increased by objects carried by the water, both floating and dragged over the bottom, e.g. pebbles, boulders, trees and debris of buildings destroyed by the tsunami (Bryant, 2001).

Tsunamis have been observed to cause extensive coastal erosion and sediment deposition (Dawson and Shi, 2000). If these deposits are preserved and recognised in the sedimentary record they can be used to study past tsunamis (Nott, 2003). Evidence of tsunamis has been found in coastal as well as marine stratigraphical sequences, but this thesis will only focus on coastal deposits. It is important to note that when using geological records to identify and study historical or prehistorical events it is necessary to be able to recognise tsunami deposits and to distinguish them from deposits that originate from storm surges.

### **3.9 Tsunami deposits: a global review**

This section presents a concise review of the nature and location (Figure 3.11) of global tsunami deposits with the aid of regional tables. The regional tables allow direct comparison of significant studies with the aim of identifying key depositional characteristics. Table 3.4a-d provides details of tsunami deposits and their key characteristics from: a) Northern Europe and the British Isles; b) North America; c) the

Mediterranean; d) central and south America; e) Pacific Islands and New Zealand; and f) Japan, Asia and Papua New Guinea. Evidence from the Australian southeast coast is presented in Chapter 4 where it is discussed, reviewed and critically analysed. Key features of tsunami deposits identified from this global summary are compiled and presented in Table 3.6.

Eyewitness accounts, historical records and studies of modern events provide graphic evidence of the ability of tsunami to erode, rework, transport and deposit sediment in the coastal zone. Recent (1992-1994) tsunamigenic events (e.g., Nicaragua, Flores Island, Hokkaido, Java, Kuriles, Mindoro), as well as the Chile (1960), Alaska (1964) and Japan Sea (1983) events, allow an insight into the complex depositional characteristics of tsunami deposits associated with high-energy events of this magnitude.

Deposit characteristics depend on a number of factors, including: tsunami height and period; local bathymetry and topography; sediment source; and vegetation and other roughness elements (Bourgeois, 1993). All tsunami deposits are inherently different, some deposits exhibit evidence of multiple waves (Dawson *et al.* 1991), but others do not, even where eyewitnesses described more than one significant wave (Bourgeois, 1993). Tsunami deposits are a product of the source environment, and grain size and sorting will commonly reflect the source material available (Bourgeois, 1993). Tsunami often erode significant amounts of sediment from the coastal zone, such material will often include large amounts of displaced and reworked vegetation and coastal fauna. Bourgeois (1993) noted that there is a general correlation between tsunami run-up heights and the extent of deposits, but cautions that there are many exceptions.

Moore and Moore (1984) attributed coral gravel on the Hawaiian island of Lanai to a mega-tsunami during the last interglacial that had a suggested run-up in excess of 190 m and possibly to more than 290 m. Recent work by Felton *et al.* (2000) suggested that a tsunamigenic origin for the deposits is premature and that sedimentary facies observed in the Lanai deposit fail to yield definitive results, suggesting that all hypotheses put forward may in fact be partially correct. The transportation and accumulation of boulder assemblages on rocky coasts requires large drag-and-lift forces, particularly if



the material is joint bounded or by other means requires initial detachment from rocky platforms, terraces or cliff fronts (Scheffers and Kelletat, 2003).

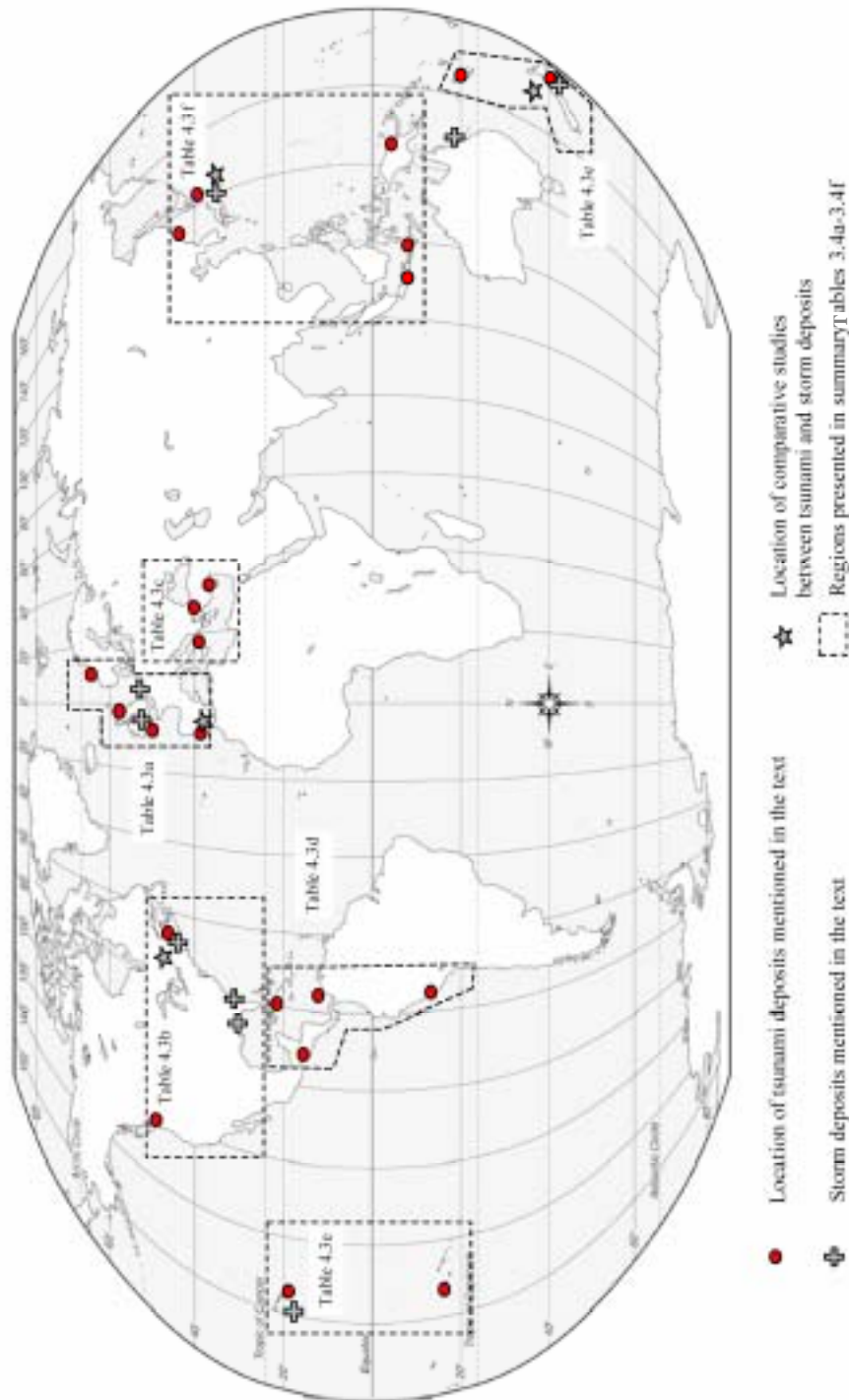


Figure 3.11 World map of tsunami and or storm locations mentioned in the preceding text. The comparative studies from Japan, New Zealand and northeastern United States are particularly important in the context of differentiating between storm and tsunami deposits.

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / tsunami signatures	Reference(s)
Western Norway.  Sand lenses and debris in coastal lakes	7000 yrs BP	Storegga slide on the continental slope of northwestern Norway.	10 - 12 m	Anomalous deposits in coastal lakes inferred as tsunami deposits. An erosional unconformity underlies the tsunami facies and is traced throughout the basins, with most erosion found at the seaward portion of the lakes. The tsunami eroded lake substrates and deposited graded and/or massive sand beds which contain shell fragments and foraminifera. The deposit also included mixed organic sediments such as rip-up clasts of peat and lacustrine gyttja in a matrix of redeposited gyttja, plant fragments, silt and sand.  Signatures (Bondevik <i>et al.</i> , 1997a) - Erosive contact - Rip-up clasts of peat (terrestrial?) and gyttja (lacustrine) - Exotic (marine) shell and microfauna	Bondevik <i>et al.</i> , 1997a Bondevik <i>et al.</i> , 1997b
Eastern Scotland.  Washover sand lenses in coastal embayments	~7000 yrs BP	Storegga slide on the continental slope of western Norway.	3 - 6 m	A thin deposit of marine sand across a surface of peat and coarse sediments. The deposits rise in elevation inland as tapering sediment wedges. The deposits contained large numbers of brackish, but most commonly marine diatoms, 60-80% of which were broken. Intraclasts of peat.  Signatures (Dawson and Shi, 2000) - coarser layer in marked contrast to the sediments, which occur above, and below. - erosional unconformity with the underlying sediments - presence of a mixed diatom assemblage, although fragmentary - variations in particle size within the sequence disclose striking similarities with those from contemporary tsunami deposits.	Smith <i>et al.</i> , 1985 Dawson <i>et al.</i> , 1988 Dawson, 1994 Dawson and Shi, 2000
Silly Isles, southwest England  Washover sand lenses in small coastal embayments  Boco do Rio, Algrave Portugal.  Washover sand lenses in back-barrier estuaries	1755 AD	The Lisbon earthquake 1 <sup>st</sup> November, 1755.	11-13 m	Up to one metre of marine sand that tapers landward and consists of a series of fining-upward sedimentary units. The sand contains inclusions of peat reworked from underlying terrigenous sequences.  The deposit includes laterally continuous sand layers, chaotic pebble horizons, large amounts of gravel sized shell debris and distinctive assemblages of (marine) microfossils. Sedimentary characteristics vary greatly both horizontally and vertically.  Signatures: (Foster <i>et al.</i> , 1991; Hindson and Andrade, 1999) - multiple fining upward units - landward tapering sandsheet - ripped-up peat clasts - erosional unconformity with the underlying sediments - marine microfossils - chaotic lateral and vertical variation throughout the deposit	Foster <i>et al.</i> , 1991 Dawson <i>et al.</i> , 1995  Hindson and Andrade 1999

*Table 3.4a – Table of tsunami deposit characteristics from northern Europe. The Storegga slide deposits described for Norway and Scotland are presented along with a summary of deposits associated with the 1755 earthquake off Portugal. Many other tsunami deposits occur in Northern Europe including Iceland and the Shetland and Faeroe islands. The deposits presented here yield diagnostic characteristics that are useful in the context of this thesis.*

Large boulders in excess of 200 t have been attributed to Holocene tsunami in the Caribbean (Scheffers, 2002) and northeast Queensland (Nott, 1997). Boulders up to 1800 t reported on the Tuamotu-Islands in the southern Pacific (Bourrouilh-Le Jan and Talandier 1985) (possibly misinterpreted see section 3.4.1) and some exceeding 2000 t described for the Younger Pleistocene on the Bahamas (Hearty, 1997) have also been attributed to tsunami deposition.

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / tsunami signatures	Reference(s)
Western coastline of North America  Vancouver, British Columbia and northern California  (sandsheets in coastal embayments)	1700AD 1964AD Possibly up to seven have occurred in the last 3500 yr.	Holocene and recent earthquakes of the Cascadia subduction zone and Alaska 1964. Local crustal earthquakes and landslides along the British Columbia coast probably cause tsunamis that are much smaller, more frequent and localized.	Up to 11 m	Evidence for repetitive tsunami is found in tidal marshes and low-elevation coastal lakes on western Vancouver Island and along the northwestern US coast. The tsunami deposits consist of sheets of sand and gravel, now preserved, in sequences of peat and mud. The deposits commonly contain marine fossils, and they thin and fine landward, consistent with deposition by landward surges of water.  Signatures (Benson, 1997) - sand sheets tapering landward away from channels - marine sediment provenance confirmed by microfossils (foraminifera and diatoms) - overall fining trend landward. - Normal grading couplets interpreted as multiple landward surges of water.	Atwater 1987 Darioenzo and Peterson, 1990 Atwater and Yamaguchi, 1991 Clague and Bobrowsky, 1994 Benson, 1997 Clague <i>et al.</i> , 2000
Northeastern North America (sand sheets)	1929 Grand Banks earthquake	1929 Grand Bank earthquake and associated sediment slump.	Up to 13 m	Tsunami deposited sandy sediment some 300 m inland, and laterally over ~400 m to an elevation ~7 m above mean sea level. No systematic variations were found in a deposit that ranges in thickness from a thin trace of sand to over 25 cm thick. Preliminary results show a fining of the sediment landward, consistent with results from tsunami-lain sands.  Signatures (McAdoo <i>et al.</i> , 2003) - thin discontinuous sand sheets in marsh environments - Preliminary finding of landward fining in grain size.	McAdoo <i>et al.</i> , 2003 Tuttle <i>et al.</i> , 2004
Texas, southern North America (sandsheets and ejecta)	K-T boundary?	Chicxulub impact event?	50- 100 m	Thick coarse clastic deposits are found as sand beds and are indicative of high energy deposition at the KT boundary at Brazos River, Texas. These deposits are interpreted to be the result of a major disturbance of the depositional environment, such as a tsunami approximately 50 to 100 metres high.  Signatures (Bourgeois <i>et al.</i> , 1988) - coarse detritus in low energy environments - sand beds that contain ejecta (spherules) indicative of proximal impact source	Bourgeois <i>et al.</i> , 1988
Northern California (bedrock sculpturing of semi-lithified mudstone plus a back-barrier sandsheet).	Late Holocene to recent 1964	Cascadia subduction zone earthquakes	<10 m	Bedrock sculpturing of semi-lithified sandy mudstone exposed on a wave-cut platform produced a variety of erosional forms that include surface scratches made by beach debris, ripple-like ridges that reflect differential erosion of bedrock, potholes, and scallop-shaped pockets and grooves, which may be straight or sinuous. Auguring and coring in a back-barrier bog and diatom analysis reveals a landward-thinning, ~17 cm thick, laterally continuous, clean, sand layer with a sharp basal contact up to 125 m inland of the modern high-tide line, which is inferred to be tsunami-emplaced. The study also suggests that tsunami may be responsible for the sculptured grooves observed in the rock platform.  Signatures (Aalto <i>et al.</i> , 1999) - sand lense - offshore diatoms - sculpturing of semi lithified bedrock	Aalto <i>et al.</i> , 1999

Table 3.4b – Table of tsunami deposit characteristics from northern America. The much studied deposits of the northwestern U.S and Canada provide a valuable insight into the deposition of tsunami deposits in varied environments and yield key information on the study of such deposits. The example provided from Texas shows the possibility of studying these deposits in ancient settings and also provides a valuable piece of evidence for meteorite impact at the K-T boundary. The example attributed to the 1929 Grand banks earthquake and slide allowed direct comparison by Tuttle *et al.* (2004) with modern storms from 1991. The example from northern California provides the only evidence for bedrock sculpturing by tsunami found outside that described by Bryant and Young (1996).

### Chapter 3. Large-scale washover deposition – a review

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / tsunami signatures	Reference(s)
Astypalaea Island, Greece  (imbricated cobble)	1956	1956 Aegean tsunami	10 m	High energy marine sediments exist as imbricated pebble deposits (Imbricated Clast Unit, or ICU) that are inferred to be marine due to the similarity between the clasts comprising the ICU and contemporary beach sediments, and the inclusion of marine foraminiferal tests within the sediment matrix. The tsunami deposit exists to +2 m above sea level. Another site found elsewhere exists as gravel with rounded clasts incorporating marine mollusca that is found on exposed cliff surfaces up to an elevation of +10 m above sea level. These gravels are also interpreted as having been deposited by the AD 1956 tsunami.  Signatures (Dominey-Howes <i>et al.</i> , 2000) - elevated imbricated cobbles with marine microfauna - elevated gravels on a cliffed coastline - exotic (marine) shell and microfauna	Dominey-Howes <i>et al.</i> , 2000
Southern Italy (boulders)	December 5th, 1456.	Local earthquake?	2 m+	Large boulders, up to 80 t in weight, scattered some meters above present sea level are found on the Ionian coast of Apulia (southern Italy). The largest boulder is about 80 t in weight and slid for about 40 m from the mean sea level up to about 1.8 m altitude. Orientation of the boulders and imbrication indicates flow from two directions although dominated by landward flow. Conventional radiocarbon age determination performed on shells collected from a large boulder yielded a calibrated age between 1421 and 1568 A.D.  Signatures (Mastronuzzi and Sanso, 2000) - elevated imbricated boulders - unidirectional boulder orientation.	Mastronuzzi and Sanso , 2000
Italy and Greece (sand sheets)	Various back to Minoan times 1300 -1600 AD	Volcanic explosions (Santorini) and local earthquakes.	Up to 20 m+	Debate continues over the Minoan tsunami event and the occurrence or lack of occurrence of tsunami deposits in the eastern Mediterranean. A full review is provided by Dominey-Howes (2002) Although often contentious the identification of tsunami deposits in this region may yet lead to further understanding of tsunami inundation histories for regional coastlines in this area. Dominey Howes (2002) points to the nature of the coast, lack of source area, subsequent erosion and complex bathymetry as possible reasons for a lack of recognizable tsunami deposits.  Signatures (Dominey-Howes, 2002) - sandsheets in bays and harbours - imbricated clasts - marine microfauna	Dominey-Howes, 2002
Marmara Sea	240 - 420AD	Earthquake in Marmara Sea	3 m +	A brittle mixed layer (uniquely rich in seeds and ostracod valves) was widely detected in cores taken from a predominantly freshwater lake. This has been interpreted as being the result of a seiche either through a salt inundation linked to a tsunami in the Sea of Marmara (the large-scale scenario) or a local hydrothermal fluid discharge (the small-scale scenario). Ostracod valves, which are usually not preserved in the lake sediments, may be incorporated as tsunami debris. The brittle mixed layer overlies cracks resulting from the direct effects of the seismic shock wave on slightly compacted sediment.  Possible signatures (Leroy <i>et al.</i> , 2002) - ostracod valves not usually found - change in water chemistry - increase in sand content - overlies co-seismic shock cracks	Leroy <i>et al.</i> , 2002

Table 3.4c – Table of tsunami deposit characteristics from the Mediterranean and Marmara Sea. The deposits presented here yield diagnostic characteristics that are useful in the context of this thesis. The deposits investigated in Greece by Kortekaas (2002) yielded little information on possible diagnostic criteria and are not included here.

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / tsunami signatures	Reference(s)
Nicaragua (sandsheet and scattered boulders)	2 Sept 1992	Mw 7.2 1992 Nicaragua earthquake	Up to 11 m	A single large wave, deposited several centimetres of sand onshore for several hundred metres where a beach ridge and flat topography limited backwash that might have otherwise reworked the deposit.  One boulder was carried from offshore at least 50 m inland and raised 1.85 m above sea level. The rock measured 2.3 m by 1.6 m by 0.5 m thick.  Signatures (Higman and Bourgeois, 2002) - laterally extensive sandsheet - graded and non-graded sediments - scattered boulders	Satake <i>et al.</i> , 1993. Higman, 2003a Higman and Bourgeois, 2002
Netherlands Antilles (boulders)	Holocene 3500 yrs BP. 1500 yrs BP 500 yrs BP	Subduction earthquakes in the Caribbean subduction complex.	Up to 12 m	Distinguished assemblages of large boulders >100 m <sup>3</sup> along with rampart formations and ridges of coarse debris. Large modern storm deposits observed are orders of magnitude lower in impact than the observed deposits.  Signatures (Scheffers, 2002) - geomorphic forms- ramparts, ridges and boulders - imbrication indicating flow direction	Scheffers, 2002. Scheffers, 2004.
Bahamas (boulders)	Last interglacial OIS 5e or 5d.	Storms or locally sourced tsunami in the adjacent Atlantic Ocean	Up to 20 m	Seven boulders measuring up to 1000 m <sup>3</sup> are scattered along the coastal ridges up to 20 m above present sea level in north Eleuthera, Bahamas. The boulders date at last interglacial in age and the largest boulder is about 10 times the size of the largest Holocene boulders moved by waves in the area. Tsunami or exceptionally large storms are put forward as possible deposition scenarios.  Signatures (Hearty, 1997) - extremely large boulders when compared to modern storm deposited examples	Hearty, 1997
Chile (sandsheet in saltmarsh)	May 22, 1960	Offshore earthquake	2-5 m	According to eyewitnesses, the tsunami deposited a widespread sand layer throughout the estuarine marshes. The sandsheet was incorporated into the estuarine stratigraphy and sedimentological analysis identified a sand layer between the 1960 saltmarsh and the present soil. Particle size characteristics and the tilt of the buried vegetation, indicate that the sand was most likely transported from the neighbouring dunes and/or sandbars located in the estuary mouth and indicate that the marsh vegetation reduced the wave transport capacity during seawater run-up.  Signatures (Wright and Mella, 2002) - thin lense of marine sand in saltmarsh stratigraphy - erosion of dunes and barrier environments	Wright and Mella, 1963 Cisternas <i>et al.</i> , 2000

*Table 3.4d – Table of tsunami deposit characteristics from the caribbean and central and southern America. The tsunami of Nicaragua 1992 and Chile 1960 are well known examples that provide key characteristics on tsunami deposited sandsheets. The material from the Caribbean and Netherlands Antilles is based on boulder research. Contentious debate continues over the uncertainties inherent to the study of shoreline processes on rocky coasts (Felton 2000; Felton and Crook, 2003).*

Large boulders and blocks (mega-clasts) found on modern rock platforms are evidence of short-lived event-based high-energy changes on wave-dominated coasts. Often these are the result of low-frequency events, such as tsunami, hurricane (cyclone) or storm waves (Sussmilch, 1912; Bourrouilh-Le Jan and Talandier, 1985; Nott, 1997; Noormets *et al.*, 2002). Modelling the wave power required to move the largest megaclasts can give reliable estimates of wave energies where wave records do not exist, and can be linked to specific tsunami and storms, e.g., Noormets *et al.* (2002; 2004).

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / tsunami signatures	Reference(s)
Tahiti	Unknown	Unknown  Note – Undifferentiated between storm and tsunami.	3 m+	Large boulders on coral reef platforms. One of the first studies of large-scale washover sedimentation. Authors could not distinguish between tsunami or storm. Boulders in excess of 1000 t are found on reef platforms. The deposit grades landward from large boulders to gravel to sandsheets in lagoons. (possibly tsunami- see text)  Signatures (Bourrouilh-Le Jan and Talandier, 1985) - boulders on reef platforms - sand in sheltered lagoons	Bourrouilh-Le Jan and Talandier, 1985.
Vanuata and Tahiti	Recent	Locally generated slides?	Up to 5 m	No deposits studied. Photographs from both islands suggest significant transport of material on coasts proximal to the source. Sediment deposition in Vanuatu appears to be in excess of 200 m from the shoreline.  Signatures (Synolakis notes) - destruction of nearshore vegetation.	<a href="http://www.usc.edu/dept/tsunami/fatuiva/">http://www.usc.edu/dept/tsunami/fatuiva/</a> and <a href="http://www.usc.edu/dept/tsunami/VANUATU/">http://www.usc.edu/dept/tsunami/VANUATU/</a>
Hawaii	1925, 1946, 1957 and 1960	Aleutian tsunamis of 1946 and 1957, the 1952 Kamchatka tsunami, and 1960 Chile tsunami.	Up to 20 m	A comparison of the modern beach deposits to those near the remains of a destroyed highway demonstrates that the sedimentary deposits within the two areas have very different rock characteristics. The modern beach is dominated by the rounding of rocks (mostly coral) by wave activity. However, in the area that has experienced prior tsunami inundations, the rocks are characterised by fracturing and a high component of basaltic material.  Signatures (Keating <i>et al.</i> , 2004) - poorly sorted cobble deposits - different sedimentology and roundness characteristics to beach face, indicative of offshore erosion	Keating <i>et al.</i> , 2004
New Zealand	Up to 15 events throughout the Holocene	Seismic activity offshore, some possibly volcanic	Up to 10 m	Deposits of sand and gravel in estuaries and coastal dune systems.  Signatures (Goff <i>et al.</i> 2001, 2004) - deposits generally fine upward and inland. - Discrete sedimentary units that can exhibit subunits reflecting run-up and backwash. - Erosional boundary with clasts and load structures. - Large range of particle sizes - Offshore microfauna (diatoms, foraminifers) - Deposit chemistry may indicate increase in salt water. - Shelly layers and rafted debris (at top of deposit)	Goff and Chague-Goff 1999. Goff and McFadgen, 2001, 2002 Goff, <i>et al.</i> , 2000, 2001, 2004.

Table 3.4e – A summary of tsunami deposits from the Pacific islands and New Zealand including recent observations from Vanuatu and Tahiti. Numerous studies from New Zealand (reviewed in Goff *et al.* 2001, 2004) have resulted in the identification of a wide range of signatures. Section 3.13.3 of the text deals directly with storm and tsunami from New Zealand.

### 3.10 Modern analogs for storm and tsunami deposition

The following section identifies studies of modern and recent storm and tsunami deposits that provide valuable insights into sedimentological differences between the fine-grained deposits. As this study aims to assign a depositional mechanism to a series of prehistoric anomalous deposits the use of modern analogs can provide key information on possible processes. It is apparent that the studied deposits are the result of overwash sedimentation. In the absence of a modern tsunami deposit the internal sedimentology of the sandsheets is compared with two modern storm deposits from large storm events in March and July 2001.

Location (deposit type)	Age(s) of deposit(s)	Source of wave generation	Est. wave height	Deposit description(s) / tsunami signatures	Reference(s)
Japan.	Holocene to recent including 1983 1993	The Japan Sea earthquake 26 May, 1983. The southwest Hokkaido earthquake 12 July, 1993.	1.5-14 m run up height  < 10 m run up height	Siliclastic deposits accumulated for both 1983 and 1993 events where there was a suitable source material and sufficient vertical run up. The thickness and mean grain size decreased with increasing distance from the sea for the 1993 event. The tsunami deposits in estuaries consist of muddy sand and/or sandsheets in fining upward sequences, with abundant transported shells, rip-up clasts, pebbles, cobbles and wood fragments, erosionally covering bay-floor muds deposited around 10 m in depth.  Signatures (Nanayama <i>et al.</i> , 2000) - decreasing thickness and grain size landward - source dependent - fining up sequences - shells and rip-up clasts	Sato <i>et al.</i> , 1995 Nishimura and Miyaji, 1995 Nanayama <i>et al.</i> , 2000
Japan (sandsheets in Pleistocene estuary sediments)	Pleistocene	Pleistocene seismic activity indicated by convoluted bedding (seismites) in the lower part of the sequence.	Unknown	Upper Pleistocene sand and mud deposits are interpreted as 'earthquake-induced tsunami deposits', which were deposited in incised valley fills. The muddy tsunami deposit in the drowned valley is up to 150 cm thick and shows a contorted structured bed in the lower part and cross-laminated sand in the upper part. The tsunami deposit in the barrier sand body up to is 270 cm thick and shows structureless sand with mud clasts in the lower part, cross-laminated sand with mud-drapes in the middle part and mud with small wave-ripples in the upper part.  Signatures: Takashimizu and Masuda (2000) - proximal seismic activity is indicated by seismites of convoluted bedding in muds. - post event tsunami are indicated by sandy beds with mud clasts eroded from the lower sequence	Takashimizu and Masuda, 2000
Japan (sandsheets in coastal lagoons)	Holocene (~500yr intervals since 7000 yrs BP)	Offshore earthquakes	Up to ~5 m	Sand sheets that extend up to 3 km inland and are preserved in the stratigraphy of coastal lakes. The beds typically grade from coarse to medium sand with clasts to fine sands and silts. Several event layers are compared to a modern tsunami from 1952 that did not breach the barrier indicating that these events are larger than those in documented history.  Signatures: (Nanayama <i>et al.</i> 2003) - graded sands in coastal lakes - mud clasts - marine to brackish diatoms	Nanayama <i>et al.</i> , 2003
Indonesia	Flores 1992 Java 1994	Offshore earthquakes	Up 23 m	Sediments exist as sandsheets with mud-clasts and coralline debris. Second mode of silty material possibly derived from offshore. Particle size analysis identified distinct variations in grain size throughout the deposits indicative of individual waves. Lateral variation indicates that the sandsheets fine landward. (See detailed review in text)  Signatures: Shi <i>et al.</i> 1995, 1996. - graded sands - silty second mode in particle size analysis	Shi <i>et al.</i> , 1995, 1996.
Papua New Guinea	Sissano 1998	Offshore earthquake – slump?	Up to ~15 m	Laterally extensive sand sheet deposited up to 750m inland. Sediments are a mixture of material eroded from offshore, the sand spit and backbarrier. (see detailed review in text).  Signatures – Gelfenbaum and Jaffe, 2003) - sand sheet fines inland - sand dollars (marine organisms) found inland - vertical grading - rip-up clasts	Gelfenbaum and Jaffe 2003, McSaveney <i>et al.</i> , 2000

Table 3.4f – Japan and Indonesia are often subject to repetitive attack by tsunami. Events described in this table and sections 3.11.2, 3.11.4 and 3.13.1 of the text are included because the onshore deposits of these events have been studied in detail. Whilst many tsunami deposits may exist in this region, few have been studied in great detail.

### 3.11 Sediment deposits from modern tsunami

Although research into tsunami deposits has increased rapidly during the last decade (Scheffers and Kelletat, 2003) the relationship between event dynamics and the sedimentology of tsunami deposits is still relatively understudied (Gelfenbaum and Jaffe, 2003). One fundamental reason for this lack of knowledge is that, in a global context, large tsunami are rare events (Dawson, 1999) and as such the study of modern events often relies on opportunistic research when an event occurs. Since 1992 there

have been 11 major tsunamis worldwide. Studies on sediments from some of these events has led to an improved understanding of tsunami inundation and the pattern of sedimentation associated with tsunami deposition, examples include; the Nicaragua tsunami of 1992 (Higman, 2003a,b; Higman and Bourgeois, 2002), the Hokkaido tsunami, Japan (Sato *et al.*, 1995; Nishimura and Miyaji, 1995), and the Flores Island and Java tsunami, Indonesia (Dawson 1994; Shi 1995; Dawson *et al.*, 1996). Presented below are descriptions of several key tsunami events from the 1990's, key not only for their size and effect but the insights gained into the sedimentology of modern tsunami deposits.

### 3.11.1 Nicaragua 1992.

The tsunami from the 1992 Nicaragua earthquake (Figure 3.12) occurred as a single large wave, that deposited several centimetres of sand (Figure 3.13) onshore for several hundred metres at Playa de Popoyo where later reworking of the deposit was possibly limited by a beach ridge and flat topography (Higman and Bourgeois, 2002).

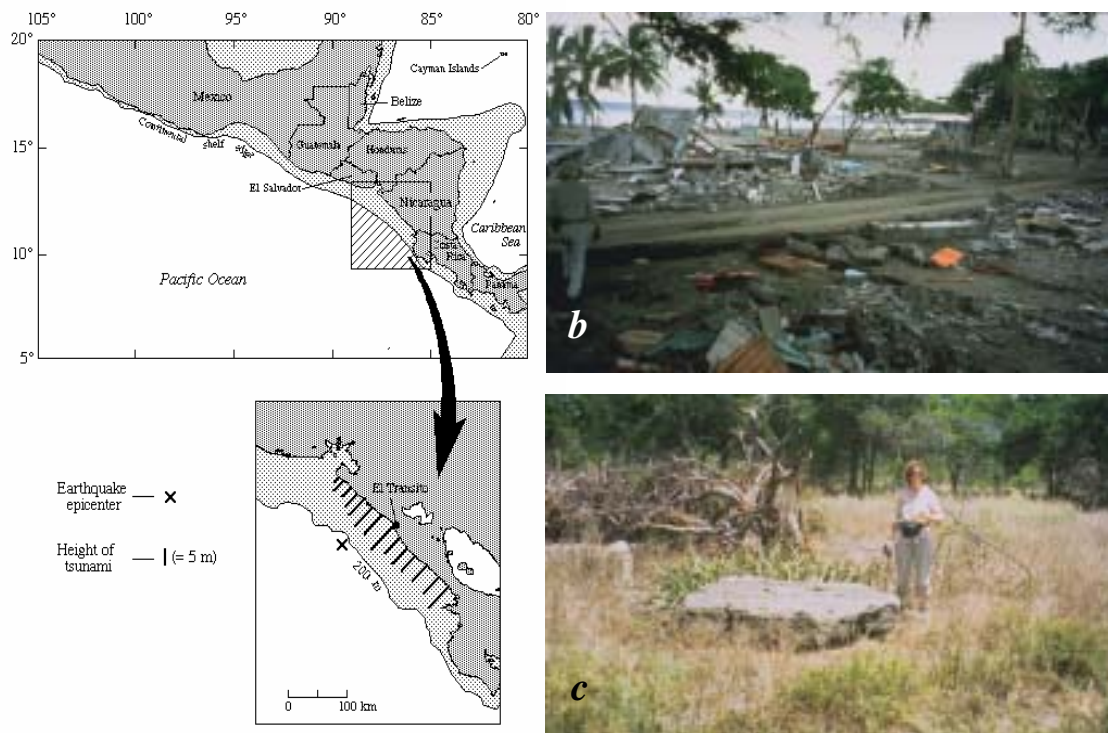


Figure 3.12 Location of Nicaragua tsunami and earthquake on the 2<sup>nd</sup> of September 1992 (Bryant, 2001, p.167). The event inundated many local communities (b) and left 116 dead, 63 missing, and another 489 injured (Incorporated Research Institutions for Seismology, 1993). The event also deposited large boulders (c) and sandsheets several hundred metres inland. A photograph of the sandsheet is presented in Figure 3.13.



Higman and Bourgeois (2003) identified normally graded sandsheets that were sampled to obtain vertically contiguous samples, spaced up to 10 mm, apart which were analysed for their settling velocity distributions. The author identified two layers within the sandsheet with stronger grading occurring in a lower layer than in the upper. This grading pattern is inconsistent with the common explanations of normal grading in a tsunami deposit, where as the tsunami comes onshore sediment settles out of suspension as the energy of the flow wanes (Shi, 1995; Dawson *et al.*, 1996; Goff *et al.*, 2001). Higman (2003) suggested that the inconsistency must be the result of some other process as graded sediments, in particular normal graded sediments, are found in many tsunami deposits (Dawson and Shi, 2000; Goff *et al.* 2001; Gelfenbaun and Jaffe, 2003) but the dynamics of sediment deposition remain poorly understood. The grading pattern in the Nicaraguan deposit may be due to pooling and channelisation where sediments undergo variable transport rates during the turbulence of tsunami inundation and subsequent drainage (Bryant, 2001). Higman (2003a) also suggested that the grading may be due to pressure differences attributed to kinetic sieving or dispersive pressures that would occur in shearing sediment slurry undergoing rapid deposition. The concept of, and relevance of, grading in tsunami deposits is discussed further in Table 3.5.

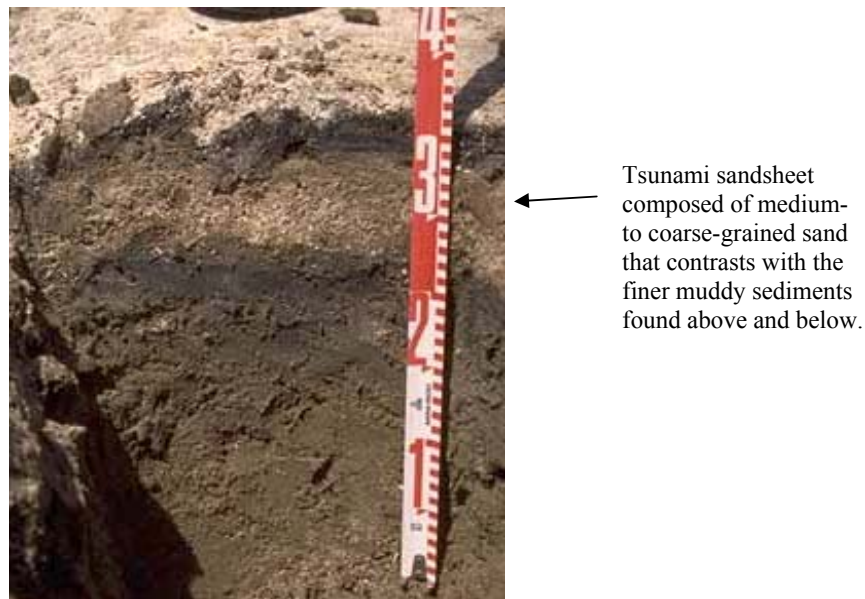


Figure 3.13 Tsunami deposits associated with the 1992 Nicaragua event outlined in Figure 3.12. Note the light coloured marine sand overlying a darker sandy soil. Such direct comparisons can allow the research into the internal sedimentology of the sandsheets. This work assists in developing an understanding of the hydrodynamics associated with these high-energy depositional events (Incorporated Research Institutions for Seismology, 1993).

### 3.11.2 Tsunami sedimentation at Flores 1992 and Java 1994

Looking at the sediments from the two Indonesian tsunami events (Figure 3.14) at Flores 1992 and Java 1994, Shi (1995) proposed that sedimentation rates during a tsunami event would be so high that resultant washover deposits could contain several populations of particles of different sizes (Figure 3.15). The sedimentation process is further complicated by turbulence, the mechanics of rapid sedimentation and the characteristics of individual sediment populations. Sediment deposition is of course, inherently dependent on source area and an adequate sediment supply with general differences in sediment populations attributed to differences in sediments from differing source areas. It is important to note that sediments associated with the two Indonesian events are tropical carbonate-dominated sands, soils and coralline debris with some boulders and, although they provide key information on tsunami sedimentation, they contrast directly with the sediments on the temperate siliclastic southeast Australian coast.

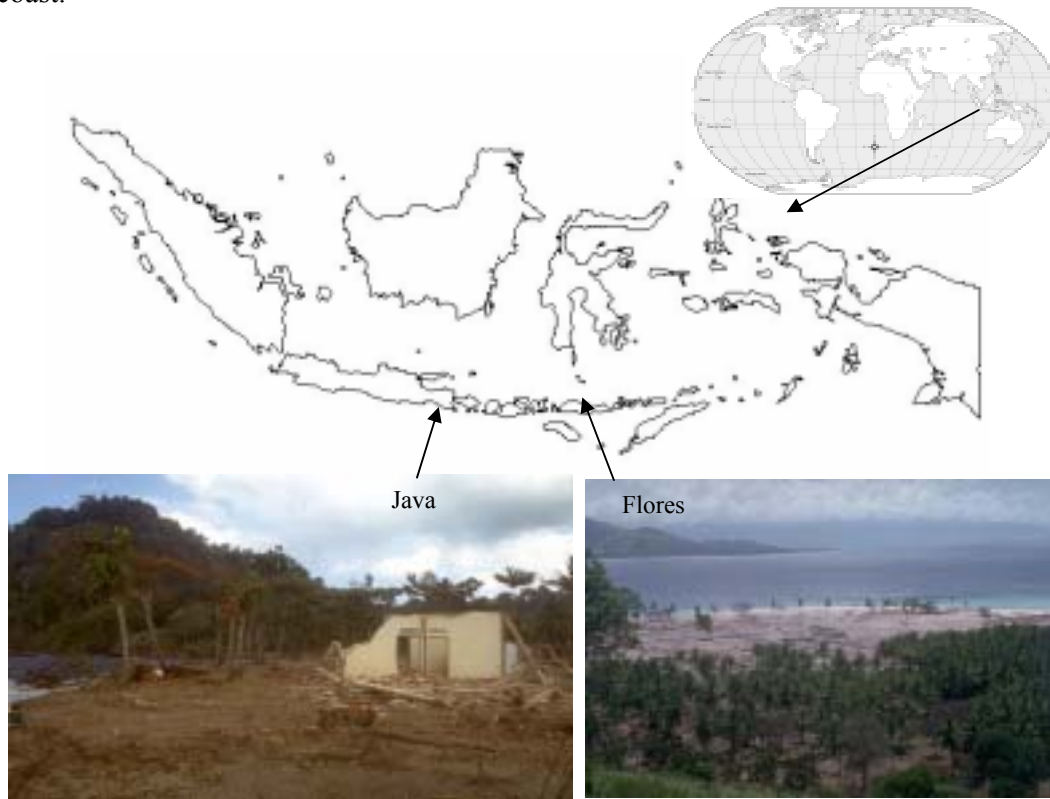


Figure 3.14 Location of Flores and Java in Indonesia. Tsunami caused by offshore earthquakes in 1992 (Flores) and 1994 (Java) caused great damage to coastal communities and left large deposits of sand and coralline debris. These deposits were the focus of a key retrospective sediment study by Shi (1995) who identified several key aspects of tsunami sedimentation.



Figure 3.15 Tsunami deposits at Rajekwesi, Java, from the east Java 1994 tsunami. Extensive parts of the coastal plain were inundated a deposit of marine sand and debris was left up to 300 m inland (a), Photograph (b) shows the sandy tsunami deposit and the underlying mud with the right side of trench inclined in order to show grading. Photographs from Bruce Jaffe (USGS).

### 3.11.3 Hokkaido coast of Japan 1993 and Japan Sea 1983

Nishimura and Miyaji (1995) investigated the sand deposits attributed to the 1993 Hokkaido tsunami and showed, as with other modern examples (Shi, 1995; Dawson *et al.*, 1996; Dawson and Shi, 2000; Gelfenbaum and Jaffe, 2003) the thickness and mean grain sizes of the tsunami deposits decrease with distance from the sea, although at times they can vary greatly across local surface undulations. They also suggested that graded bedding is present in thick tsunami deposits another key feature of tsunami deposits (Dawson, 1999; Goff *et al.*, 2001). Nishimura and Miyaji (1995) also revealed that spatial distribution and lithofacies of new storm surge deposits are significantly different from those of tsunami deposits (see section below on comparative study by Nanayama *et al.*, 2000).

Minoura and Nakaya (1991) studied the deposits laid down by the 1983 Japan Sea tsunami as well as past tsunamis on a coast with abundant sediment sources in the form of coastal dunes and beach ridges. Three different types of tsunami deposits originating from the 1983 tsunami were identified (Figure 3.16):

- Type A: landward transported material from beaches and dunes forming washover fans, which are preserved in the coastal marshes.
- Type B: deposition of beach and dune sand in a lake and erosion of the lagoonal lake bottom causing transport of molluscs from the lake bottom up into shallower environments.

- Type C: earthquake-induced cracks in the beaches and dunes enable incoming seawater brought by the tsunami to rush into the inter-dune ponds, depositing beach and dune sand.

Minoura and Nakaya (1991) concluded that tsunami waves higher than just 1 m were already recorded as type C deposits in the sediments of inter-dune ponds, whereas type A and B sediments are only deposited by larger events.

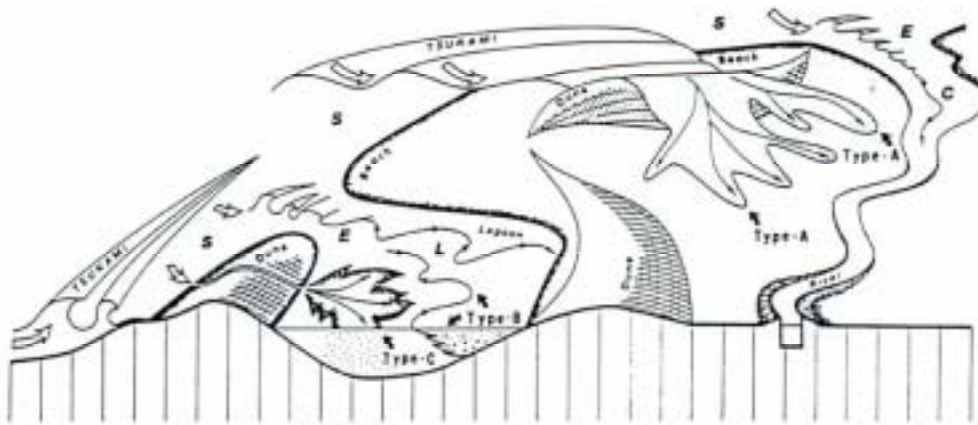


Figure 3.16 - Schematic diagram of three types of tsunami sedimentation attributed to the 1983 Japan Sea tsunami and identified in back barrier environments. The different deposits and their processes are discussed in the text (from Minoura and Nakaya, 1991).

#### 3.11.4 Sissano Lagoon 1998

Studies of the well-documented Sissano lagoon tsunami in Papua New Guinea that occurred on 17 July, 1998 show that the event left a distinct sandy deposit (Figure 3.17) up to 26 cm thick distributed continuously across the coastal plain (Gelfenbaum and Jaffe, 2003).

##### 3.11.3.1 Sedimentary characteristics of the Sissano deposit

The deposit was composed of graded sands dominated by upward-fining sediments suggesting that sediment may have fallen out of suspension before the water retreated. Gelfenbaum and Jaffe (2003) did note that some parts of the deposit show multiple graded beds and rip-up clasts of mud and soil that indicate erosion of the underlying soil and may suggest multiple waves, which eroded onshore soil facies (Figure 3.18). Gelfenbaum and Jaffe also estimated that up to 2/3 of the material in the tsunami deposits are thought to have come from offshore.

### **3.12 Problems associated with differentiating between storm and tsunami deposits in the geological record.**

Well-researched inductive geological investigation of palaeo-overwash deposits requires modern depositional analogs. Most research on overwash deposits has focused on either tsunami or storm deposits but very few have actually compared sites of both storm and tsunami deposition. This is attributed in part to regional focus of event-based research but also to a general lack of research on shorelines where both processes occur with regularity (Goff *et al.* 2004). Broad generalisations can be made about the processes and products of tsunami and storm overwash on a global scale but analysis of regional problems is often hindered by an absence of directly comparable deposits at the same location. In part, out of necessity, this is often overcome by drawing comparisons between studies of sediments attributed to storm and tsunami events from widely separated sites around the world (Gelfenbaum and Jaffe, 2003).

### **3.13 Direct comparison of storm and tsunami deposits**

Four notable exceptions exist (Figure 3.11). The first is the study by Nanayama *et al.* (2000) who compared the sedimentary differences between deposits associated with the 1959 Miyakojima typhoon and the 1993 Hokkaido-nansei-oki tsunami in northern Japan. In the second, Goff *et al.* (2004) studied the 2002 Easter storm in New Zealand and compared them to a tsunami deposit attributed to the 15<sup>th</sup> century Okoropunga tsunami. These studies, along with a third from the northeast coast of the United States by Tuttle *et al.* 2004, are discussed below as they provide directly applicable comparisons between the two processes and provide a key framework for the development of testing criteria.

#### **3.13.1 Comparative studies of storm and tsunami deposits from northeast Japan.**

The study by Nanayama *et al.* (2000) involved a trench survey of both the 1993 tsunami deposits outlined above (Section 3.11.3) and the 1959 storm deposits. The deposits were found to be of similar thickness, decreasing landward from a maximum of about 50 cm. Significant differences between the deposits were noted and the authors recorded four layers in the 1993 deposit, which contain evidence of landward- and seaward-directed flow from two main waves, in direct contrast to the 1959 storm deposits that comprise one layer from a flow that was exclusively landward.



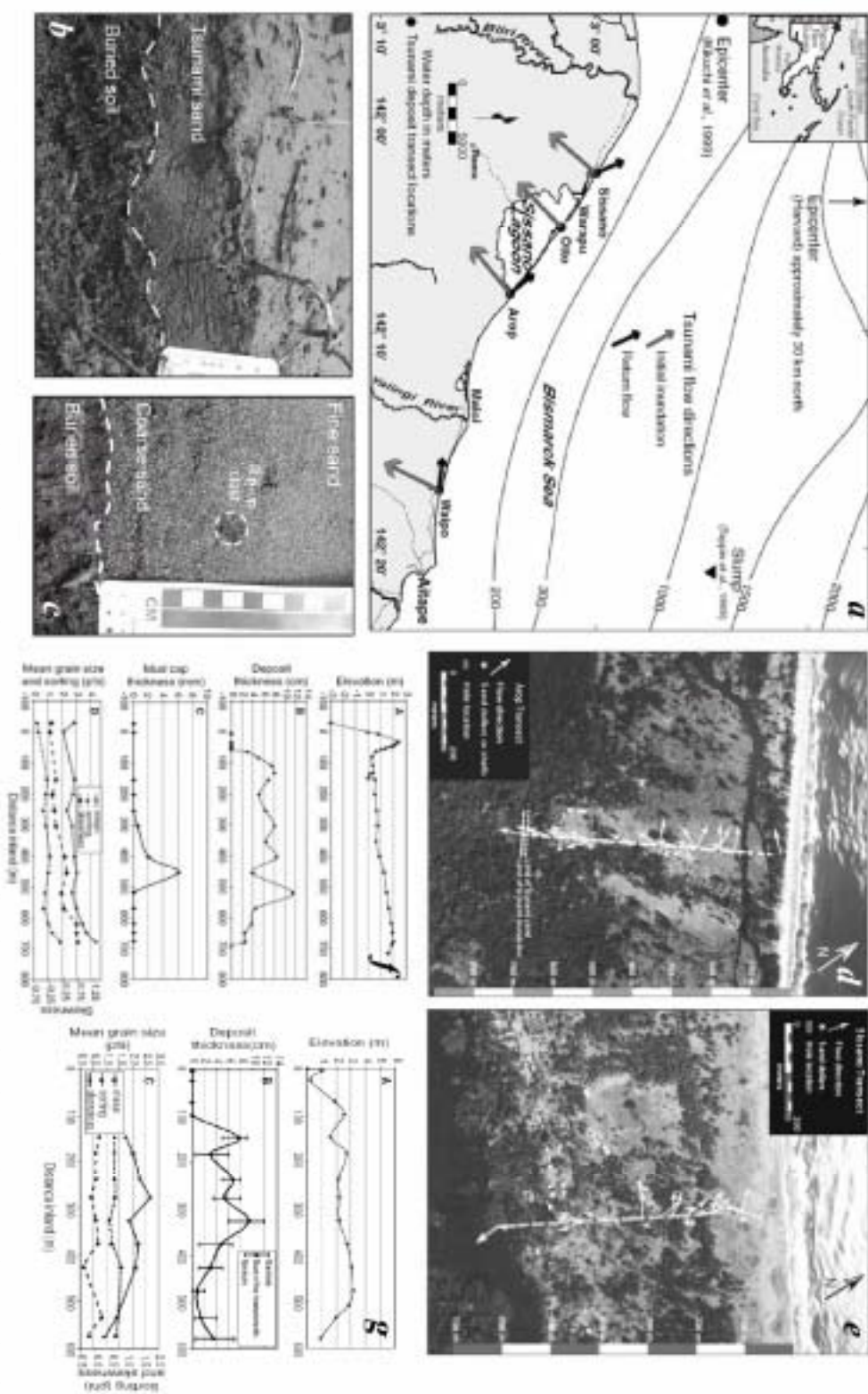


Figure 3.17 a) location of Sissano Lagoon on the northern coast of Papua New Guinea showing flow direction and study sites. b-c) two photographs of the tsunami deposit - note the rip-up clast in (c). d-e aerial photographs of transects at Sissano and Arop indicating flow directions and the presence of sand dollars (indicative of marine sediments). f-g horizontal profiles of elevation, deposit thickness, mud cap thickness (f only) and particle size characteristics from the Sissano and Arop profiles. A well defined landward fining is identified in the Arop transect. (Gelfenbaum and Jaffe, 2003).



the same coast. Firstly the spatial distribution of the storm deposits is less extensive than that of tsunami, not at all homogeneous and appears more greatly affected by onshore undulations in topography. Secondly they concluded that the storm deposits often contain parallel laminar structures and that mean grain size sometimes increases with distance from the sea, although they provided no explanation for this.

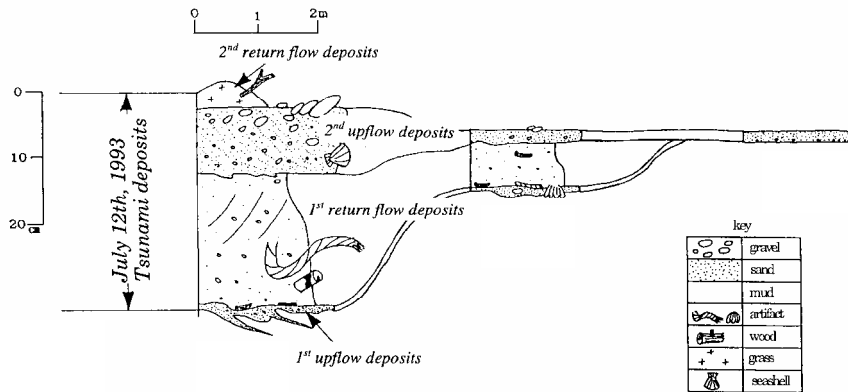


Figure 3.19 – Interpretation of the excavated face presented in Figure 3.18b. Two sets of upflow and backflow deposit are identified. The upflow deposits consist of marine sand and cobbles in contrast to the back flow deposits, which contain significant amounts of soil, stream gravel and debris suggesting terrestrial erosion (Nanayama et al., 2000).

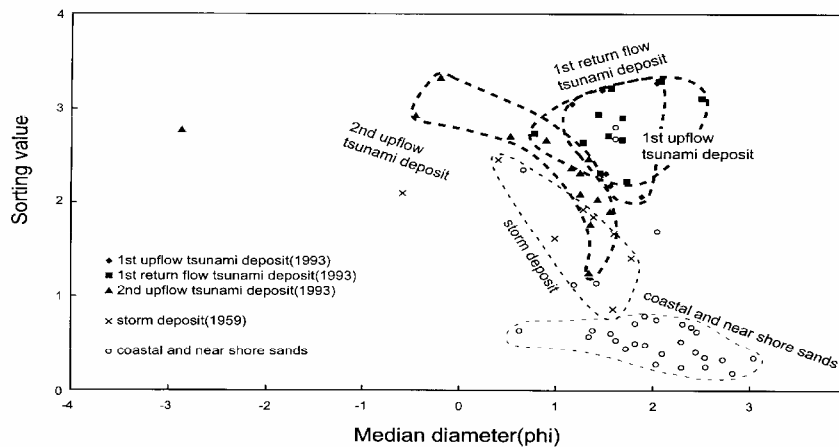


Figure 3.20 - Bivariate plot of sorting and median diameter of 1993 tsunami and 1959 storm deposits. Also presented is the analysis of nearby coastal and nearshore sands. The tsunami deposits exhibit significantly greater sorting values than the storm deposit and coastal sands. The tsunami deposits are considered to be more poorly sorted (Nanayama et al., 2000).

This study highlighted several key differential criteria for tsunami and storm deposits; firstly that tsunami deposits are often the result of bi-directional flow and contain both nearshore and shallow marine sediments attributed to landward flow along with terrestrial material that can be attributed to backflow. These characteristics contrast directly with storm deposits which have unidirectional flow and contain predominantly nearshore marine material often in the form of parallel laminar beds with foreset beds



representative of landward accretion during successive overwash of storm waves. The authors also indicated that the tsunami deposit exhibited significantly poorer sorting values than the storm deposit or coastal sediments (Figure 3.20)

### 3.13.2 The 1929 Grand Banks earthquake and tsunami compared with the 1991 storms on the northeastern US coast

Tuttle *et al.* (2004) compared the tsunami deposits thought to be related to the November 18, 1929 'Grand Banks' earthquake with washover deposits related to the storm of October 30-31, 1991, suggesting that they fundamentally differ in their sedimentary characteristics and positions on the landscape.

#### 3.13.2.1 The 1991 storm deposit

The 1991 storm washover deposits (Figure 3.21) consist of interbedded and laminated coarse-, medium-, and fine-grained sand, exhibiting delta foreset stratification and subhorizontal, planar stratification with channels (Tuttle *et al.*, 2004).

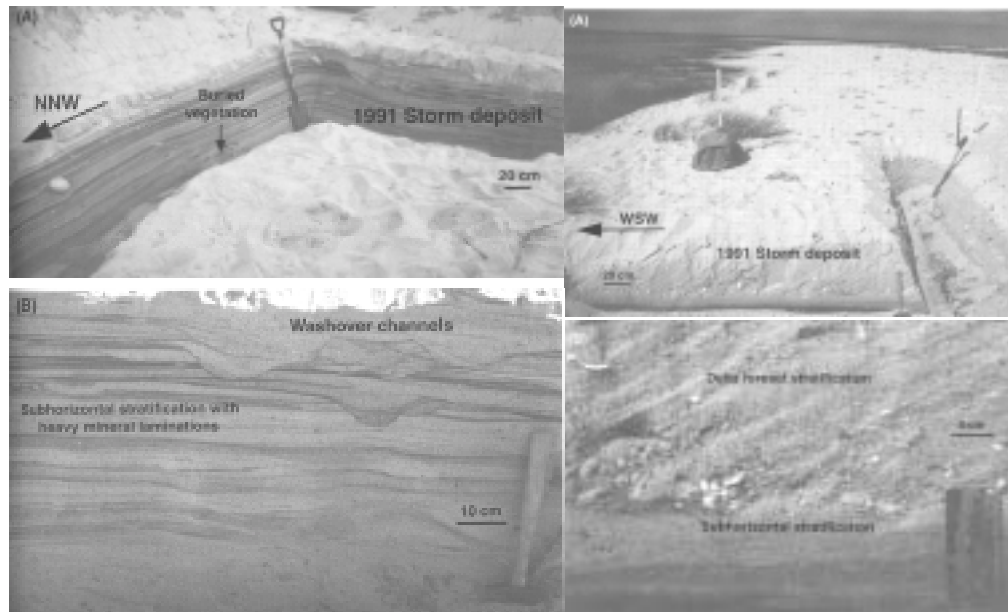


Figure 3.21 - 1991 storm deposit from Marthas Vineyard northwestern United States. The deposits exist as a) interbedded, laminated fine- to coarse-grained sand. The heavy minerals in the lithology accentuate the laminated appearance. Some deposits b) exhibited two layers in the storm deposit, a lower laminated layer and an upper layer exhibiting foreset cross-bedding that are most likely representative of terrestrial and subaqueous deposition respectively (Tuttle *et al.*, 2004).

Significant differences also exist with regard to landscape position. The tsunami deposits occur at the landward extent of tidal ponds and up to 340 m inland. One deposit

reaches a height in excess 6 m above mean sea level, as well as 3 m above the tops of the barrier-beach bars and related dunes. In contrast the storm washover deposits occur up to 94 m inland and only exist immediately landward of barrier-beach bars and in adjacent tidal ponds to maximum levels of 1.2 m above mean sea level. At no time do they exceed the elevation of the barrier-beach bars (Tuttle *et al.* 2004).

### 3.13.2.2 The 1929 tsunami deposit

A sandsheet found in the upper fill of a marsh at Taylor's Bay on the Burin Peninsula, Newfoundland, indicates that the 1929 tsunami had deposited sediment some 300 m inland, and laterally over ~400 m to an elevation ~7 m above mean sea level (McAdoo, 2003). No systematic variations in the thickness of the deposit were found and the deposit ranged from traces of sand to over 25 cm thick. Sediment samples were obtained over a 10 m grid and results indicate a fining of the sediment landward, consistent with results from some other tsunami-lain sands (Dawson *et al.*, 1996; Goff *et al.*, 2001). Furthermore, Tuttle *et al.*, (2004) indicated that the sediments of the 1929 tsunami deposits are composed of 1 to 3 subunits of massive to fining-upward, very coarse- to fine-grained sand (Figure 3.22).

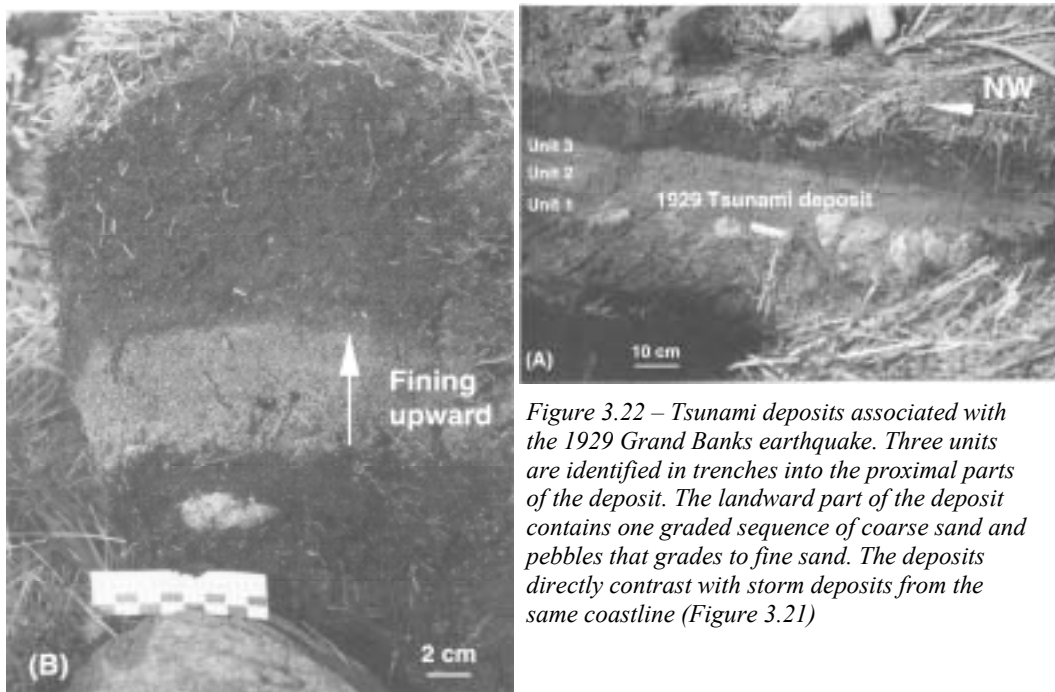


Figure 3.22 – Tsunami deposits associated with the 1929 Grand Banks earthquake. Three units are identified in trenches into the proximal parts of the deposit. The landward part of the deposit contains one graded sequence of coarse sand and pebbles that grades to fine sand. The deposits directly contrast with storm deposits from the same coastline (Figure 3.21)

### 3.13.3 Sedimentary differences between a recent storm and the 15th-century tsunami from southeastern North Island, New Zealand.

Goff *et al.* (2004) compared a deposit attributed to a 15th-century tsunami with the Easter 2002 storm deposits on the southeast of the North Island of New Zealand (Figures 3.23 and 3.24). They identified considerable contrasts including local extent, thickness, and grain size characteristics. The study was limited by the coarseness of both deposits which prohibited useful micropalaeontological and geochemical comparisons outlined in Goff *et al.* (2001). The study by Goff *et al.* (2004) is directly comparable to the present study in that both studies are located on high-energy coasts where micropalaeontological and geochemical investigations of deposits yield little differentiation.

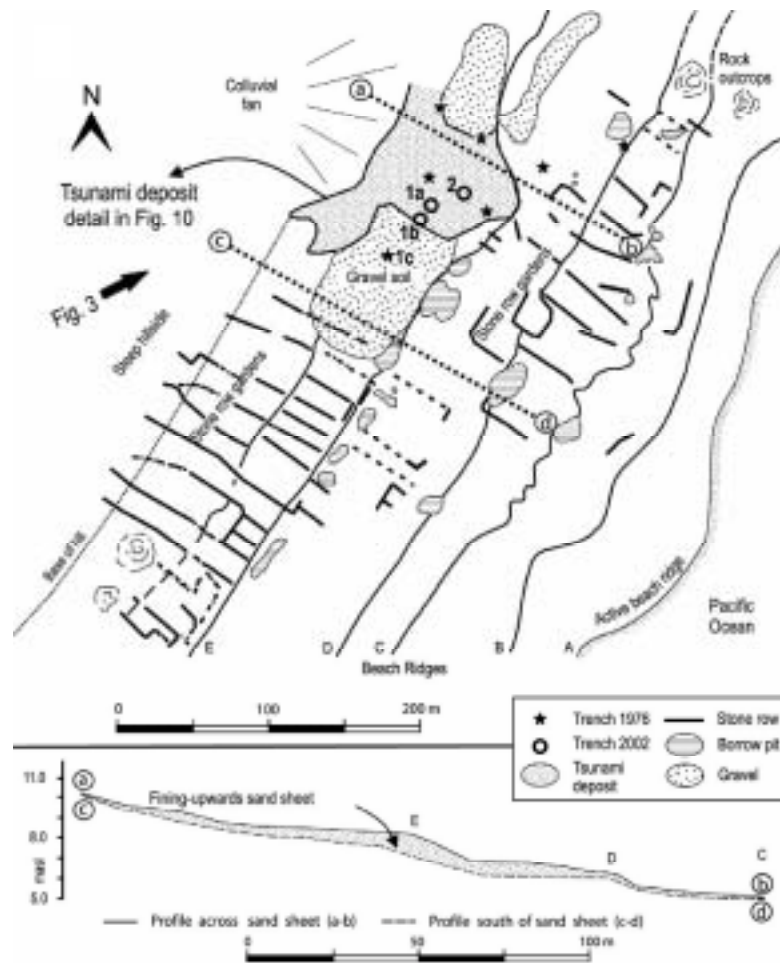


Figure 2.23 - Map of the Okoropunga study site of Goff *et al.* (2004) on southeastern side of the North Island of New Zealand showing the mapped 15<sup>th</sup> century tsunami deposit. The elevations recorded along Profiles a-b and c-d are shown at the bottom of the figure and extend the tsunami deposit as far as beach ridge C.

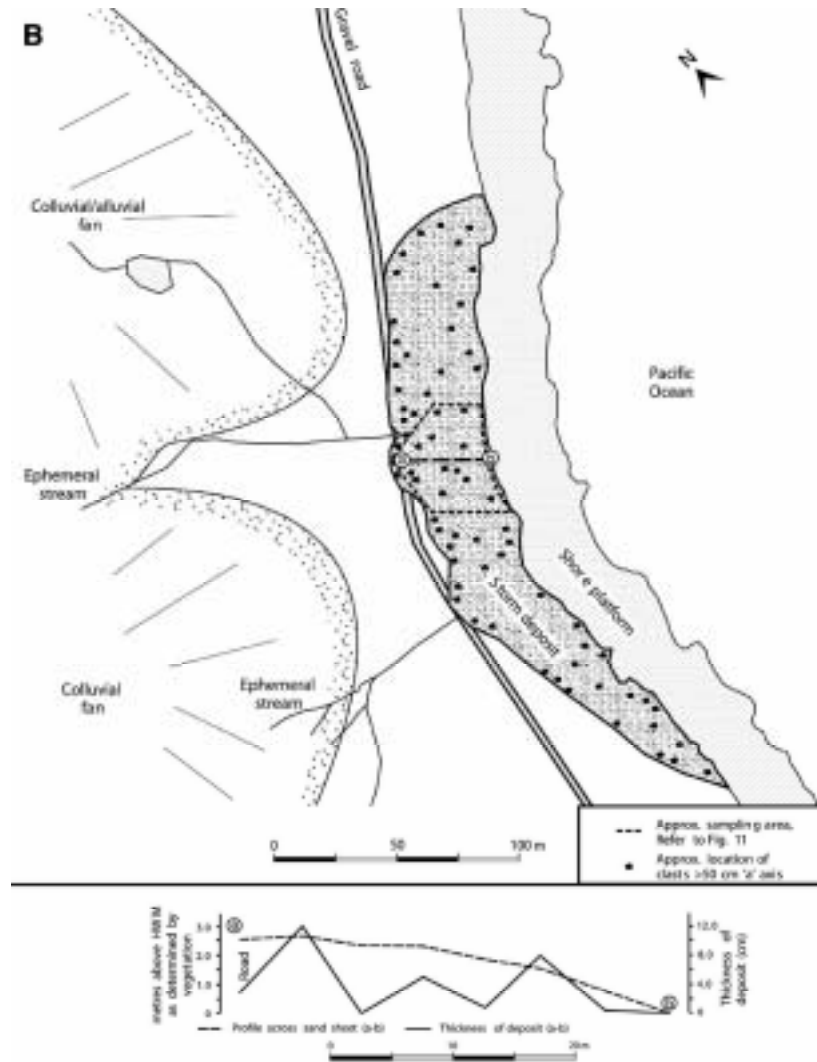


Figure 3.24 - A storm deposit at Toi Bay on the southeastern coast of North Island of New Zealand showing the extent of the mapped storm deposit and the surrounding geomorphological features. Deposit thickness and elevation changes along Profile a-b are given at the bottom of the figure.

### 3.13.3.1 Sedimentology of the 15th-century tsunami deposit.

The sandsheet attributed to the 15<sup>th</sup> century tsunami covers more than a hectare, is up to 70 cm thick, and has a minimum volume of at least 4000 m<sup>3</sup> (Goff *et al.* 2004). The sheet rises up to 10.5 m above present sea level where it pinches out, and extends up to 250 m inland from the present beach, and 200 m inland from beach ridge C, which was the shoreline at the time of deposition (Figure. 3.24).

The deposit was identified by McFadgen (1980), and has only recently been attributed to tsunami (Goff and McFadgen, 2001). The deposit thins abruptly at the margins, fines

inland (Figure 3.25) and silt rip-up clasts comprising material from the underlying compact silty-sand are identified where the marked lateral thinning of the deposit began. The grain size distributions of the tsunami contrast distinctly with the confining units. The overlying gravel has distinct bimodal distribution, however the authors attributed this to anthropogenic mixing of sediments during prehistoric times (Goff *et al.* 2004)

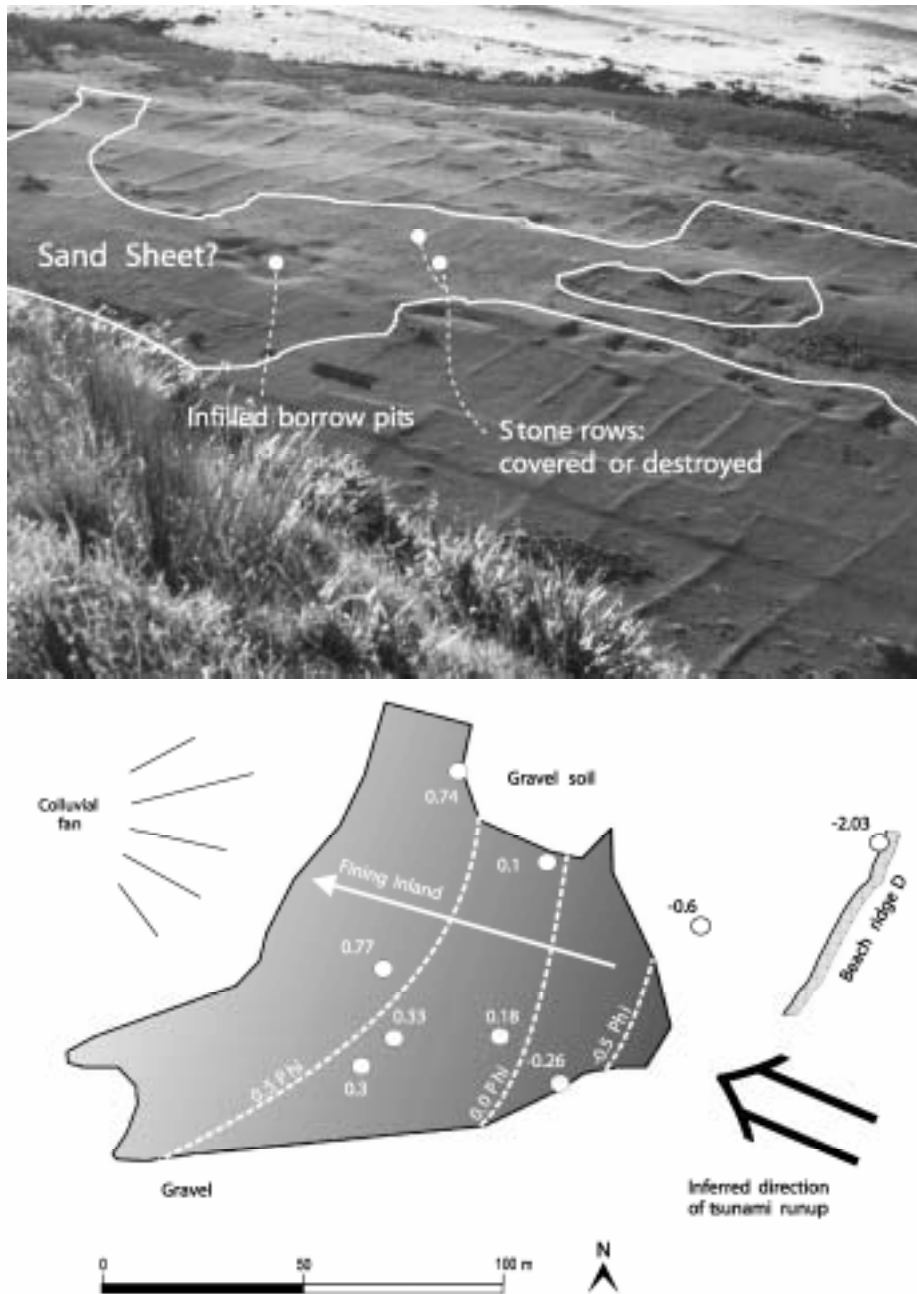


Figure 3.25 - a) Oblique photograph of Okoropunga (Figure 3.23) showing the inferred extent of the tsunami deposit (sandsheet) and the associated archaeological features (Goff *et al.*, 2004). b) Schematic of grain size variation across the tsunami deposit. The deposit is noted to fine significantly in a landward direction.

### 3.13.3.2 Easter 2002 storm deposit.

The storm deposit was investigated along a 40 m transect perpendicular to the shore in the middle of the deposit, plus a series of shore normal transects of variable length at ~5 m intervals from 5 to 35 m inland (Goff *et al.*, 2004).

Cobble- and boulder-sized clasts were found scattered across the depositional surface and appear contemporaneous with a coarse sand veneer that overlies crushed vegetation. The coarse sand is less voluminous (~250 m<sup>3</sup>) than the tsunami deposit, varied in thickness from 0-12 cm and covers a maximum of area 5000 m<sup>2</sup>. Crushed vegetation and inundation of the coastal road indicate the recent deposition of these sediments.

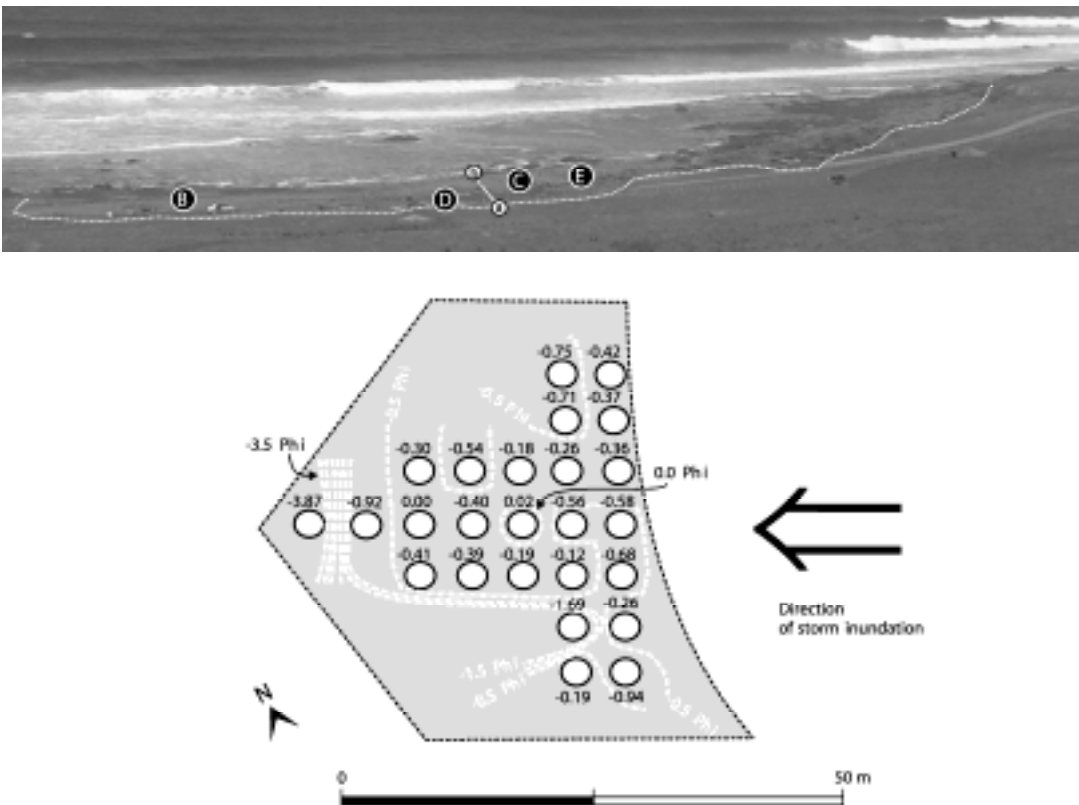


Figure 3.26 - Toi Bay storm deposit (Figure 3.24). (a) Oblique aerial photograph of inundation area indicating extent of storm deposit (vehicle near centre-left of photo for scale). (b) Variations in mean grain size for the Toi Bay storm deposit contoured at 0.5 phi intervals. The deposit appears to coarsen significantly at the margins.

Goff *et al.* (2004) found that the tsunami deposit thins abruptly at the margins and fines inland in direct contrast to the storm deposit, which exhibited highly variable characteristics including a marked coarsening at its landward extent (Figure 3.26). Sediment characterisation through grain size analysis showed that the storm deposit was



slightly better sorted and coarser than the tsunami deposit (Figure 3.27b) although the authors suggested that the coarser grain size may be a product of differential sampling rather than a genuine indicator of wave energy.

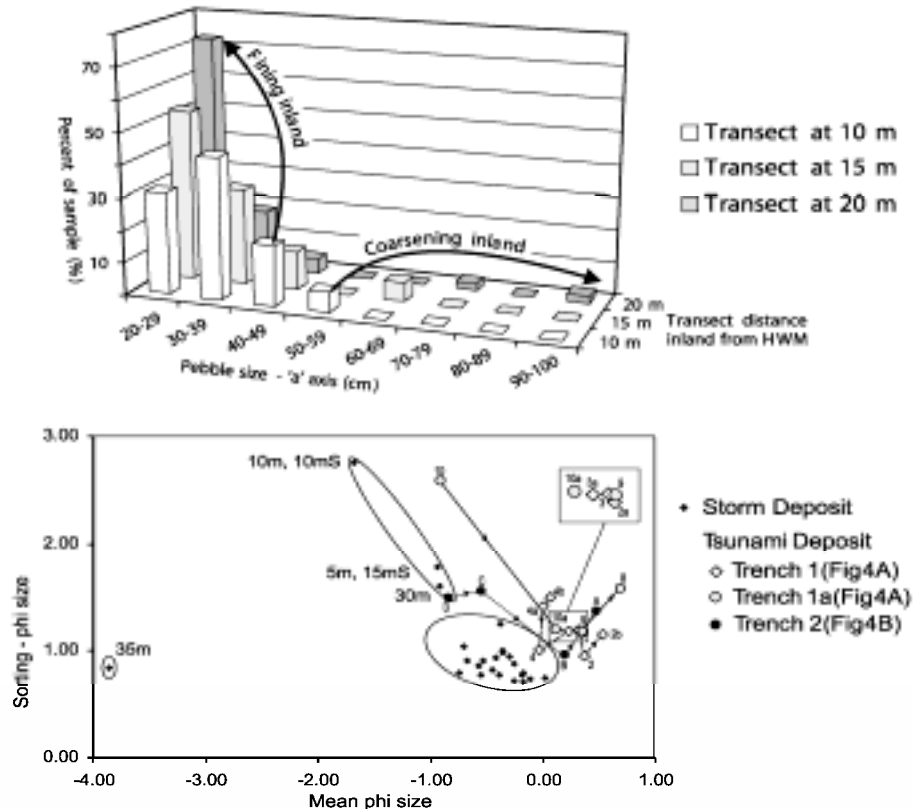


Figure 3.27 a) Toi Bay storm deposit (Figure 3.24) showing pebble measurements taken along three transects (20 m long: extending 10 m north and south perpendicular to the central transect a- b. b) Bivariate plot of mean grain size against standard deviation for tsunami and storm deposits (based upon Tanner, 1991 and Luque et al., 2002). Arrowed lines indicate the progression of samples in each set from the lower to upper sections of the tsunami deposit. The tsunami deposit is far more poorly sorted than the storm deposit.

As with examples from Indonesia (Shi, 1995) and Japan (Nishimura and Miyaji, 1995) poorer sorting was found in the tsunami deposit and is thought to reflect the wider range of grain sizes entrained by the tsunami both on land and offshore. Comparative differences in the inundation characteristics of both events were also reflected in the contrast between the sharp contact for the storm deposit and the erosional contact and entrainment of rip-up clasts for the tsunami deposit.

### 3.13.4 Storm and tsunami deposits from Martinhal Portugal

Kortekaas (2002) identified a series of sandy lenses in the fill of a lowland swamp on the southwestern coast of Portugal. The lenses are attributed to the 1755 Lisbon

earthquake tsunami and a post-tsunami storm event (Figure 3.28). Significant contrasts exist in the sedimentology of the two deposits, in particular the tsunami deposit appears to be much more poorly sorted than the overlying storm deposit (Figure 3.29). Kortekaas (2002) suggested significantly different (higher) sorting values and the presence of large boulders and rip-up clasts of mud within the tsunami deposit, allowed differentiation between the deposits.



Figure 3.28 – Photo of trench at Martinhal in southwestern Portugal. Unit 2 is interpreted as a result of the 1755 Lisbon earthquake. The unit contains a boulder and four fining upward sequences. Directly overlying this unit is a well-sorted sand layer (Unit 1) which is attributed to storm deposition and can be seen wedging out within the trench.

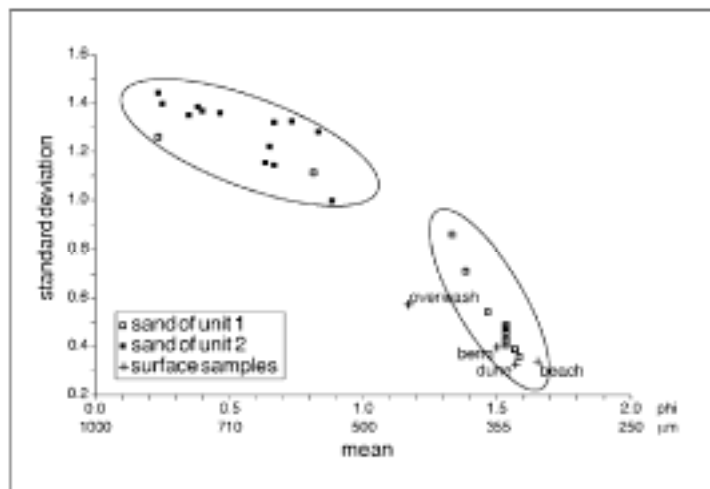


Figure 3.29 – Mean grain size plotted against the standard deviation for the two sand layers, recent beach, berm, dune and overwash deposits in a core from Martinhal in southwestern Portugal. Unit 1 is interpreted as the result of storm overwash and unit 2 is attributed to the 1755 Lisbon earthquake and tsunami. Note that the tsunami deposit is more poorly sorted than the storm deposit.



### 3.13.5 Comparison of storm and tsunami deposits

The set-up, hydraulics and sedimentary features of storm and tsunami deposits remain poorly understood. This understanding can only be furthered through the detailed analysis of modern tsunami and storm deposits. Tsunami sedimentation and erosion are inherently complex processes and the characteristics of a tsunami deposit are highly dependent on the available source material and the energy and run-up of the waves.

There is no globally applicable tsunami criteria or fingerprint (Kortekaas, 2002). What can be compiled for the many deposits attributed to tsunami is a suite of sedimentary features (Table 3.5), often called signatures (Bryant, 2001; Kortekass, 2002; Goff *et al.*, 2001, 2004). Often, as outlined below, these features are not genuinely signatures of tsunami but are more likely to be indicative of inundation of oceanic water and marine sediment. Palaeowashover deposits may be attributed to an event type through careful analysis of spatial features such as the elevation, lateral extent and run-up of the deposit along with sedimentary features such as internal grading, the presence of intraclasts, and particle size distribution. These analyses when combined may lead to a suite of evidence that can point to storm or tsunami as the likely depositional agent. This review indicates however that many of these signature characteristics of tsunami are equivocal. Generally most of the signatures only indicate the marine origin of the deposit and hence storm surges and even sea level change or regional subsidence may show similar characteristics.

Recent work by Kortekaas (2002), Felton and Crook (2003) and Switzer (2004) have recognized the equivocal nature of many so called tsunami signatures. This stated there remain many cases in the literature where a tsunami origin is stated with little consideration given to alternative interpretations such as exceptionally large storms.

Although work continues on the differences between tsunami and storm deposits and their preservation in the geological record much uncertainty and conjecture remains. This review has focused on sites where tsunami and storm deposits are directly compared with the aim of deciphering criteria for the analysis of elevated deposits of unknown origin.

Tsunami signatures	Discussion
Deposit is usually identified as a thin anomalous lenses of sediment composed of marine material from the nearshore or coastal zone	Thin lenses of marine sediment can also be attributed to storm surge and in rare cases aeolian deflation of dunes. Deposits are often attributed to tsunami by their spatial distribution and position in the landscape. Thick, volumous lenses of marine sediment in low energy environments such as back-barrier lagoons may be attributed to tsunami if they are found to extend more than 500 m from the coast. In contrast with tsunami deposits storm deposits rarely extend more than 500 m inland (~500 m is approximately the maximum deposition of a storm deposited sandsheet recorded in the literature).
Generally deposits fine and become thinner inland.	Landward fining is generally indicative of a marine origin rather than a fluvial origin. In addition to landward fining, most washover deposits thin inland, a characteristic that is thought to be indicative of decreasing wave energy away from the sea. This characteristic is found in both tsunami and storm deposits and should not be considered diagnostic for either process
Lower contact is unconformable or erosional	Tsunami deposits are often recorded as significantly erosional as they strike the coast. This is supported by the presence of intraclasts of the underlying material within the lower parts of the deposit. The majority of literature on storm deposits indicates that storm washover is generally depositional with little erosion. It is very rare to find intraclasts in a storm deposit; hence intraclasts may be used as circumstantial evidence for tsunami inundation.
Graded bedding within the deposit.	Recent literature indicates that the presence or absence of graded beds in a tsunami deposit is something that requires significant re-evaluation. Originally many tsunami deposits were identified as containing graded beds that exhibited fining up sequences indicative of each wave of a tsunami train. Recent studies indicate that bedding in modern tsunami deposits often contains a mixture of normal or reverse graded beds that can range from several centimetres to ~1 m thick. It also noted that often massive bedding with little structure is found in tsunami deposits. Storm deposits are usually composed of many thin laterally extensive near-horizontal bedforms. The absence of the complex bedding associated with tsunami events could be considered diagnostic of storm deposition associated with repeated inundation by individual washover pulses.
Increase in marine diatoms.	The presence of marine diatoms or mixed assemblages is indicative of a marine origin for the deposit. Both storms and tsunami are capable of transporting marine diatoms during washover events. The presence of broken or fractured diatoms is indicative of high energy, although further investigation is needed before broken or marine diatoms can be used as a distinguishing criterion for tsunami.
Marine microfauna including Foraminifera and Ostracoda.	The analysis and identification of marine microfaunal assemblages has been used as evidence for storm and tsunami deposition. Future investigation of this technique may yield a distinguishable criterion if statistically significant differences in assemblages can be attributed to each event. Until this is resolved the presence of marine microfauna can only be used to indicate a marine incursion and should not be considered as indicative of either event type.
Geochemical signatures	Increases in the elemental concentration of sodium, sulphate, chlorine, calcium and magnesium have been recorded in washover deposits attributed to tsunami in New Zealand. This change in geochemistry is indicative of inundation by seawater. It cannot be used as indicative of either storm or tsunami deposition.
Shells and shell-rich sand deposits	Marine macrofauna (shells) are once again indicative of marine origin of the sediment. The presence of shelly beds in both storm and tsunami deposits once again suggests that shelly lenses or shelly-sand deposits are not diagnostic of either event. It may be possible to attribute shelly lenses to tsunami if the shell assemblage is such that it comes from a source not affected by the action of storm events.
Bi-modal particle size distributions	Particle size analysis that identifies a bimodal distribution can, in the most elemental sense, indicate the presence of sediments from two different sources. It can be said that generally storm deposits (particularly washover sand deposits) have uni-modal particle size distributions. Studies of modern tsunami deposits indicate that these deposits are often bi-modal, with a second sediment population derived from offshore (fine sediments) or backwash (coarse sediments). Bi-modal poorly sorted sediments may be indicative of tsunami deposition.
Generally poorly sorted and can contain material indicative of many sources	Generally tsunami deposits tend to be much more poorly sorted than storm deposits. This signature should however be treated with caution as tsunami and storm deposits are both a product of their source. It is logical to conclude that a poorly sorted source would generate a poorly sorted deposit.

Table 3.5 - List of tsunami ‘signatures’ identified in the literature covered in this review. It is apparent that many of these signatures are equivocal and are merely indicators of marine inundation. Signatures such as the presence of marine shells, foraminifers, diatoms or anomalies in geochemistry provide excellent evidence of marine inundation but should not be used to differentiate storm or tsunami deposition as they are indicative of both processes.

### **3.14 Synthesis**

Sandsheets found in back-barrier environments are generally the product of relative sea level change or overwash deposition. Differentiating between those attributed to sea level change and those produced by washover activity is often relatively easy if undertaken on a regional scale. Deposits that are the result of transgression due to relative sea-level change do not have a directional component and are hence fundamentally different in spatial distribution and occurrence to those of storm or tsunami deposits.

Washover deposits are the result of disequilibrium events and are best recorded in environments where washover deposits exhibit maximum differentiation from normal coastal processes. Where recorded in the sedimentological record of coastal embayments these deposits may provide palaeoreconstruction potential for the study of washover through prehistoric timeframes.

At first glance the most recognisable geological record of washover deposition occurs as boulder deposits on rocky platforms. Although striking these deposits are difficult to interpret due to a lack of well-defined depositional criteria developed from event based comparisons (Felton and Crook, 2002). Washover sandsheets are the most popular medium for the study of washover deposition by both storm and tsunami. In direct contrast to the analysis of boulders, the study of fine sediment sheets (usually sand) is well advanced and numerous modern analogs exist. The analysis of storm deposits and many modern and palaeo-tsunami deposits has led to key insights into the study of the sedimentary characteristics washover deposits (Table 3.5).

Of particular interest is the direct comparison of storm and tsunami deposited sand sheets from coastlines affected by both types of event. These studies are based on modern examples and provide key information for the differentiation between deposits from storms and those deposited by tsunami. A differential criteria based on global research into both types of deposit is presented in Table 3.6 and forms the basis of this research. The basic premise is to define internal sedimentological characteristics and mineralogical differences that can be used to distinguish between overwash deposits from storms and tsunami.

Diagnostic criteria	Storm deposits	Tsunami deposits
Contact with underlying sediments	Sharp contact non-erosional. Deposits drape existing landforms and are less erosional	Sharp often erosional contact with eroded clasts incorporated into the lower parts of the deposit. Some material may be 'rafted' and appear in the upper layers of the deposit
Source sediments	Mainly nearshore material. Washover sandsheets dominated by beach and nearshore sand	Wide range of material from inner shelf to terrestrial debris. Extensive erosion by the event allows incorporation of material from a wide variety of landforms.
Sorting	Generally poor to moderately sorted material with a uni-modal particle size distribution.	Poorly sorted sand, clasts and debris often bi-modal in particle size distribution.
Graded beds	Thin (<3 cm) laminae with foreset or tabular bedding defining landward accretion.	Thick (>5 cm) often chaotic beds sometimes graded. Sediments can appear as massive, laminated, normally or reverse graded beds.
Flow direction	Unidirectional landward flow. Generally little terrestrial material is included in the deposit	Bi-directional flow with backflow deposits that contain terrestrial material.

Table 3.6 – Generalised sedimentological differences between sandsheets attributed to storm and tsunami deposition. The identification of these diagnostic criteria are inherently related to regional differences in source area that is directly related the energy regime and sedimentation in the coastal zone.

### 3.15 Conclusions

- Sandsheets that are the result of overwash deposition are characteristically different from those attributed to relative sea level change due to an inherent directional component that is often easily identified in a regional context. The sandsheets investigated in this project are orientated from east to southeast and no similar deposits exist in a northeast orientation.
- Boulder deposits found on rocky coasts can provide striking evidence of overwash events. Without detailed knowledge of fabric analysis and well-developed facies models for high-energy events on these coasts, such deposits give equivocal results and often remain undifferentiable in many cases.
- Sandsheets found in low energy back-barrier environments are often indicative of washover deposition by storm surge, waves or tsunami. Differentiating between these deposits in geological sequences can only be accomplished by developing well-defined facies models using mineralogy and sedimentological features from deposits of known origins.

- Many global examples of washover sand deposits attributed to storm and tsunami exist. Tsunami signatures identified in the literature can often be interpreted as purely indicating marine inundation. Recent research into modern tsunami and storm events has provided several key identifiable features (Table 3.6) for tsunami deposits that may allow the investigation of older sequences to be less complicated.
- The southeast Australian coast lacks historical evidence for large tsunami and no modern tsunami deposits exist along this coast. In the absence of a modern tsunami deposit the deposits investigated in this study are compared to global examples and the criteria defined in the text of this chapter along with comparison to the modern storm deposits studied in Chapter 6.

## **Chapter 4**

### **Evidence for Quaternary tsunami events from the southeast Australian coast: a critique and review.**

This chapter reviews evidence for Quaternary tsunami inundation reported from the southeast Australian coast. Much of this research has been of a geomorphic nature and until recently has focused on geomorphic forms and processes (Switzer *et al.* in press). The following text contains a review and re-analysis of many of the cited features using multiple hypotheses for deposition. The new analysis focuses on two site-specific debates. It is apparent from many study sites on the southeast Australian coast that some features may require further analysis as the initial study appears complicated by a lack of modern analogs and relevant facies models (Felton and Crook, 2003). In particular results indicate that boulder deposits and sculptured bedrock, although compelling can often yield equivocal results. In many cases an argument can be built that a deposit is at least in part attributed to tsunami but may also be partially or completely due to preferential weathering and other coastal processes such as large prehistoric storms or long term accretion and biological processes involved with erosion.

This thesis relates to sedimentary evidence from sandsheets in estuaries and contrasts directly with much of the research presented in the monograph of Bryant (2001). Sand sheets are mentioned in the text of Bryant (2001) but much of the focus is on the presence of large clasts or ‘floaters’ along with the occurrence of elevated sand and shell beds. In contrast to the early studies, this study compares the internal facies and stratigraphy of the deposits in this project to two modern storm deposits from the same coast highlighting differences between the deposits. The study then compares the deposits to washover sediments in a global context with the aim of deciphering possible depositional scenarios.

#### **4.1 Early work on tsunami evidence from the southeast Australian coast**

Initial evidence for tsunami activity on the southeast coast of Australia came from two papers (Bryant, 2001). The first by Young and Bryant (1992), focused on boulder deposits from rock ramps on the far south coast of New South Wales in which the authors attributed several large rock accumulations on coastal ramps to a tsunami possibly coincidental with the Pleistocene tsunami of 105 ka identified by Moore and

Moore (1984) in Lanai, Hawaii. This hypothesis was challenged by (Jones, 1992) who showed that such an event in the Hawaiian Islands would reach Australian east coast with little possibility of catastrophic effects. Bryant, (2001) clarifies the age of the event, suggesting the deposits are much younger. A second paper by Bryant and Young (1992) furthered the tsunami hypothesis with more boulder evidence from a number of sites (Figure 4.1) and introduced chenier ridges, bi-modal shelly sand deposits, and sandsheets as evidence for tsunami inundation.

Many papers followed throughout the 1990's with three major publications by Bryant *et al.* (1996), Bryant and Young (1996) and Young *et al.* (1996) describing a broad spectrum of evidence for Quaternary tsunami activity along the southeast coast of Australia. This published evidence was reviewed in a paper by Bryant and Nott (2001) and a monograph by Bryant (2001).

#### **4.2 Reviews of a recent summary monograph (Bryant, 2001)**

The monograph by Bryant (2001) received mixed and often negative reviews. Some debate centered on the structure of the book, a lack of evidence of peer review and the referencing style adopted for the text, in particular the “departure from scholarly norms” (Felton and Crook, 2003). Many tsunami specialists and geophysicists were critical of parts of the monograph often suggesting that peer review of several key elements of the book are required to justify some of the speculative hypotheses forwarded in the text. An early review by Synolakis and Fryer (2001) was particularly critical of the book, citing problems with discussions on tsunami wave dynamics, historical evidence, inaccuracies in the text and the use of tide gauges as key flaws in the book. Similar critical reviews followed by Dengler (2002) and Curtis (2002). Both authors highlighted inaccuracies and flaws within the text. Although critical in its context a detailed review by Satake (2002) provides encouragement and indicated that the author looks forward to a revised and more authoritative second edition that is supported by peer reviewed research. Further reviews such as that of Dawson (2003) also supported large portions of the monograph and suggested that further research and peer review of new research and speculative hypotheses may result in an authoritative second edition.



Figure 4.1 a) and b) map of locations on the southeast Australian coast mentioned in this review. Study sites for this study are also identified.

For the most part these reviews suggest that in part the material from the southeast coast of Australia to which this text has set out to review provides some promise for future work. The reviews (both good and, bad) highlight several key research questions that must be answered before many of the tsunami signatures, described in the research of Bryant and Nott (2001) and Bryant (2001), can be more commonly accepted or rejected. Firstly research into these features must make reference to a detailed sea-level history for the area in question as many ‘raised’ features such as beach deposits, shore platforms and cobble mounds may be attributed to former fluctuations in sea level. If sea level can be discarded as a possible source of these features, it must be described in



a regional sense as many regions have complex sea level histories that inevitably affect the geomorphic expression of a coast. In this project the probability of attributing the sand sheets to sea level change is dismissed due to sedimentological differences and spatial variation along the coast.

Secondly hypotheses forwarded as tsunami formed features must be tied directly to modern examples. Chapter 3 reviewed the characteristics of many modern and ancient sedimentary deposits attributed to modern tsunami. Geomorphic and sedimentary features such as cobble mounds, bedrock erosion, clast transport and imbrication remain poorly understood and the use of these features as tsunami signatures requires detailed facies analysis and comparison with modern analogs. Imbricated boulder piles and significant bedrock erosion have been cited by Bryant (2001), Bryant *et al.* (1992, 1996) and Young and Bryant (1992) as features of tsunami deposits but little peer-reviewed material is available that provides unequivocal evidence of these features from modern tsunami events.

#### **4.2.1 Historical evidence for tsunami on the southeast Australian coast.**

Australia is an island continent and the likelihood of tsunami striking the coast over long time scales is very high. Tsunami by their nature can travel over thousands of kilometres with little net loss of potential power. An excellent example is the Alaskan earthquake that caused a tsunami that devastated parts of coastal Japan a distance of more than 1800 km (Satake *et al.*, 1996). The problem in Australia is that the historical record is not very long and does not contain very large events. The largest tsunami measured on the Sydney tide gauge had a height of only 1.07 m. It was generated by the Arica, Chile, earthquake of 10 May 1877. The Chilean tsunami of 22 May 1960 measured less than 0.8 m on this gauge, but is thought to have produced run up of 4.5 m above sea level along some parts of the coast (Bryant, 2001). The event caused damage in harbours in Newcastle, Eden (run-up of 2.5m) and Sydney. The following article appeared in the Brisbane Courier Mail on 25 May 1960 and describes the damage in Sydney harbour:

“In Sydney Harbour freak currents tore away moored boats and upset shipping. The huge tide tore from their moorings about 30 launches and small craft and two barges at The Spit. Barges were swirled in among drifting launches, overturning several of them and damaging

others. One of the barges smashed into the Spit Bridge. As many as 800 logs were set adrift from moorings at Balmain shipping yard, which were then swept down the Parramatta River. A strip 100 yards by 60 yards wide was swept away from Clontarf Reserve Point Park, exposing a high tension submarine cable”.

### 4.3 Tsunami signatures from the southeast coast

The monograph of Bryant (2001) and a review paper of Bryant and Nott (2001) summarised much of the geological evidence for tsunami from the Australian southeast and northwestern coastlines. In particular, much of this material comes from the previously published geomorphic evidence for large-scale overwash by late Holocene tsunami that had been presented from the Australian southeast coast (Figure 4.1) by Bryant *et al.* (1992, 1996), Young *et al.* (1997), Bryant and Nott (2001) and Bryant (2001). Bryant *et al.* (1996) and Bryant and Nott (2001) presented four broad signatures (Figure 4.2) of these tsunami: erosional bedrock sculpturing, imbricated boulders, constructional features such as mounds of sand and cobbles in sheltered embayments, and uncemented clastic deposits including extensive chaotic sandsheets. Much of this evidence comes from geomorphic studies of coastal beach ridges, rock platforms, cliffs and dunes.

Further complications arise from the analysis of boulder deposits such as the study of Young *et al.* (1996). Although these deposits provide compelling evidence for large-scale movement by oceanic events, it is impossible to definitively attribute a single depositional mechanism to these deposits. The analysis is complicated by two limitations. Firstly a general lack of facies models for rocky shorelines has been identified by Felton (2002) and Felton and Crook (2003). Secondly it is impossible to attribute these deposits to a unique event. One cannot definitively state that the boulders are purely the result of tsunami washover. It is likely that both storm and tsunami may play a role in the development of the high-level boulder beds and the degree to which these events and the number of events (steps) in movement are not definable. A recent publication by Noormets *et al.* (2004) on megaclast (boulder) transport in the Hawaiian islands suggests that some of the boulders were possibly detached by tsunami and have subsequently been moved by storm and/or tsunami.

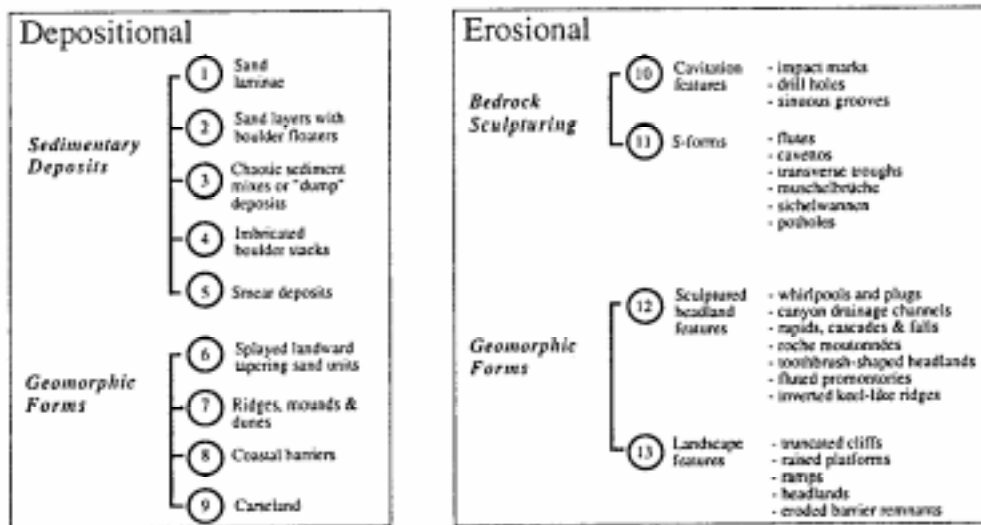


Figure 4.2 Depositional and erosional signatures of tsunami identified on the Australian coastline. The text of this chapter reviews several key signatures and re-examines three examples (from Bryant and Nott, 2001)

Evidence for tsunami based on geomorphic signatures identified along the southeastern Australian coast has been widely published (Bryant *et al.*, 1992, 1996; Young and Bryant, 1992; Young *et al.*, 1996; Bryant and Young, 1996) and can be classified as either depositional or erosional (Figure 4.2). Singly or in combination, they allude to the presence of large tsunami (Bryant and Nott, 2001).

The Bryant and Nott (2001) subdivided the identified depositional signatures into sedimentary deposits and geomorphic forms. The sedimentary deposits, except for imbricated boulders, are less dramatic because they do not form prominent features in the landscape (see section 3.9 for discussion). Bryant *et al.* (1996) and Bryant and Nott (2001) suggested that sand laminae and sand layers containing boulders are buried beneath the surface are evidence for tsunami but provide few examples in the literature.

#### 4.4 Depositional evidence

Over the last 15 years Bryant and others have presented a broad range of geomorphic forms they describe as depositional signatures. Two geomorphic forms that stand out are term chaotic 'dump' deposits and imbricated boulder piles (Figure 4.2). The most dramatic deposits attributed to mega-tsunami are large boulders piled up to 30m above sea level. These piles take many forms, but include boulders up to 106 m<sup>3</sup> in volume

and weighing as much as 286 tonnes (Figure 4.3). These boulders are imbricated and stacked on top of each other in parallel lines at various locations along the east coast of Australia (Young *et al.*, 1996; Nott, 1997; Bryant and Nott, 2001).



Figure 4.3 Large boulder deposit at Gum Getters Inlet (person for scale) on the southeast coast near Jervis Bay. This entire boulders assemblage was interpreted as being emplaced by tsunami by Bryant *et al.*, (1996). Some boulders such as those circled in blue appear to be recent rock falls. Figure 4.9 shows modern blocky erosion in this area and alternative hypotheses for the genesis of this deposit.

#### 4.5 Erosional evidence

Published literature from the southeast Australian coast also suggests that mega-tsunami can be identified by their large- and small-scale erosional signatures sculptured into bedrock at two scales (Young and Bryant, 1992; Bryant and Young, 1996; Bryant *et al.*, 1996). It is important to note that these features are still to be described for tsunami prone areas and that this evidence has met with considerable skepticism in the past.

Bryant *et al.* (1996) presented several large-scale features that dominate headlands. These features, outlined in Figure 4.4, are hypothesised to be the result of the effects of gravity, flow concentration or jetting, erosive channelisation that produce linear canyon features 2–7 m deep, and pool-and-cascade features incised into resistant bedrock on the lee side of steep headlands. Many rock shelves on the southeast Australian coast look like an inverted toothbrush and Bryant and Nott, (2001) suggested that this is the result of large scale erosion by very high velocity water jets generated by tsunami. Young *et*

*al.* (1996) and Bryant (2001) also point to keel like structures (Figure 4.5) as evidence for large-scale erosion by tsunami.

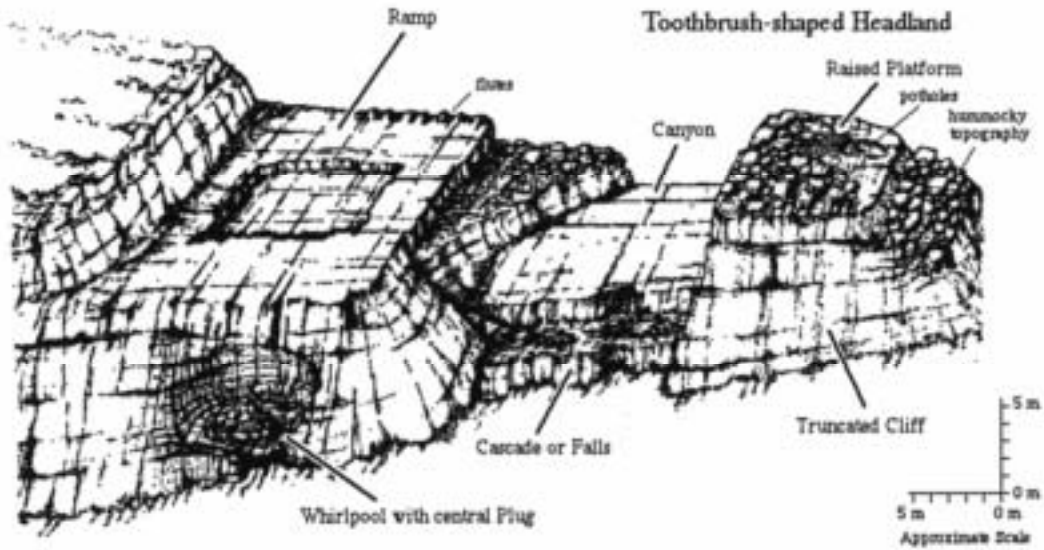


Figure 4.4 Schematic diagram of headland representative of those from the southeast Australian coast. Large-scale bedrock sculpturing as interpreted by Bryant and Young (1996) with some smaller scaled features superimposed (drawing from Bryant and Nott, 2001).



Figure 4.5 Inverted keel-like forms at Cathedral Rocks. The stacks are hypothesized by Bryant and Young (1996) and Bryant and Nott, (2001) as either the plugs of bedrock left in the centre of circular vortices or remnants of promontories streamlined by the flow (photograph from Bryant and Nott, 2001).

Perhaps the most controversial erosional feature attributed to tsunami or mega-tsunami are whirlpools formed in bedrock (Figure 4.4) on the sides of headlands (see Section 4.8). These features are by described in detail by Bryant and Young (1996) and Bryant (2001). The features contain a central plug of rock and show evidence of smaller vortices around their rim. The hydrodynamics producing such features are analogous to flow in tornadoes. To be formed in one event such features would require exceptionally high velocities that can only be induced by extremely high-energy events.

#### **4.6 Two examples attributed to tsunami**

Two examples of deposits and geomorphic forms attributed to tsunami are re-evaluated in the following sections. The first pertains to a series of accretionary beach ridges (cheniers) and the possible genesis of these forms by late Holocene tsunami. The second considers and reevaluates boulder accumulations found on the exposed headland of Little Beecroft Head and a rock platform within the shelter of Jervis bay at Greenfield Beach. The deposits are studied with reference to the coastal stratigraphy indicating that they many of the clasts (boulders) have been moved in a landward direction.

##### **4.6.1 Storms, chenier ridges, tsunami or a combination: Cullendulla Creek, Batemans Bay**

The contemporary morphology of Cullendulla Creek is presented in Figure 4.6 where a chenier beach-ridge/estuarine wetland system is observed in the lower catchment. The chenier/beach ridge sequence onlaps a bedrock catchment of Ordovician sediments consisting of siltstone, claystone, sandstone, quartzite and chert found on the western side of Cullendulla Creek within the beach ridge and wetland system, and the metamorphic Wagonga Beds consisting of siliceous and carbonaceous cherts with abundant quartz veins, on Square Head. Cullendulla Creek drains a small catchment and enters Batemans Bay through a small channel confined against Square Head (Figure 4.6)

The cheniers are long, low (3 m to 6 m high) narrow beach ridges formed roughly parallel to the shoreline. Cheniers are differentiated from other beach ridges by the material they overlie. Cheniers overlie estuarine muds, contrasting with beach ridges that overlie sandy sequences. A chenier plain represents multiple episodes of recurring ridge and mudflat formation on prograding shore sectors (Otvos, 2000). Under this definition at least two semiparallel chenier

ridges or ridge sets, sandwiched between tidal-subtidal mudflats, must be present (Otvos and Price, 1979). Nine ridges are identified in the Cullendulla Creek system. Although the whole sequence is interpreted as a chenier ridge sequence (Donner and Junger, 1981; Thom *et al.*, 1981, 1986) only the most northerly (6 - 9 in Figure 4.6) ridges are cheniers by definition as the seaward ridges overlie sands and are thus considered beach ridges.

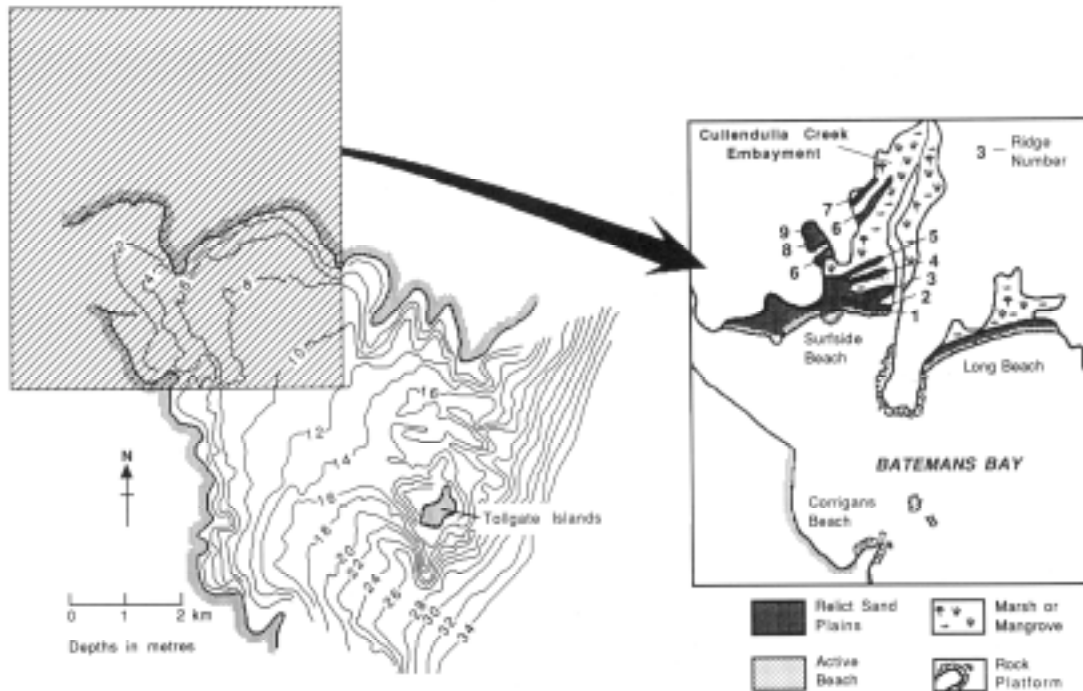


Figure 4.6 Bathymetry map of Batemans Bay and location of the Cullendulla Creek embayment. The morphology of the embayment is outlined in the inset. Nine chenier and beach ridges are identified. Ridges 6 to 9 are cheniers and 1 to 5 are beach ridges. The genesis of the ridge sequence is debated by Bryant *et al.* (1992) and Thom *et al.* (1986) who attributed them to tsunami and long-term accretion respectively.

At present the most seaward ridge is showing evidence of progressive erosion and overtopping by waves (WBM Oceanics, 1999). The supply of sand the contemporary beach system is probably dependent on a combination of intense flood events and wave-induced current circulation. Flood sediments from the Clyde River accumulate offshore from the present beach and are reworked by currents and waves and deposited onto into the beach systems. A report by WBM Oceanics (1999) suggested that when the nearshore zone is depleted of sand, increased wave attack and erosion by overtopping and/or movement of the beach sand offshore to the depleted zone might occur.

#### 4.6.1.1 Evolution of the chenier/beach ridge plain

A complete understanding of the evolution of the Cullendulla system will only be achieved through a detailed sedimentological study of their sedimentary characteristics.



Initial studies by Donner and Junger (1981), Thom *et al.* (1981, 1986), Bryant *et al.* (1992) and Bryant (2001) all show inconsistencies in stratigraphy and interpretation. The study by Thom *et al.* (1986) supported the earlier work of Donner and Junger (1981) that suggested the embayment was a chenier ridge plain. The prograded nature of the deposits was demonstrated by Thom *et al.* 1981 and Donner and Junger (1981) who presented a series of radiocarbon dates that showed a poorly defined decrease in age in a seaward direction (Figure 4.7).

#### 4.6.1.2 The tsunami hypothesis of Bryant *et al.* 1992

Work by Bryant *et al.* (1992) provided chronological evidence of mixed dates obtained from sediment and shells collected from the beach/chenier ridge system (Figure 4.7). The dating program included thermoluminescence dates along with conventional radiocarbon on shelly fauna. The presence of young dates in the landward ridges was interpreted by Bryant *et al.* (1992) as evidence for deposition by tsunami. Furthermore this hypothesis was extended in the monograph of Bryant (2001) who suggested that the ridge system is evidence that ‘tsunami have deposited chenier-like ridge and banks in this sheltered reentrant’ (Bryant, 2001, p73) citing the convoluted nature of the bedrock embayment and the sheltered nature of the bay.

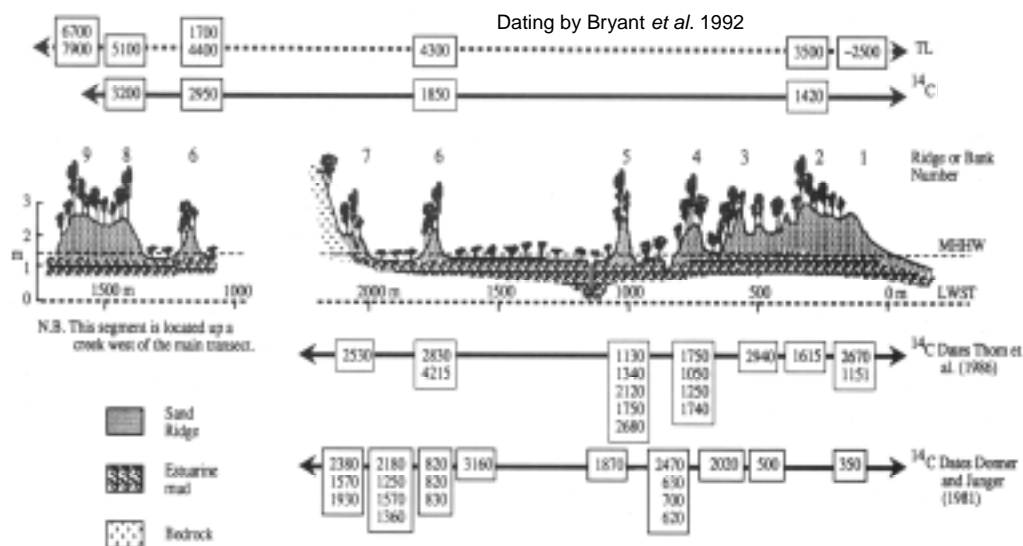


Figure 4.7 Schematic cross-section of the chenier and beach ridge plain of Cullendulla inlet (Bryant, 2001). The dating of the deposits provides a fragmented history of deposition throughout the Holocene and the general trend of landward increase in ages is indicative of the prograded nature of the ridge sequence. The mixture of old and young dates in many parts of the sequence is problematic. It is possible that reworking of the system by large-scale washover, as suggested by Bryant *et al.* (1992) and Bryant (2001), has modified the ridge sequence.



#### **4.6.1.3 Washover of a chenier/beach ridge complex**

Washover of the chenier/beach ridge system by tsunami or exceptionally large storms may explain the mixed dating results obtained from sediments in the sequence. The low lying ridges (<3 m) of the prograded sequence could have easily been overwashed incorporating younger sediments into the upper fill of the system. This will only be resolved after detailed study of the stratigraphy of the sequence. Although many dates have been obtained from this sequence the dating and depositional history of this embayment remains unresolved. Significant limitations exist in both dating programs as the majority of radiocarbon dates were obtained from shell hash and small bivalves. The mixed dating may be a product of the shell hash dating although this was not been discussed by Thom *et al.* (1981). It is also worth noting that the TL dating technique requires well-bleached sediments to obtain reliable dates. Considerable uncertainty exists in the bleaching capability of washover deposits and this may contribute to the mixed dating results identified by Bryant *et al.* (1992).

Without detailed sedimentological study it is difficult to comment on the nature of any overwash sediments. It is likely that a tsunami event would have flattened the seaward ridges and caused significant modification to the system, a feature not well-defined by the cross-sections of Bryant *et al.* (1992) or Thom *et al.* (1981). Investigation of this deposit using techniques and criteria developed in this deposit may clarify this debate in the future.

#### **4.6.2 Boulder deposits from Greenfields Beach and Little Beecroft Head, Jervis Bay**

Several large accumulations of boulders are found on coastal rock platforms and ramps in the Jervis Bay region of southeastern Australia. These deposits are elevated above sea-level and in many places consist of imbricated boulders of varied size. Two sites are presented here, the first occurs within the relative shelter of Jervis Bay at Greenfields Beach and the second on the more exposed parts of the coast at Little Beecroft Peninsula. The Greenfields beach site is a small shallow dipping rock ramp with elevated boulders some 7 m above contemporary sea level. This deposit contrasts directly with boulders on top of Little Beecroft Peninsula that exist up to 30 m above sea-level. In both cases the boulders are erosional remnants of the local pebbly

sandstone stratigraphy. Some boulders at both sites exhibit obvious signs of imbrication as a response to flow in a landward direction whilst other larger clasts appear characteristic of fallen blocks with no hydraulic reworking. Young *et al.* (1996) and Bryant *et al.* (1997) have attributed boulders at both sites to tsunami. These deposits, although compelling, require further investigation before tsunami can be invoked as the depositional mechanism. As discussed in the following text the presence of imbricated boulders is not diagnostic of tsunami but merely indicative of landward flow. It is also noted that in many cases rockfalls on this steep coast may appear in imbricated states.



Figure 4.8 Location of Little Beecroft Head and Greenfields Beach in the Jervis Bay region. Little Beecroft Head is a dramatic cliffed coastline (Figure 4.9) that is open to consistent high-energy waves and contrasts directly with the Greenfields Beach site that has the morphology of a shallow dipping shore platform (Figure 4.10) and lies within the shelter of Jervis Bay.

#### 4.6.2.1 Methodology used in this study

Boulders at both sites were measured for dimension, orientation and lithology and compared to the local stratigraphy. Supplementary notes were also taken on: grain size, imbrication, dip direction, jointing, cross-bedding, bioturbation and relative size and

abundance of lichens. These features were used as indicators of boulder source and for signs of transport and direction.

#### 4.6.2.2 Modern erosion at Little Beecroft Head and Greenfields Beach

Modern erosion at both Little Beecroft Head and Greenfields Beach is best described as blocky erosion along joint lines in the shallow dipping strata (Figures 4.9 and 4.10). The blocky nature of the erosion results in large accumulations of boulders that are found along the shoreline around Little Beecroft Head and Gum Getters Inlet (Figure 4.3).

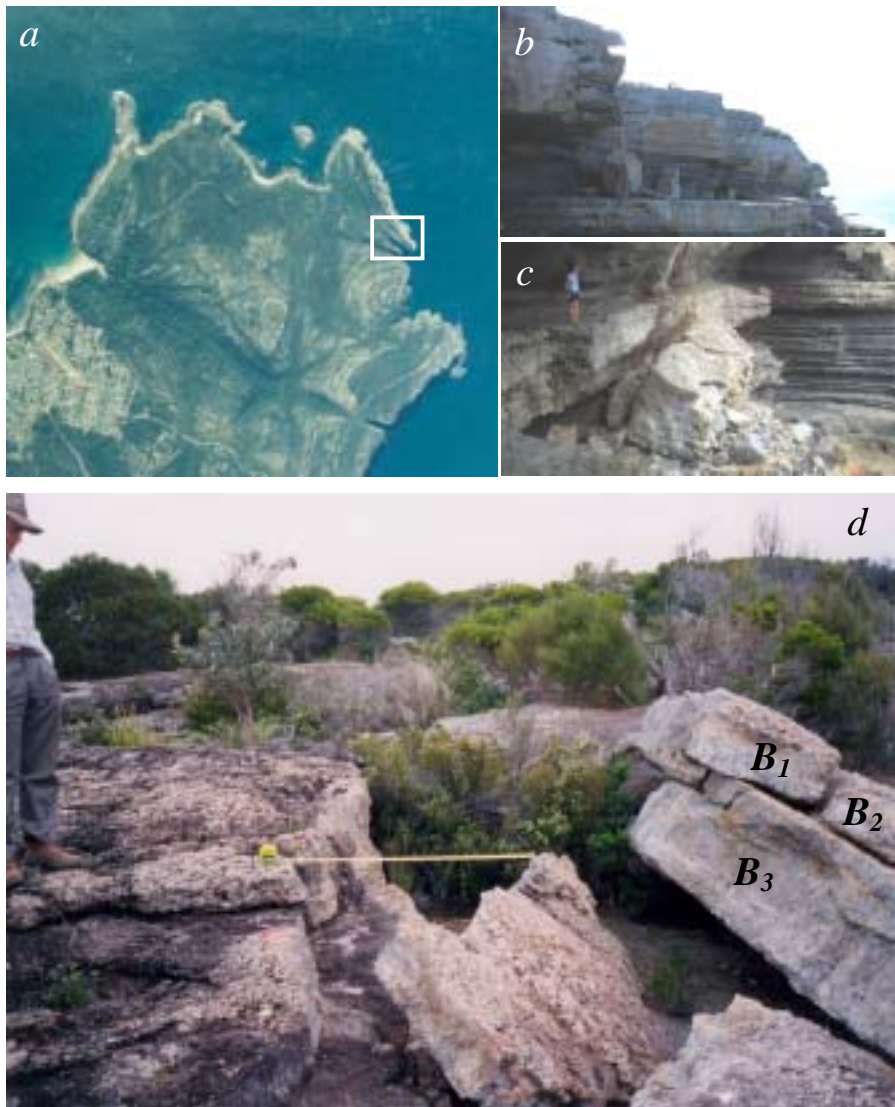


Figure 4.9 a) Aerial photograph of Beecroft Head showing the exposed nature of the coast and the location of Little Beecroft Head. The blocky nature of modern erosion on the steep cliffed environments at Little Beecroft Head. Such erosion can create very large boulders (b and c). It is important to note the dipping nature of the eroded blocks (d) as it is likely that subsequent erosion and the sliding of blocks marked B1, B2 and B3 would give a imbricated nature to the deposit (see below).

The high-energy shoreline of the Little Beecroft Head is characterised by steep cliffs and rock falls that topple periodically to the rock platforms or sea below (Figure 4.9b). This shoreline contrasts with that occurring at the low energy site of Greenfields Beach (Figure 4.10b) where modern erosion on a gently dipping rock ramp leads to the formation of numerous eroded blocks over time.



*Figure 4.10 Boulder accumulations on the rock platform south of Greenfields Beach. The blocky nature of modern erosion is clearly visible along joint lines in the pebbly sandstone. Some boulders, including the one the author is standing next to, appear anomalous.*

#### **4.6.2.3 Imbricated boulder accumulations at Little Beecroft Head and Greenfields beach their physical characteristics.**

Several boulders accumulations exist at both sites that exhibit obvious signs of imbrication or considerable movement. Although many boulder piles and individual boulders exist on top of Little Beecroft Head (see below) only three main sites are presented here. Examination of the stratigraphy interpreted by Tye (1995) suggests that many of the boulders are likely to be remnants of the formerly overlying lithology (Appendix 2). Two lithologies of boulder were found on top of Little Beecroft Head. One of these lithologies is found in both the underlying and overlying stratigraphy, the other lithology a quartz rich sand with larger gravel clasts is not found below.

Reconnaissance of the large headlands to the south of Little Beecroft Head show many randomly orientated boulders that exist as eroded remnants of the formerly overlying stratigraphy. The first boulder site presented here lies at an elevation of approximately 30 m on the southeastern end of the headland. Here two small detached boulders are found that exhibit clear signs of transport (Figure 4.11). One boulder weighing just over 1 tonnes rests on a smaller boulder and the detachment site is interpreted as being approximately 3 m to the southeast.

The second site on Little Beecroft Head consists of one large boulder that rests across a large prominent joint in the platform (Figure 4.12). This boulder is the largest on the platform and weighs more than 22 tonnes. Young *et al.* (1996) and Bryant, (2001) suggested that this boulder was emplaced by a Holocene tsunami where they cited its different lithology, elevation and irregular contact as evidence for transport from lower in the cliff sequence. Analysis of the stratigraphy of Tye (1995) indicates that the pebbly lithology of the boulder suggests that it is more likely to be an erosional remnant of the coarser overlying stratigraphy (now eroded) than the finer sequences below. The heavily bioturbated sandstone block appears to have been transported as it rests across a prominent joint. Analysis of jointing through the block shows that it is rotated approximately 55° to the jointing in the surface below. It is impossible to say whether its present position is the result of washover of the headland or rock fall during earlier erosion. It is however possible that both scenarios have occurred.



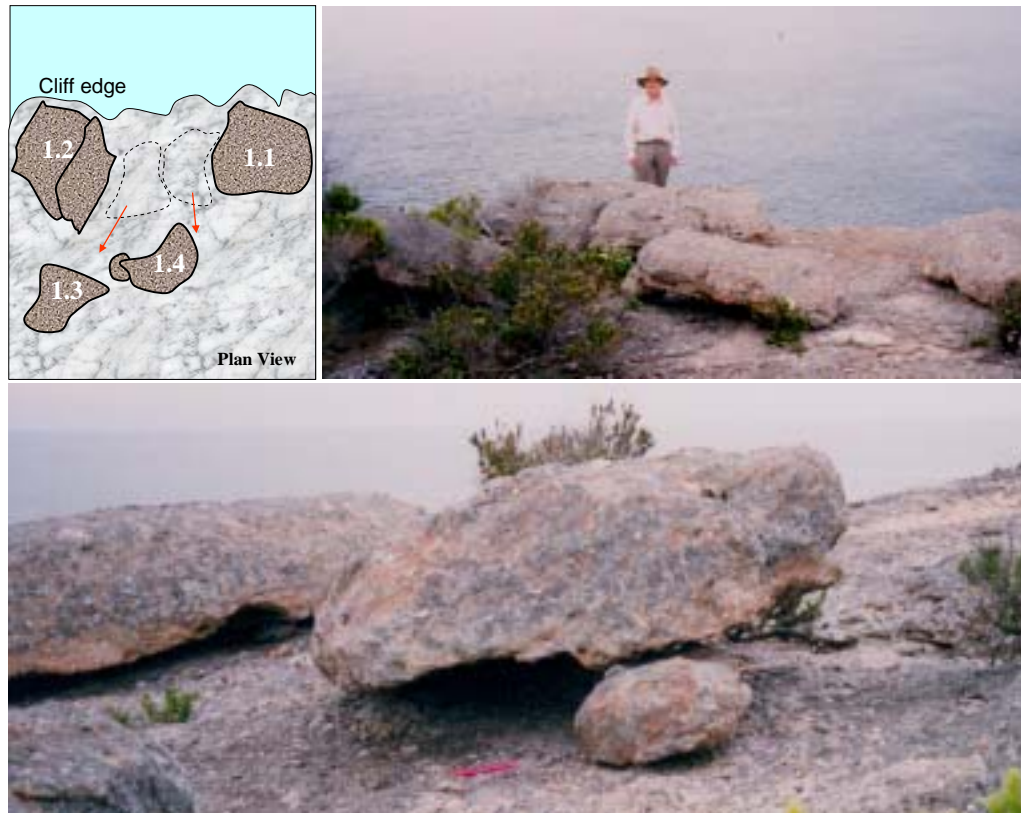


Figure 4.11 At the southern end of Little Beecroft Head lies an accumulation of six small boulders. Two boulders appear to have moved and rest on small fragments of similar lithology. The boulder to the left has split along a joint that corresponds to the underlying platform.



Figure 4.12 A very large boulder in excess of 22 tonnes lies across a prominent joint in the rock platform. The boulder consists of pebbly sandstone that is different to the underlying lithologies. The site presented in Figure 4.11 is at the end of this headland.

The third and most dramatic site occurs approximately 15 m to the northwest of the large boulder where five boulders, of different lithology and up to 3 tonnes, are found imbricated in a stack (Figure 4.13). These boulders are found at an elevation of approximately 33 m AHD and are orientated facing southeast suggesting flow from the southeast across the platform.



*Figure 4.13 Imbricated boulder assemblage at an elevation of more than 30 m at Little Beecroft Head. This stack of 5 imbricated boulders contains 2 different lithologies and indicates flow from the left of the photo.*

Within the shelter of Jervis Bay another site exists on a rock platform south of Greenfields Beach (Figure 4.14). The Greenfields Beach site is a small shallow dipping rock ramp with boulders elevated some 7 m above contemporary sea-level. These deposits contrast directly with boulders on top of Little Beecroft Head that exist up to 30 m above sea-level. The boulders in this area are also considerably blockier in shape than those found on Little Beecroft Head. The lower rock ramp appears cleared of boulders although large boulder accumulations appear on the upper ramp and at the northern end but not at the southern end (Figure 4.15).



Figure 4.14 The rock gently dipping rock shelf to the south of Greenfields Beach lies within the shelter of Jervis Bay and has very low energy. Two study sites highlighted in red on the rock platform include wave cut notches that are incised into a cross-bedded sandstone. The latter has a distinctive lithology, which allowed minimum transport distances to be calculated for boulders of this lithology.



Figure 4.15 The lower parts of the ramp are completely devoid of boulders (a). It is interesting to note that large boulder accumulations exist on the upper platform and at the northern end of the rocky outcrop where they exist as a pile of imbricate boulders (b). Few boulders were found offshore or at the southern end of the outcrop and none are found on the lower platform.



The upper ramp is composed of bioturbated pebbly sandstone which erodes to form joint bounded blocks (Figure 4.10). This lithology provides little structural and lithological information making it difficult to decipher whether a rock has been transported or not. In contrast a finer cross-bedded sandstone unit is found in two large wave cut notches on the lower part of the ramp which exposes the stratigraphy of the underlying sequence. Inspection of the overlying local stratigraphy suggests that any boulders that contain cross-bedding must have originated from this unit (Figure 4.16).



*Figure 4.16 A fine-grained sandstone unit found at the base of the rock shelf is exposed in a wave cut notch (foreground) and contains recognizable cross-bedding. This unit contrasts with heavily bioturbated pebbly sandstone unit (back ground) that overlies the finer unit and allows identification of boulders transported from the wave cut notches.*

Numerous cross-bedded boulders are found at Site 1 on the central part of the platform. Many of these boulders lie at least 8 m away from the notch and weigh between 2-8 tonnes (Figure 4.17). The boulders are often found mixed with boulders of the pebbly sandstone lithology and many are found imbricated against other boulders. At site two to the north, several large cross-bedded boulders are also identified with the largest weighing more than 15 tonnes. This boulder must have come from the seaward wave cut notch (Figure 4.18) and is thought to have moved at least 30 m horizontally and more than 2 m vertically. This boulder suggests that an event of significant magnitude

has been able to detach and transport boulders up the ramp and deposit them up to 30 m from their original position. In addition to transporting the boulders such an event would need to pluck the boulders from the notch and lift them over the lip of the notch.

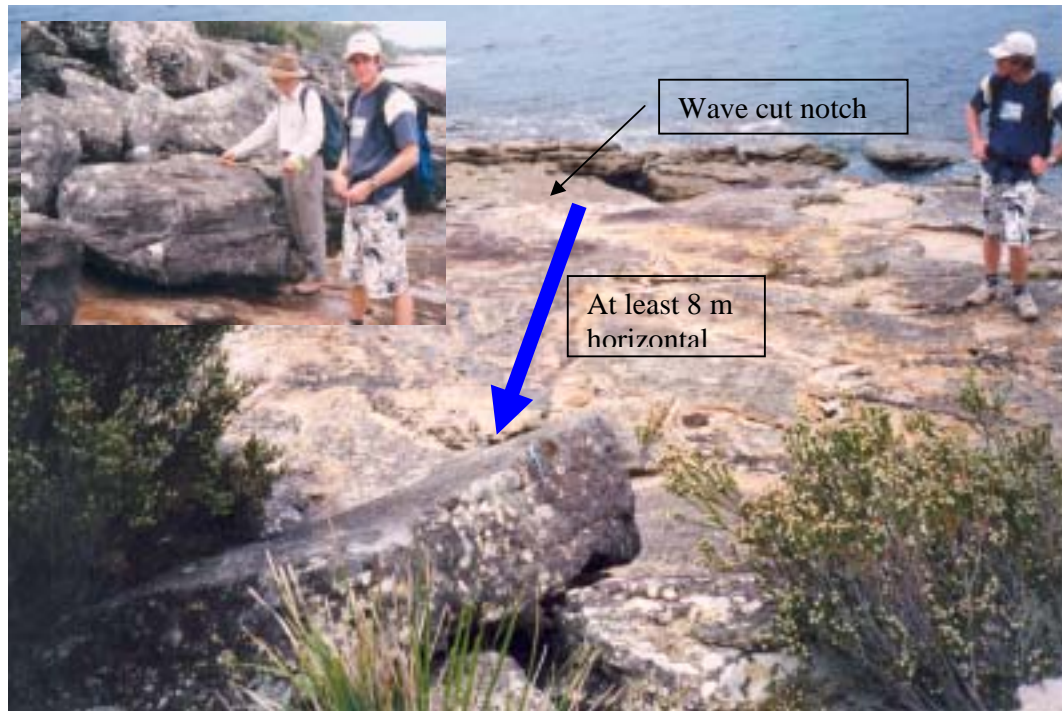


Figure 4.17 Many boulders were identified that were composed of cross-bedded sandstone and could only have come from the seaward wave cut notch. The boulder in the main photograph must have moved at least 8 m horizontally and at least 3 m vertically to get to this position on the upper platform.

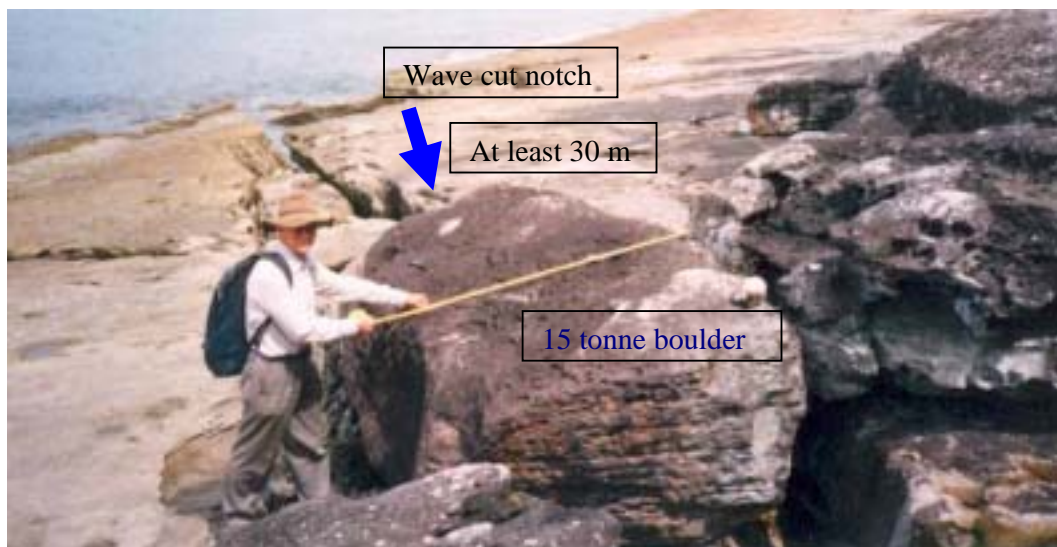


Figure 4.18 This cross-bedded boulder is composed of fine sandstone and has dimensions of 2.5 x 2.6 x 1.0 m. It is estimated to weigh approximately 15 tonnes and must have come from the wave cut notch in the background. It has moved at least 30 m horizontally and more than 2 m vertically.

#### **4.6.2.4 Application of the boulder transport models and equations of Nott (1997, 2003)**

Application of the boulder transport equations (Appendix 3) for subaerial and joint bounded boulders proposed by Nott (2003) were applied to 50 measured boulders from Greenfields Beach. Of these boulders 14 were of the fine-grained cross-bedded lithology of the lower platform and the remaining 36 were of the pebbly lithology of the upper platform. Twenty boulders are found in an imbricated pile at the northern end of the platform that starts at approximately 4.5 m above sea level (Figure 4.19). This analysis was not conducted on the boulders at Little Beecroft Head as this environment is specialized (elevated 30+ m) and the equations are, therefore, deemed not applicable to the analysis by the equations of Nott (2003).

To provide a modern analog the boulder called ‘Mermaid Rock’ at Ben Buckler Head north of Bondi Beach Sydney was also analysed using the equations of Nott (2003). This sandstone block measures 6.1 x 4.9 x 3.0 m and weighs approximately 235 tonnes. The block appears inverted relative to its original orientation in the bed and was deposited by a large storm on or in the days preceding July 15, 1912.

The results are presented in Table 4.1 and indicate that the boulders would require a minimum tsunami wave height of at least 2.5 m or a storm wave height in excess of 10 m to move the smallest of the transported boulders. For example the 15 tonne boulder presented in Figure 4.18 has dimensions of 2.5x2.6x1.0 m and assuming the boulder was joint bounded (i.e. it had to be plucked from the wave cut notch), then using the equations of Nott (2003) a tsunami wave 4.5 m high would be required or a storm wave 19 m high.

Using the equations of Nott (2003) and assuming that the boulder at Ben Buckler Head was joint bounded then this analysis indicates that detachment and transport of this boulder would require a tsunami wave in excess of 11.5 m high or a storm wave in excess of 46 m high. It is apparent from looking at the comparison of the boulders at Greenfields Beach with the modern example of Mermaid rock that the movement of boulders on rock platforms is more complicated than the simple linear equations and



model of Nott (2003). Such analysis of a modern example points to inherent flaws in the workings of Nott's equation (2003) as records of the 1912 storm indicate storm wave heights of less than 10 m (Sussmilch, 1912). It is also important to note that boulders such as that in Figure 4.18 need to be considered in terms of both transport distance, mode of transport (eg bouncing, rolling or suspended) and resistance to detachment.



Figure 4.19 Pile of 20 imbricated boulders found at the northern end of the rock platform. All boulders in this pile are of pebbly sandstone lithology and exist from 6-7 m AHD.

Parameters	Explanation of term	Results					
Min Height of Wave (m)		Greenfields 1	Greenfields 2	Greenfields 3	15 tonne boulder	Imbricated pile	Clast at Bondi
T (sm)	Tsunami submerged boulders	0.24	0.94	1.13	1.84	0.77	2.42
S (sm)	Storm wave submerged boulders	0.98	3.75	4.53	7.37	3.08	9.70
T (sa)	Tsunami subaerial boulders	<b>0.18</b>	<b>0.83</b>	<b>1.04</b>	<b>1.74</b>	<b>0.68</b>	<b>2.35</b>
S (sa)	Storm wave subaerial boulders	<b>0.71</b>	<b>3.31</b>	<b>4.16</b>	<b>6.94</b>	<b>2.72</b>	<b>9.40</b>
T (lift)	Tsunami joint bounded boulders	2.94	2.54	4.71	4.75	3.12	11.59
S (lift)	Storm wave joint bounded boulders	<b>11.78</b>	<b>10.17</b>	<b>18.85</b>	<b>19.00</b>	<b>12.47</b>	<b>46.36</b>

Input							
a	a axis of boulder (m)	1.98	1.71	2.48	2.5	1.64	6.1
b	b axis of boulder (m)	0.7	1.64	1.83	2.6	1.29	4.9
c	c axis of boulder (m)	0.51	0.62	0.88	1	0.64	3
Vol	volume of boulder (a*b*c) (m <sup>3</sup> )	0.70686	1.738728	3.993792	6.5	1.353984	89.67
p(s)	density of boulder (g/cm <sup>3</sup> )	2.1	2.1	2.4	2.4	2.4	2.4
p(w)	density of water (g/ml)	1.02	1.02	1.02	1.02	1.02	1.02
Cd	coefficient of drag	2	2	2	2	2	2
Cl	coefficient of lift	0.178	0.178	0.178	0.178	0.178	0.178
Cm	coefficient of mass	2	2	2	2	2	2
u*	instantaneous flow acceleration (m/s <sup>2</sup> )	1	1	1	1	1	1
g	gravitational constant (m/s <sup>2</sup> )	9.8	9.8	9.8	9.8	9.8	9.8

Table 4.1 Analysis of boulders from Greenfields Beach compared to the storm deposited boulder at Bondi using the equations of Nott, 2003. The average of three boulders piles is presented as Greenfields 1,2 and 3 along with the 15 tonne boulder (Figure 4.20) and the average of the 20 boulders from Figure 4.19. Note that the formerly joint bounded and now storm deposited boulder from Bondi would require a storm wave greater than 46 m according to the analysis of Nott, 2003.



Figure 4.20 A 235 tonne block at Mermaid Rock, Ben Buckler, north Bondi, Sydney. Using the equations of Nott (2003) analysis suggested that transport would require a tsunami wave greater than 11.5 m high or a storm wave height in excess of 46 m. The storm event of 1912 is recorded as producing storm waves that did not exceed 10 m and suggest that these equations need more testing with modern examples.

#### 4.6.2.5 Boulders accumulations of the Jervis Bay region: can they be attributed to an event type?

The boulders on top of Little Beecroft Head and at Greenfields Beach definitely provide evidence of transport of by very large events. Although compelling there are a number of unresolved issues that require attention before attributing these deposits to either storm, tsunami or both. The first problem lies with the age of the deposits and the history of the events. Radiocarbon dating by Young and Bryant (1992) of encrusting shells suggested that many of the boulders in the Jervis Bay region are late-Holocene in age. If this is a true indication of the age then sea level change cannot reasonably invoked as a mechanism for deposition. If however the deposits are older (>2500yrs)

then higher sea-level (up to 2 m) may be invoked to be partially responsible for at least the Greenfields boulders. It is unlikely that these problems can easily be overcome.

The second and major problem lies in defining the event history. It is impossible to know if the boulders were emplaced by single or repetitive events. One fundamental and unanswered question limits analysis of these types of deposit. Is it possible that a tsunami, series of high-energy storms or combination of both processes can deposit a boulder accumulation that exhibits imbrication but is purely the result of repeated stacking and not a response to a single flow?

#### **4.7 Comment on the use of boulders, ridges and geomorphological features as indicators for large-scale washover events**

This chapter has reviewed a range of deposits and features presented as evidence for tsunami over the last decade as described by Bryant and co-workers from southeastern Australia (Bryant *et al.* 1992; Young *et al.*, 1996; Bryant, 2001; Bryant and Nott, 2001). In particular this chapter has presented a review and re-analysis of key sites at Cullendulla embayment and Jervis Bay.

It is apparent that the Cullendulla embayment requires detailed stratigraphic and sedimentological investigation to understand the genesis of the sequence and the role of washover in its development. Detailed study of the stratigraphic and landform relationships are required in order to test the hypothesis that the prograded chenier/beach ridge sequence was overwashed in the late-Holocene causing mixed and anomalously young dates from the reworked system.

The identification of imbricated, reworked and transported boulders from coastal rock platforms and cliff tops shows vivid evidence of large washover events. Some boulders at both sites exhibit obvious signs of imbrication as a response to flow in a landward direction whilst other larger clasts appear characteristic of fallen blocks with no hydraulic reworking. The imbrication of these deposits appears to only occur in boulders up to a threshold size, thus providing a constraint on wave power for the depositional event or events. Both of these sites were studied by Young *et al.* (1996) and Bryant *et al.* (1992; 1996) who attributed the boulder deposition to tsunami.

Although striking these deposits present significant analytical problems some of which have been discussed controversially (Felton and Crook, 2003). It is also important to note that recent publications from Scotland Hansom (2001), Sommerville *et al.* (2003) and Ireland (Williams and Hall, 2004) have attributed very large boulders that lie in chaotic and imbricated piles on top of vertical cliffs up to 50+ m above sea level to large storms in the North Sea over the last 50 years. Although these deposits provide compelling evidence for large-scale movement attributed to storm events it remains very difficult to attribute the depositional mechanism to single or multiple events. The analysis is complicated by two insurmountable limitations. Firstly, a general lack of facies models for rocky shorelines has been identified by Felton (2002) and Felton and Crook (2003). This is particularly the case on the southeast Australian coast where very little research has been conducted on the rocky coasts. Secondly it is impossible to attribute these deposits to a unique event. One cannot definitively state that the boulders are purely the result of tsunami washover. It is likely that storm and tsunami may have both played a role in the development of the high-level boulder beds and the degree to which these events and the number of steps in movement are not definable.

#### **4.8 Bedrock erosion features**

One of the more controversial aspects of tsunami research on the Australian southeast coast is the use of bedrock sculptured features as indicators of large scale erosion by tsunami (Bryant and Young 1996; Bryant and Nott, 2001). Bedrock sculpturing is a field of the earth sciences that has long been studied by those in glaciology (Boulton, 1974). More recently evidence of bedrock sculpturing has been invoked as indicative of evidence for large-scale terrestrial floods (Baker, 1991). Although significant advances have occurred the last decade many aspects related to the physical processes of bedrock sculpturing by water remain unresolved. In particular, it is a new branch of coastal science that remains poorly understood and as such should only be considered as a process indicator if other well-developed proxies are indicative of the same process.

The production of flutes and s-forms in rock platforms affected by fluvial erosion has been attributed to the action of sustained flows of extremely high velocity occur during extreme floods (Baker, 1991). In such an environment the action of large floods can be the only logical cause of considerable sustained high velocity flow. This is not the case in coastal settings as even small waves (1-2 m) can produce extremely high velocities at

the coast (Denny *et al.*, 2003). In order to understand the production of s-forms, flutes and others erosional forms on coastal rock platforms several key questions must be considered. Firstly, it is imperative that before invoking tsunami as a cause of such features one must consider if repetitive inundation of a rock platform by storm waves or storm surges can also produce geomorphically similar forms?

#### **4.9 Synthesis**

The southeast Australian coast lacks historical evidence for large tsunami inundation (Bryant, 2001). Several geomorphic lines of evidence for prehistoric tsunami events have been presented over the last decade (see reviews by Bryant, 2001 and Bryant and Nott, 2001). The geomorphic focus of this research contrasts with the rest of the world where laterally extensive sandsheets found in estuaries and on coastal plains have dominated the research into tsunami and storm deposition (Scheffers and Kelletat, 2003).

The large scale geomorphic impacts of tsunami remain poorly understood and it is apparent that many aspects of this research require re-evaluation with modern analogs. Features such as large-scale bedrock erosion, ridge formation and boulder deposition and imbrication need to be studied with direct comparison to modern storm and tsunami.

Although problems exist with the analysis of event-to-deposit relationships with boulder accumulations, it is important to re-iterate here that even though no particular mechanism can be invoked for these deposits they do at least locally represent evidence for very large overwash events on this coast.

##### **4.9.1 Why would tsunami evidence exist on only a few patches of the coastline?**

As stated in Chapter 3 global investigations of tsunami have not identified clear, unambiguous and regionally extensive sedimentary bodies within the on-shore (terrestrial) geological record. In some regions, such as the Aegean Sea, tsunami deposits exist as sediment layers less than 15 cm thick that contrast with other areas of the world such as Japan and Indonesia where tsunami deposited sandsheets are much thicker over extensive areas (many 10's km).



Parts of Scotland and the west coast of North America (Dawson *et al.*, 1988; Atwater, 1992; Clague 1997; Dawson and Smith, 2000; Clague *et al.*, 2000) also contain very clear geological evidence for prehistoric tsunamis over geographically large areas. However on other coasts, like those of Greece, the coastal environment appears to only preserve to preserve a patchy, limited and thin record of tsunami deposits (Dominey-Howes, 1996).

This is a critical point to consider since many authors such as Dawson (1996) and Dawson and Shi (2000) have argued that tsunamis may only be distinguished from other high-energy marine floods (such as storm surges) within the geological record on the basis of their uniqueness within the stratigraphic column and the wide areas over which they are identified.

The poor history of tsunami deposits on any coast can be attributed to many sources but the most likely causes are: an inadequate sediment supply in the coastal zone available for reworking and deposition - this may be the case on many headlands where high-energy conditions mean little sand sized sediment is available for transport; some deposits may be reworked by later processes and are, therefore, not recorded, (such reworking could occur in the entrance of many estuaries) and in many cases the influence of bathymetry will be great and is often unknown. For example, shoaling of the Sissano lagoon tsunami of September, 1998, caused waves more than 15 m high to occur at the mouth of Sissano lagoon while only 30 km along the coast run-ups were less than 1 m (Tappin *et al.*, 2000).

#### 4.10 Conclusions

- Much of the evidence for prehistoric tsunami from the southeast Australian coast has been of a geomorphic nature and have not been proven against modern analogs. Such investigation contrasts with the rest of the world where the investigation of fine sediments in coastal settings have dominated the literature.
- Evidence for tsunami sedimentation presented for the southeast Australian coast has also relied on the analysis of boulders deposits with little reference to modern analogs and detailed facies analysis.

- Reviews of evidence from Cullendulla inlet suggest that further detailed stratigraphic analysis may clarify the debate on the genesis of the ridge system and the mixed dating results from the upper sections of the sequence.
- Analysis of boulder deposits in the Jervis Bay region provide compelling and reliable indicators of very large washover events on sheltered rock shelves and exposed cliffs. The analysis of these deposits is complicated by a lack of detailed facies-to-event relationships in the literature. The study is also complicated by the inability to determine if a boulder assemblage is the result of a single or multiple events and furthermore whether those events were storm waves, surges, tsunami or a combination of events.
- The use of bedrock erosion features as indicators of tsunami action should be considered with caution. Such features should only be used if directly comparable to similar features identified in modern settings by known agents.
- Although this review identifies significant problems with the analysis of boulders and geomorphic forms, there remains a suite of unusual geomorphic features and boulders accumulations that require very high-energy events to describe their depositional characteristics (for example the 15 tonne boulder at Greenfields Beach). The most likely agents for this suite are exceptionally large storms or tsunami. It is noted however that such a storm would need to be several orders of magnitude larger than any storm in recorded history on this coast.

## Chapter 5

### Overview of field, sedimentology and dating methods use in this study

#### Introduction

Field techniques used in this study include the interpretation of topographic maps, aerial and oblique photograph to allow comparison of embayment orientation wave energy and morphology. These interpretations were used to develop drilling programs and analyse landforms. Sediments were collected from grab samples and cores from varied locations at each study site. In all cases grab samples were collected from the surface and offshore of each embayment.

Selected sediment samples were analysed using a variety of sedimentological techniques including particle size analysis, textural analysis and elementary mineralogy. In many cases further sub-samples were taken for additional analysis of carbonate content, organic content, micropalaeontology, detailed mineralogy and heavy mineral analysis.

In order to develop a chronological framework for the project several dating techniques were applied to sediments and shelly fauna collected from cores and excavated faces. These techniques are discussed briefly here with a detailed description of the dating program developed in Chapter 10.

#### 5.1 Physiography overview and field site selection

The physiography of the embayed New South Wales coastline was discussed in Chapter 2. The elevated sandsheets investigated in this project all lie in embayments opening to the southeast. In order to identify possible locations for the potential preservation of such sandsheets detailed analysis and interpretation was undertaken of several 1:100,000 topographic and geological map sheets along with their corresponding aerial photographs.

This analysis allowed the identification of embayments that may contain washover sandsheets to be targeted for fieldwork. Several key areas were targeted (Figure 5.1) and initial investigation involved a field reconnaissance to many of these sites. The sites were assessed for research accessibility, previous research and indications of the

presence of a sandsheet. Several embayments were shown to exhibit sandsheets in their upper fill but were culled due to accessibility issues or a relative lack of background data when compared to other potential sites. As indicated previously sites that were selected are Killalea Lagoon and Batemans Bay with minor initial studies at Crooked River and to a lesser extent Werri Lagoon, Cullendulla Inlet, Seven Mile Beach and Callala Bay that were culled after initial investigation (Figure 5.1).



Figure 5.1 Location of study sites and culled study sites. Accessibility for drilling was a key determinant of site selection combined with access to previous data. All sites selected offered the greatest potential for investigation with little limitations on access.

Complementary to this study is the inspection of two coastal boulder deposits and two modern storm deposits in the Jervis Bay region (Figure 5.1). The two sites at Little Beecroft Head and Greenfields Beach were selected as they have both been interpreted in the past as deposited by tsunami (see Section 4.6.2). During a field trip to the boulder deposits at Little Beecroft Head, the site at Abrahams Bosom Beach (storm deposits) was selected by chance due to the identification of storm deposits. This embayment differs in physiography and orientation to the other embayments studied but provides a key reference to modern washover processes.

### **5.1.1 Aerial photography and satellite imagery**

Aerial photographs form an integral part of the fieldwork component of this study. They were used in conjunction with geological, topographic, orthophoto and sand resource maps to delineate the extent of the sandsheets.

This initial interpretation of both digital and hard copy 1:25,000 air photographs from the selected field sites provided a platform for the development of drilling and surface sampling programs and allowed initial landform identification (Table 5.1). Aerial photography was used to investigate potential sites as outlined above. The aerial photographs also allowed accurate landform mapping of features such as dunes, mudflats and estuary or lagoon margins. The same techniques were used to determine environmental characteristics such as topography, drainage, vegetation and land use. The aerial photographs also helped to identify sample locations and to determine accessibility to different areas.

Interpretation of aerial photographs also allowed the coarse analysis of boulder orientation on the rock platforms providing an indication of possible flow direction during deposition. This was applied to the boulders studied and mentioned previously in Section 4.6.2.

Satellite imagery was used to look at embayment orientation and to outline gross morphological differences in the coastal set-up that are most likely related to the lithology of the coastal sequence. Satellite imagery was also used in the case of

Batemans Bay as the aerial photograph coverage of this site was inadequate for studying the bathymetry and sediments of the outer bay.

### 5.1.2 Embayment topography

Detailed topographic information was obtained from several different sources including topographic maps, 1:10,000 orthophoto maps and surveying of drillholes and ground penetrating radar (GPR) transects. The study of each embayment's gross topography provided important information about landform features, drainage and landscape evolution.

Location	Material	Physiographic use
Batemans bay	1:25000 Aerial photos	Landform mapping.
	1:100000 Geology sheet	Catchment characteristics
	1:50000 Topographic sheet	Landform mapping
	Landsat TM image	Orientation study
	Bathymetry and Topography image (WBM) Oceanics	Grab sampling locations
Killalea lagoon	1:25000 Aerial photos	Landform mapping, orientation study.
	Digital 1:25000 Aerial photo (Kiama Council)	Drilling and sampling locations
	1:100000 Geology sheet	Catchment characteristics
	1:50000 Topographic sheet	Landform mapping
	1:10000 Orthophoto	Landform mapping
	Previous maps and x-sections (Jones and Elliot 1981)	Drilling and sampling locations
Abrahams Bosom Beach	1:25000 Aerial photos	Landform mapping. Drilling and sampling locations
	1:100000 Geology sheet	Catchment characteristics
	1:50000 Topographic sheet	Landform mapping
	DEM of Jervis Bay	Orientation study

*Table 5.1 Materials used for initial site investigation, landform mapping and 3D embayment model development. Analysis of aerial photographs and maps allowed for potential drillhole sites and accessibility to be analysed before initial investigation. Digital data was used to develop 3D models of the embayments using GIS software.*

### 5.3 Drilling and coring program

Drilling and coring programs were conducted at Killalea Lagoon, Abrahams Bosom Beach and Batemans Bay. Each program was developed with the aim of obtaining the most stratigraphic information from each site with the cost-effective use of resources. Cores were obtained using vibracoring, impact coring, D-auger and hand auger techniques (Table 5.2).

Location	Grab samples	Drillholes	Vibracores	Push cores	Hand- or D-auger	GPR transects
Batemans bay	33	0	7	0	4	2
Killalea lagoon	32	22	12	0	17	3
Abrahams Bosom Beach	9	0	0	5	3	0
Other sites	22	0	8	0	15	0

*Table 5.2 Overview of the drilling program. Several cores and grab samples were collected from other sites during initial investigation (including Crooked River, Werri Lagoon, Cullendulla Inlet).*

### 5.3.1 Vibracoring

Vibracoring makes it possible to extract a relatively undisturbed core of unconsolidated, sandy or muddy sediments. The wacker vibracoring rig adopted for this study is slightly modified from that of Lanesky *et al.* (1979). It was used to agitate aluminium core barrels up to 7 m long (75 mm diameter) into the unconsolidated sediments. Where the depth to basement was in excess of 6 m the entire length of the core could be driven into the ground but, on average, cores of 2-3 m were extracted. A total of 35 cores were collected using this method, of which 22 are presented in this study.

### 5.3.2 Impact coring

Impact or push coring was used at Abrahams Bosom Beach and Killalea lagoon. All cores from Abrahams Bosom Beach, along with OSL samples from Killalea and Batemans Bay were obtained using push or impact coring techniques. This technique involved pushing or pounding a PVC pipe into the sediment (Figure 5.2). All pipes used in this study were 50 mm diameter PVC pipe. Cores were taken back to the university where they were sampled as described in sections 6.5 and 10.4 (OSL).

### 5.3.3 D-coring

D-coring (Russian peat sampler) was used in Killalea Lagoon to investigate the occurrence of breaches of the lagoon and to investigate the landward extent of the marine sandsheet investigated in Chapter 7. The D-corer is modified from that of Jowsey (1966) and unlike impact coring or vibracoring the samples are immediately

visible for inspection allowing quick assessment of subsurface stratigraphy. D-coring obtained continuous cores to depths of approximately 1.5-2 m. Visual logs were taken and samples were collected in the field for laboratory analysis.



*Figure 5.2 Impact coring at Abrahams Bosom Beach. A 50 mm PVC pipe is hammered into the sediment. The core is then capped and removed. Maximum core length using this method was ~2 m.*

#### **5.3.4 Hand augering**

Like the D-corer the hand auger provides a quick and effective tool for gaining a preliminary understanding of the subsurface stratigraphy of a study area. The hand auger was often used to initiate holes for vibracoring and to determine the extent of the sand sheets. In Killalea Lagoon effective hand augering was limited to around the top 2 m of the deposit due to the presence of the water table below which sediment would usually slump out of the tool before withdrawal. Investigation of the barrier and surrounding hillslopes at Killalea was not as adversely effected by slumping and the hand augering to depths of less than 2 m proved effective in collecting fragments of weathered bedrock beneath the sedimentary material.

#### **5.3.5 Excavated faces**

Faces were excavated where possible to facilitate investigation of the subsurface stratigraphy. In particular, faces excavated into the storm deposits at Abrahams Bosom Beach and the beach deposits at Batemans Bay (Figure 5.3) allowed the investigation of contacts between facies units along with characteristics of individual facies sub-units.





*Figure 5.3 Excavated face at Batemans Bay. The shell-rich deposit of primary interests is observed in the upper sequence below the dark organic band. The shell-rich is at 2.4m AHD and contains abundant large bivalves and oyster shells.*

Excavated faces also allowed collection of samples for dating from the shell-rich deposit and beach ridge sequence at Batemans Bay (Figure 5.3). The excavated faces allow for very detailed facies analysis when compared to the core data. In particular excavated faces were extremely beneficial to the study of the Bateman Bay sequence.

All faces were initially hand excavated with a shovel before the face was ‘cleaned’ with a small trowel and brush to expose contacts and yield minimal disturbance to the

stratigraphy. Notes were taken on facies relationships and samples taken for analysis at intervals outlined in Figure 5.4.

### **5.3.6 Notes on coring in shell-rich beach ridge sequences**

The coring program for the Batemans Bay site involved three days of fieldwork with the anticipated collection of up to 10 vibracores and hand auger holes that were to have complemented the excavated faces. Initial efforts with a handauger were unable to successfully auger through more than 20-30 cm of sediment before striking resistance often bending the blade of the auger. Vibracoring through the material was slightly more successful as it reached penetration of up to 2 m. However these cores were only obtainable when undertaken in steps of up to 60 cm and involved the weight of two men (~180 kg) to assist in penetration. The shell-rich sequences are deemed very unsuitable for the above techniques and would require much heavier (and more expensive) equipment. It is important to note here that the ground penetrating radar (GPR) technique employed in the same area gave well-defined results for stratigraphic interpretation of the sequence and yielded results that negated the need for an extensive ‘heavy duty’ drilling program.

## **5.4 Surveying and GPS**

Laser theodolite surveying, dumpy level surveying and GPS techniques were employed to produce accurate location maps of the study areas and sample sites. The data collected are used in conjunction with aerial photographs and a variety of local and regional maps to record the location of infrastructure such as roads and paths as well as the precise location of sampling sites. The accurate surveying of sample sites also allowed all spot heights to be related the Australian Height Datum (AHD) and hence all subsurface features to be related to present sea-level.

## **5.5 Sampling program**

Samples were obtained using a variety of sampling techniques including coring outlined above, and both onshore and offshore grab sampling. The sampling and analysis program is summarised in Figure 5.4, which shows the sampling flow sheet that was applied to all cores, face and grab samples.

### **5.5.1 Grab samples**

Grab samples were collected from onshore and offshore using a variety of techniques. Offshore samples from Batemans Bay and Minnamurra embayment (Killalea) were taken with the aid of a boat with a (Macintyre type) grab sampler. Onshore grab sampling was usually obtained using a small trowel or shovel. Locations were recorded on draft sampling maps and by using a GPS and transferred to regional and study site maps for report/thesis production. Sampling regimes for individual sites are described in the appropriate sections of Chapters 6, 7 and 8.

All grab samples were stored in snap-lock plastic bags and transported back to the sedimentology laboratory at the University of Wollongong. Samples were sealed and those that were collected wet were kept wet in a cool room at 4°C along with all cores. This was done to inhibit the potential for oxidation of the sediments upon exposure to air.

### **5.5.2 Sampling cores**

The sampling program for cores obtained using the methods described above is best described as quasi-systematic. For all cores a minimum sampling interval of 5 cm was set, the implication of which dictates that sampling for all cores was at least undertaken in 5 cm intervals. Samples were often taken at higher resolution across stratigraphic boundaries or at horizons of particular interest (e.g. microfauna).

All cores were systematically cut in half, photographed and logged (see relevant chapter sections). Logs made reference to the location of shells, changes in sediment colour and obvious differences in sediment composition. For the most part one half of each core was sampled and the other half archived for future reference. Exceptions to this case occurred when extra sample was required for analysis; in such a case material was then taken from the archived core.

## **5.6 Sedimentology techniques employed**

It is a fundamental premise of sedimentology that every sedimentary unit is formed as a result of its response to a certain set of environmental conditions (Blatt *et al.*, 1980). In order to investigate the depositional environments of the samples collected for this study, all samples were investigated using a number of basic physical sedimentology

techniques. These techniques were used to characterise the sediments into basic lithological facies, e.g. washover sands, shelly beach face sands or lagoonal muds. In many cases this initial facies description then dictated the analysis of that facies and further division into subfacies.

Furthermore, an understanding and comparison of the textural and compositional characteristics (mineralogy) of sediments from various depositional environments within a particular sedimentary system, such as an estuary or lagoon, can allow the interpretation of sediment transport pathways and allow one to distinguish source environments (Gao and Collins, 1992). Figure 5.4 summarises the preferential use of techniques for different facies and outlines the approach undertaken to develop depositional models for the depositional sequences.

### **5.6.1 Analysis of physical sedimentology**

Initial analysis of all samples to allocate basic facies was conducted using appearance in cores and sample bags, particle size and particle texture along with basic mineralogy. These parameters were determined through observation of cores and grab samples, laser particle size analysis and binocular microscopy.

#### **5.6.1.1 Particle size analysis**

Samples were analysed for particle size using a Malvern Mastersizer 2000 particle size analyser. The instrument is a laser diffraction based instrument that measures the particle size characteristics of a sediment sample using the principles of laser diffraction and relies on the fact that the diffraction angle is directly proportional to the particle size. The angle and intensity of laser light scattered by suspended sediment sample are selectively measured and converted to a volume distribution based on the Mie optical theory (de Boer *et al.*, 1987).

The size range defined by the manufacturer as applicable to the instrument is 0.4-2000  $\mu\text{m}$ . Most samples analysed appeared to be within this size range by visual inspection, those that were not were dried at  $\sim 70^{\circ}\text{C}$  for 48 hours and then sieved to remove particles greater than 2000  $\mu\text{m}$ . Representative sub-samples were then dispersed in the sample preparation bath by physical and ultrasonic agitation. Agitation continued

until both the particle size distribution observed and the laser obscuration level had stabilized (Figure 5.5).

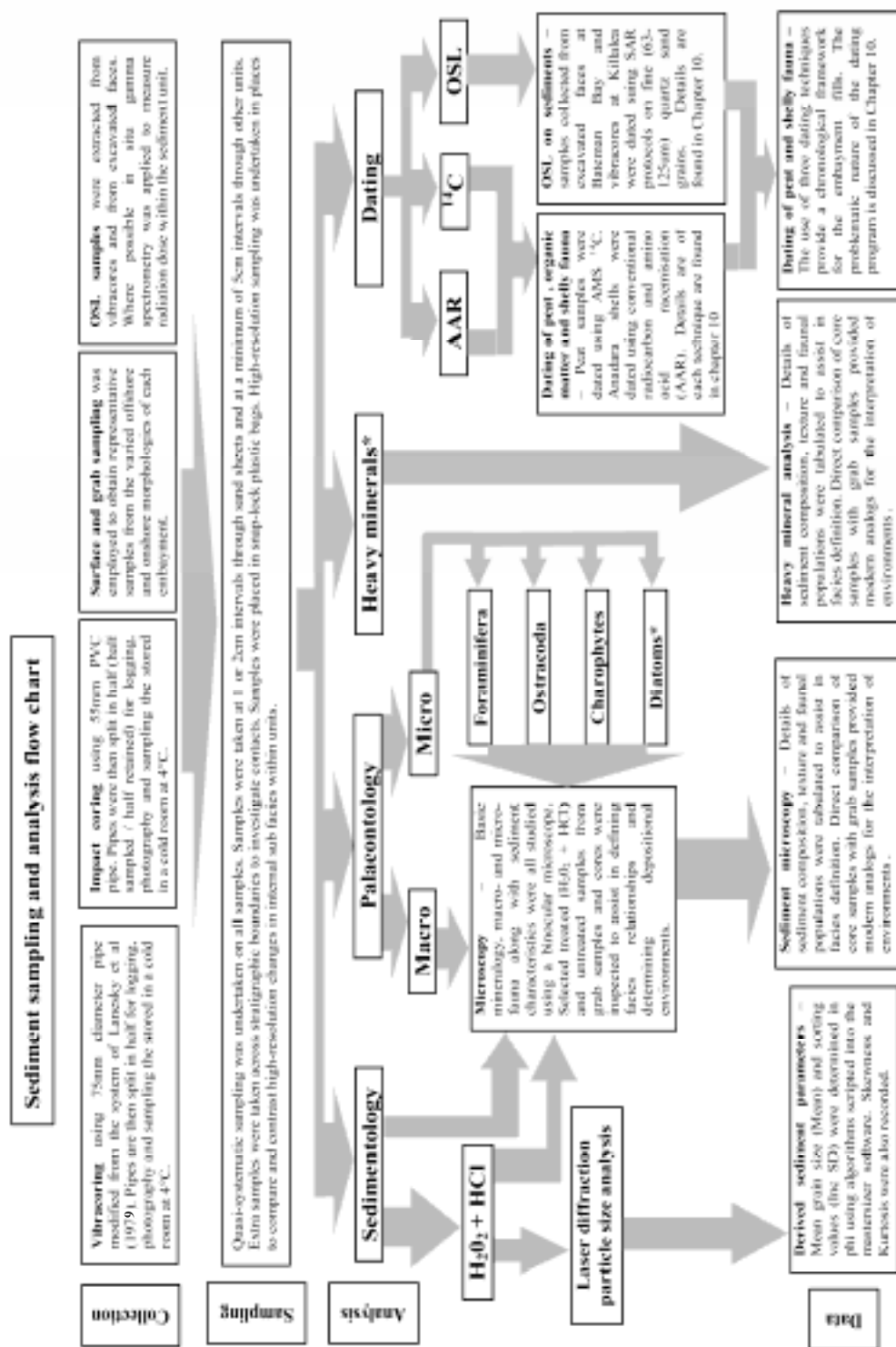


Figure 5.4 Flow chart of sampling program. The majority of samples were initially analysed for sediment content and grain size. Initial facies interpretation then dictated the need for further, selective detailed analysis. Major techniques are discussed in relevant sections of chapter 7, 8 and 9, dating techniques are discussed in Chapter 10.

The sample quantity needed for analysis varied with its grain size distribution although it was generally noted that 0.1 – 0.2 g of fine silts to 1 – 2 g of medium sand were required to obtain the correct attenuation of the laser beam. The instrument provides an indication of the degree to which the laser beam is being obscured by the particles passing between the lenses. Called the obscuration level the manufacturer suggests that a level of 5-30% gives reproducible results. Low levels of obscuration can yield results that are indistinguishable from background whilst high levels may cause problems with internal refraction or backscatter.

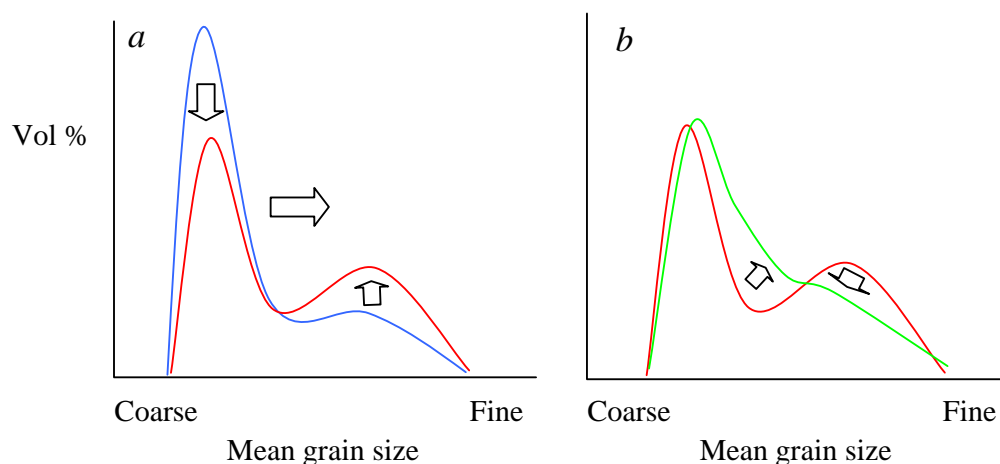


Figure 5.5 Initial samples (blue) disaggregate (a) to a stable distribution (red) continued circulation and agitation can lead to reflocculation (b) due to the build up of electrostatic charges. This is generally a much greater problem in fine grained (<63  $\mu\text{m}$ ) sediments.

All samples were then analysed using the polydisperse mode over three experiments with results calculated on 10,000 sweeps (10 seconds). The polydisperse mode is particularly applicable to samples that contain a wide range of particle sizes and is hence used for most natural samples. Following measurement, particle size statistics (mode, sorting, skewness and kurtosis) are computed following the inclusive graphics method (Figure 5.6) with distributions expressed in volume units. Other calculations on the number of modes, and percentage clay, silt and sand were used to characterise the sediments according to particle size.

A test of instrument precision by Fenely (2003) showed excellent precision for the instrument with a sandy silt sample (Figure 5.7). Testing during this program, indicated that precision decreases in poorly sorted samples and with increasing clay content.

Mean		Standard deviation	
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$		$\sigma_G = \exp \left( \frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6.6} \right)$	
Skewness		Kurtosis	
$Sk_G = \frac{\ln P_{35} + \ln P_{64} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$		$K_G = \frac{\ln P_5 - \ln P_{95}}{2.44(\ln P_{25} - \ln P_{75})}$	
Sorting ( $\sigma_G$ )		Skewness ( $Sk_G$ )	
Very well sorted		Very fine skewed	
Well sorted		Fine skewed	
Moderately well sorted		Symmetrical	
Moderately sorted		Coarse skewed	
Poorly sorted		Very coarse skewed	
Very poorly sorted			
Extremely poorly sorted			
		Kurtosis ( $K_G$ )	
		Very platykurtic	
		Platykurtic	
		Mesokurtic	
		Leptokurtic	
		Very leptokurtic	
		Extremely leptokurtic	

Figure 5.6 Grain size parameters, formulas and suggested descriptive terminology using the graphical method of logarithmic ( $\phi$ ) values of Folk and Ward (1957). ( $\phi = -\log 2 \text{ mm}$  unit;  $P_x$  are grain diameters in  $\phi$  units at the cumulative percentile value of  $x$  (Blott and Pye, 2001))

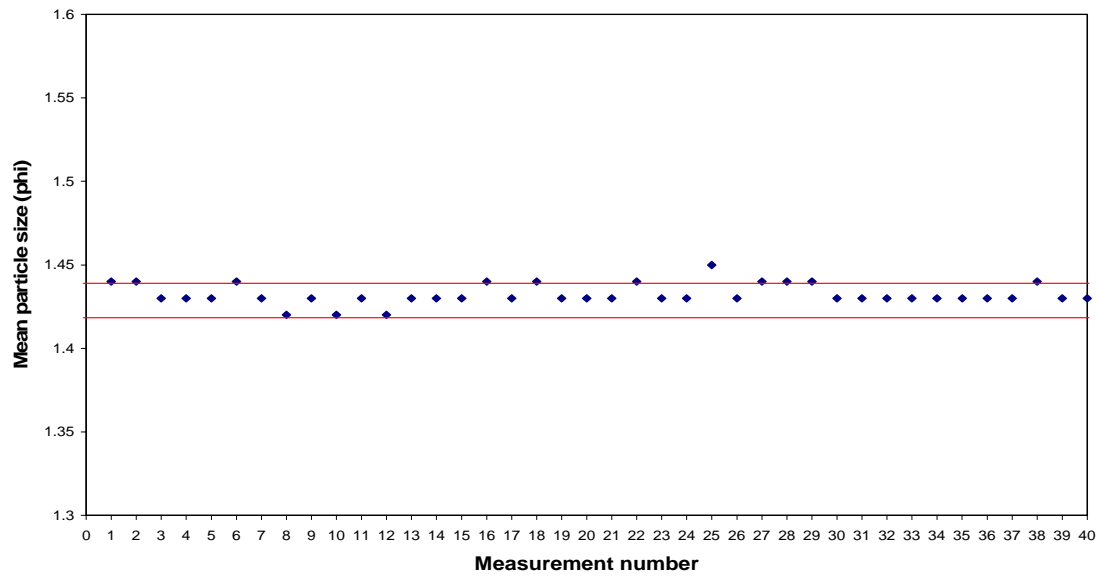


Figure 5.7 Scatter graph showing mean particle size for the same sample measured 40 times using the Malvern Mastersizer 2000. Dots represent mean particle size for each measurement, while red lines show 99% confidence intervals (Fenley, 2003).

### Mineralogy and textural characteristics

Surface samples were also analysed for textural and compositional properties under a x100 binocular microscope. Observations were made and results recorded with reference to mineral composition, degree of sorting, particle shape, particle size, surface appearance and colour (Figure 5.4). These results were tabled to assist in the characterisation and allocation of facies and sub-facies. In some cases detailed mineralogy was conducted on the fine heavy mineral fraction (63-125  $\mu\text{m}$ ) as outlined

by Switzer *et al.* (2005; see Figure 5.4) Carbonate content was determined by weight difference on selected samples from selected cores and grab samples (see relevant sections) following a digestions method based on Ellingboe and Wilson (1964).

Compiled particle size data and mineralogy were plotted on bivariate plots and analysed using Ward-based cluster analysis. The bivariate plots, in particular the relationship between mean size and sorting aid interpretation of depositional history by identifying clusters to which relative energy envelopes can be assigned (Folk, 1954; Folk and Ward, 1957; Tanner, 1991; Lario *et al.*, 2002).

### 5.6.2 Macro- and micro-palaeontology

Macrofossils were extracted for identification from Batemans Bay samples using wet sieving with a 500 µm sieve. Microfossil identification of Foraminifera, Ostracoda and Charophyta was undertaken on subsamples taken from grab samples and cores from Batemans Bay, Abrahams Bosom Beach and Killalea Lagoon. These microfossils were obtained after gently wet sieving samples through a 125 µm sieve, drying the residual and subsampling using a sample splitter. In cases where the host sediment was dominated by sand grains microfossils were then separated using heavy liquid separation procedures modified from Callahan (1987), using an aqueous sodium polytungstate ( $3\text{Na}_2\text{WO}_4 \cdot 9\text{WO}_3 \cdot \text{H}_2\text{O}$ ) solution of 1.8 g/cm<sup>3</sup> density.

A simple filtration technique allowed the separation of the floating material. Foraminifera and Ostracoda species were then isolated and placed on a palaeontological grid using a water-soluble adhesive. Micro and macro faunal species were identified using the reference works of Jensen (1995), Loeblich and Tappen (1994) Yassini and Jones (1995) and Garcia *et al.* (2003).

### 5.7 Dating program

Four dating techniques, AMS and conventional radiocarbon, amino acid racemisation (AAR) and optically stimulated luminescence (OSL), were used to assess the geochronology of the deposits investigated in this study. Shell samples collected from cores and excavated faces at Batemans Bay were dated using conventional radiocarbon techniques complemented by amino acid racemisation. Peat samples from Killalea



Lagoon were dated using AMS radiocarbon. These chemical techniques complemented the optically stimulated luminescence (OSL) technique that dates the deposition of the sediments.

Dating of the sediments confining the washover deposits aims to chronologically bracket the washover sheet and test the possibility of obtaining a confining age based on radiocarbon techniques. Each technique is reviewed in Chapter 10 where results and limitations of the dating techniques are presented. The dating program is then incorporated into the depositional models for each deposit culminating in an overview of the chronological development of the two main study sites at Batemans Bay and Killalea Lagoon.

## **5.8 Synthesis**

The field methods used in this study provides a cost effective, economically viable program designed to extract the most information from each site studied. Sites were selected on the basis of; presence of identifiable washover sand sheets, previous research available and field access. Two main study sites were selected and five were culled in order to give the project increased focus.

Sites were investigated with a sampling program based on excavated faces, coring, grab sampling and geophysics (GPR). Mapping of landforms identified key target areas for all techniques and allowed analysis of sediment pathways and sources. Quasi-systematic sampling of cores allowed the investigation of shallow subsurface stratigraphy with extra samples taken at higher resolutions where stratigraphic relationships were to be investigated.

Samples were subjected to a number of sedimentological techniques to classify the sediments with the aim of allocating initial facies. Often this initial facies determination resulted in the identification of further analyses required to completely characterise the facies with a chief aim being to determine the depositional environment for each facies identified.

## **5.9 Conclusions**

- A landform mapping program was instigated in order to investigate likely study sites for this project using a criteria based on previous research, preliminary investigation and access for research. Two main study sites were chosen based on these criteria.
- Analytical sediment samples were obtained using a variety of surface and shallow subsurface techniques. These samples were analysed and compared to modern environments to identify facies landform associations with the aim of developing depositional models
- A dating program using chemical techniques (AAR and radiocarbon) on shell material and peat, in conjunction with (OSL) dating of sediments, was outlined and is discussed further in Chapter 10. The aim of the program is to provide a chronology to the depositional models developed from the subsurface drilling program.

## Chapter 6

### Modern storm deposits from southeast Australian Coast

#### Introduction

This chapter presents a modern analog for storm deposition from the study area. The deposit consists of two washover sandsheets at Abrahams Bosom Beach (Figure 6.1). The deposits were laid down during two storm events in March and July 2001. These deposits provide a valuable insight into storm deposition on this coastline and provide modern analogs for the study of deposits of unknown origin.

Large storm surges often deposit material into back-barrier environments and onto rock shelves. Although storm deposits of sand, cobbles and boulders occur on many coasts, wave-dominated coasts like those found in southern Australia can be considered noisy, where storm events rarely leave depositional signatures that last more than a few days. As stated in Chapter 3 the preservation of storm deposits often relies on relative disequilibrium between the event and the background energy regime for that part of the coast.



*Figure 6.1 Location of Abrahams Bosom Beach, which is only open to the largest of swells from the east to northeast. Note that a tongue of marine sand can be seen in the estuary of Abrahams Bosom Beach possibly indicating an earlier storm deposit had occurred just before the photo was taken.*

### 6.1 Action of storms on the southeast coast of Australia

King (1972) indicated that storm surges tend to result in erosion rather deposition along the Australian southeast coast. Although an erosional signature for storm surges may be typical for the southeastern coast of Australia (Thom, 1974; Chapman *et al.*, 1982), some workers have attributed constructional (depositional) features to storm surge particularly in the cyclone prone North Queensland coast (Hayne and Chappell, 2001; Nott and Hayne 2001). Along the Australian coast storm surges occur more commonly on the northern coastline and are often the product of intense low-pressure systems associated with tropical cyclones (Nott, 1997). Modern studies of contemporary and paleaeostorm deposits from the tropical northeastern coastline have highlighted geological evidence for super-cyclones over the last 5000 years, these events are an order of magnitude above those in recorded history and are represented by depositional ridges of coralline debris.

The NSW coast does not experience tropical cyclones but is subject to intense low-pressure systems called “east coast low” systems (Figure 2.7) that often initiate heavy rain, high winds and large waves (Bryant, 1997). These events are dramatic but there is little sedimentological or geomorphological evidence to suggest that they generate storm surges of considerable force. Bryant *et al.* (1996) attributed this lack of action to the narrowness of the continental shelf, and the nature of the storms themselves, with overwash deposits in estuaries often hidden in the high-energy wave-dominated regime of the coast and/or reworked by the action of waves and tides.

This study presents the first detailed morphostratigraphical analysis of an overwash sequence from the southeast coast of Australia providing a direct analog for the study of overwash deposits on this coast and similar high-energy coasts worldwide.

Two storm events in March and July 2001 generated large swell from the east-northeast capable of breaching small sheltered barrier systems on the southeast coast of Australia (Figure 6.2). Both events are associated with large swells from the northeast generated by intense low-pressure systems in the southwest Pacific. The March event is not considered a storm surge event (Figure 3.5), however the role of strong onshore winds on the 8th of March may have produced a considerable piling up of wave energy on the coast although no barometric component is recorded (Bureau of Meteorology, 2001).

The March event produced a larger swell component than the July event and washover deposition is entirely attributed to swell magnitude and direction superimposed on evening high tides and onshore winds. The July washover is different and can be considered as a classic storm surge characterised by a super-elevation of coastal sea level associated with the landfall of a small east coast low that was superimposed on high tides with significant storm swell.



*Figure 6.2 Sandsheet and associated debris (foreground) deposited at Abrahams Bosom Beach in July 2001. This sand sheet and an underlying one were deposited during the storms of March and July 2001.*

## **6.2 Abrahams Bosom Beach**

Abraham's Bosom Beach is a small pocket barrier complex on the southeast coast of Australia (Figure 6.2). Two storm washover events were the result of large swells from the northeast generated by intense low-pressure systems in the southwest Pacific. Both events were capable of breaching the barrier and depositing a fan-shaped tongue of marine sediment into the back-barrier estuary, with the larger event able to remove reed beds from the lagoon and carry marine sediment more than 150 m into the estuary.

## **6.3 The storms of March and July 2001**

Both storms, although characteristically different in set-up, produced very large swell from the east to northeast, a significant factor in the deposition of these overwash deposits (Figure 6.3). Large swells from this direction are not in equilibrium with the

dominant southeast swell conditions on the east coast and are, therefore, more likely to impact upon sheltered environments characterised by low energy.

### 6.3.1 The March swell

The storm swell in March was produced by a large low- pressure system that formed off the Queensland coast and tracked southeast before crossing the northern New South Wales coastline near Byron Bay on the evening of the 8<sup>th</sup> of March, 2001 (Figure.6.3a) causing extensive flooding and wind damage. Wind gusts were recorded up to 139 km/hr at Evans Head with a mean wind speed of 100 km/hr (Bureau of Meteorology, 2001). While very large storm waves struck the northern NSW coast, large even swells of relatively long period struck the southeast coast, with a maximum potential wave height peaking at around 5 m (AHD; Figure 6.4) as indicated by the Port Kembla wave rider buoy and tide gauge at HMAS Creswell some 15 km southwest of the study site.

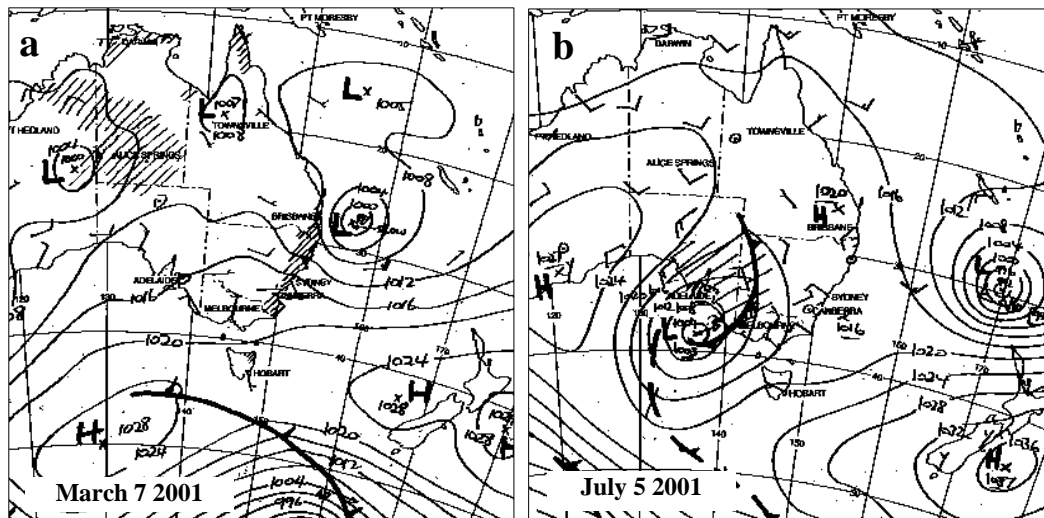


Figure 6.3 a) Synoptic chart of March 7 2001 showing an intense low pressure system off the southeast coast of Queensland that generated large swell from the northeast to east. b) Synoptic chart of July 5, 2001 showing a deep low pressure system in the southwest Pacific that generated large swell. Also note the presence of a small low-pressure system off the Victorian coast that later intensified off the New South Wales coast causing the surge component of the event.

Accounts from local residents suggest that a new sandy deposit appeared in the estuary on the 9<sup>th</sup> of March 2001 infilling the lagoon with large amounts of sand and depositing debris around the sand banks. This is supported by the wave data, which suggests the maximum potential wave height of around 4.8 m (AHD) occurred in the early hours of the 9<sup>th</sup> of March 2001 (Figure 6.4).

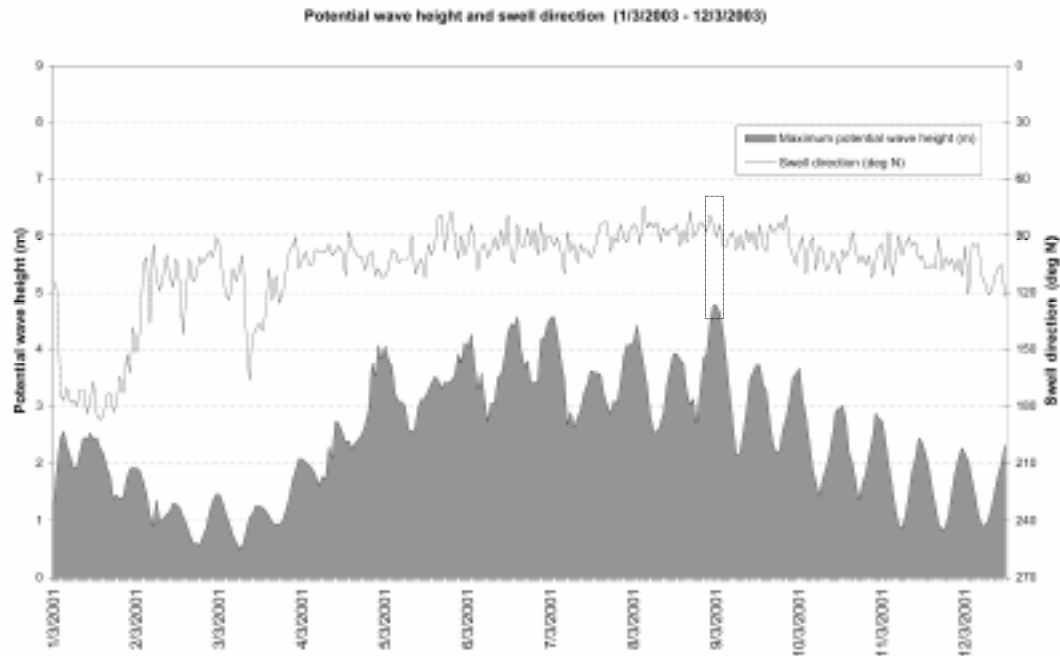


Figure 6.4. Wave direction and potential wave height for periods of 1-12 March 2001. Large swell events from the east to east-northeast are identified using swell direction and magnitude from Port Kembla (60 km north of Abrahams Bosom Beach) with magnitude superimposed on corrected tidal data from HMAS Creswell in Jervis Bay some 15 km southwest of the study site. Two large swell events are observed both from the east and south to southeast. The washover event is highlighted with a stippled rectangle (data courtesy of Manly Hydraulics Laboratory, 2001).

### 6.3.2 The July storm surge and swell

The graph of potential wave height against direction (Figure 6.5) shows a considerable swell from the east-northeast ( $060^\circ$ ) to east ( $090^\circ$ ) direction starting on the 5<sup>th</sup> of July and continuing to a peak on the evening of the 6<sup>th</sup> of July, 2001, before waning and being replaced by a new swell from the east-southeast. This swell although large (greater than 3 m potential wave height) is not as large as the swell associated with the March 2001 event previously discussed. However, the storm deposit from the July event is considerably more extensive and voluminous than that deposited in March. An obvious contrast between the events exists and can be attributed to difference in the morphology of the small barrier at the time of breaching, along with the storm events and their associated position, track and swell characteristics. The March event generated large even swells from the east-northeast that traveled in excess of 800 km to reach the site. Although strong onshore winds occurred that day ( $>60$  km/hr) the likelihood that they would have caused any significant atmospheric component appears low. In contrast the July event is associated with a small east coast low combined with, and superimposed upon, a large swell emanating from a tropical storm that started off the Queensland

coast and intensified as it tracked southeast before dissipating north of New Zealand (Figure 6.3b). This combination caused exceptionally large wave energy at the coastline during the late afternoon to early evening of the 7<sup>th</sup> of July, 2001. The washover was extensive, carrying sediment and debris more than 150 m into the estuary and was capable of removing vegetation (reeds) and depositing material to heights of 1 m above sea-level approximately 300 m from the coast.

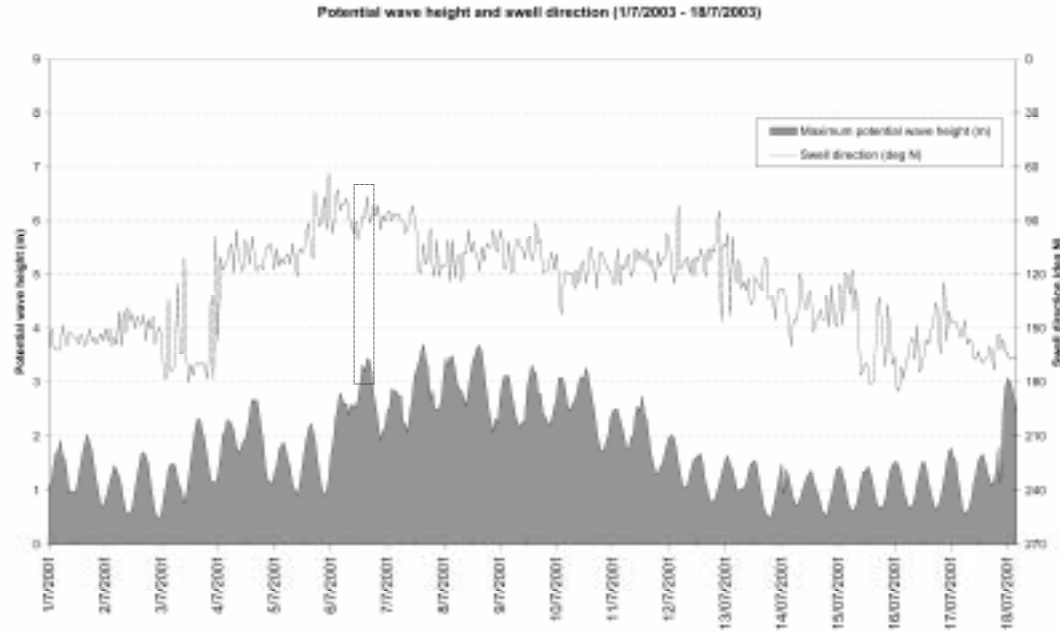


Figure 6.5. Wave direction and potential wave height for periods of 1-18 July 2001. Large swell events from the east to east-northeast are identified using swell direction and magnitude from Port Kembla (60 km north of Abrahams Bosom Beach) with magnitude superimposed on corrected tidal data from HMAS Creswell in Jervis Bay some 15 km southwest of the study site. Several large swell events are observed both from the east and south to southeast (data courtesy of Manly Hydraulics Laboratory).

#### 6.4 Morphology, field work, sampling techniques and sedimentary analysis

This section outlines the embayment morphology, characteristics of the small estuary and the relationship between inherited barrier morphology and the likelihood of the occurrence and preservation of overwash deposits. This section also stresses the importance of selecting a ‘low noise’ site, one that is sheltered and not subject to repeated high energy coastal processes of the open beaches in the region and is, therefore, likely to record high energy disequilibria such as rare storm swells from the northeast to east. The second part of this section outlines the methods, both field and laboratory based, used to define the stratigraphy and internal sedimentology of the two overwash deposits studied, including the application of detailed laser-diffraction particle size analysis.



The present morphology is observed in Figure 6.6 and shows a small compound barrier system consisting of a Holocene barrier that onlaps an older, presumably Pleistocene system that is confined by and onlaps sandstone bedrock cropping out at both ends of the beach. The western portion of the barrier system is well developed and consists of a series of poorly defined well-vegetated dunes up to 4 m high. The eastern part of the system confines a small estuary that is rarely open to the sea and drains an elevated partially dissected sandstone plateau to the east, south and west. During extended times of fair weather or southeast swell the small barrier accretes both vertically and laterally, and is modified by storm events and flooding in the estuary. The likelihood of storms breaching the system and the deposition of sediment is strongly dependent on the morphology of the barrier at the time. Two successive storm events may be more likely to breach the system if the period between events does not allow the barrier to rebuild (accrete) after the initial erosional event.

#### **6.4.2 Sampling**

Samples from push cores were taken at 2 cm intervals with one part of the second overwash deposit sampled at higher resolution (0.5 cm intervals) from core ASABBVC-3. Grab samples were obtained from the modern beach face through to the vegetated dune in two transects, one near the entrance to the estuary and the other in the middle of the beach (Figure 6.6b).

Excavated faces were sampled in 2 cm slices taken from clean surfaces cut into the washover deposits. All the samples were placed in sample bags for transport to the laboratory, where they were split using a stainless steel riffle sampler. Sub-samples for particle size and texture analysis were placed in small vials, the remainder of the material was returned to the original bag.

#### **6.4.3 Analytical sedimentology on fine-grained storm deposits**

Sediments were analysed for grain size, grain texture, mineralogy and the presence of shell hash or microfauna using a binocular microscope. This was done at intervals of approximately 5 cm with additional samples inspected across stratigraphic contacts. Particle size analysis of sedimentary deposits can provide fundamental information on the dynamics of deposition through the analysis of lateral and vertical trends within deposits (Lario *et al.*, 2001).

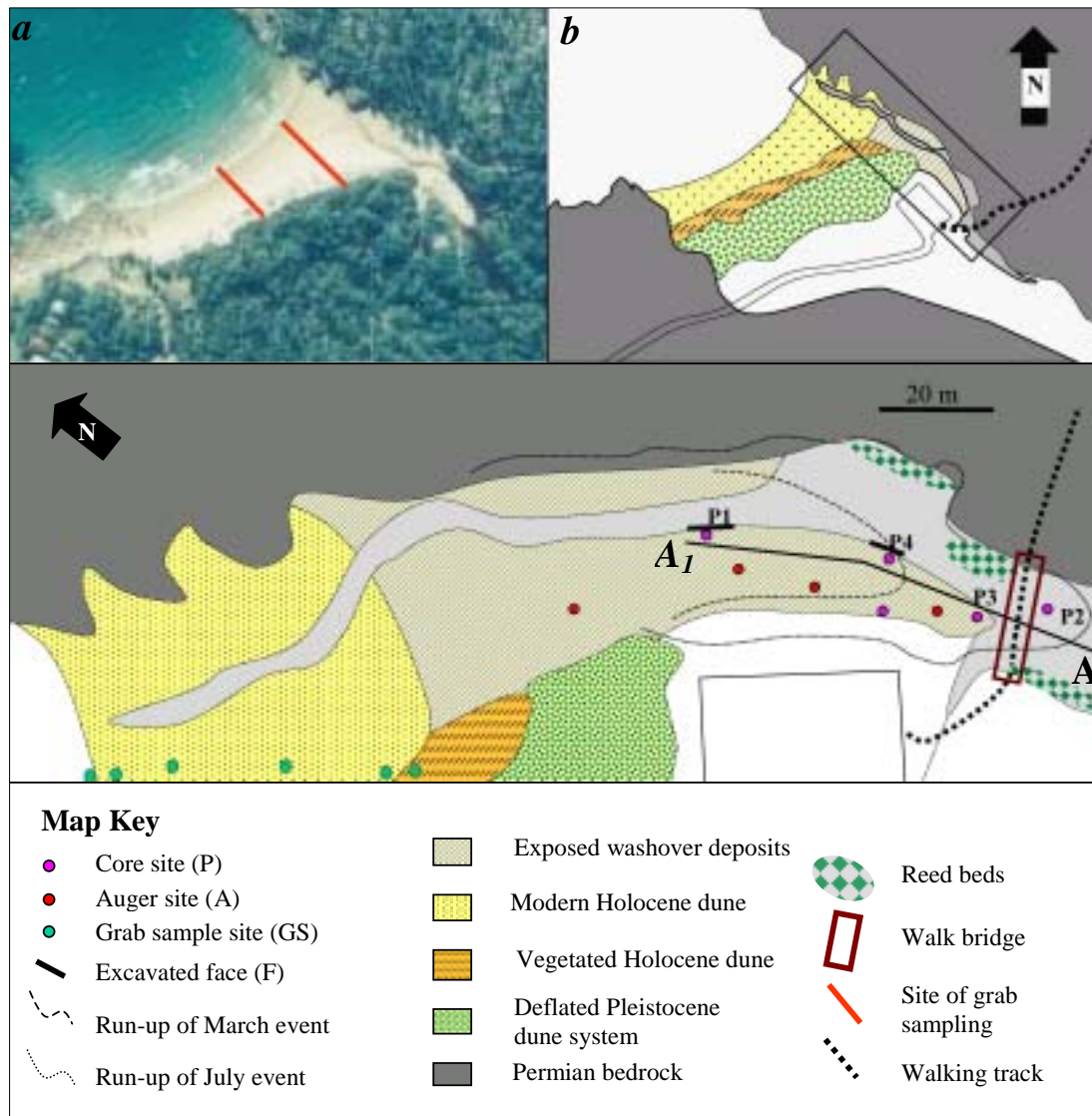


Figure 6.6 Aerial photograph and map of Abrahams Bosom Beach showing embayment morphology and study site location. A schematic map is presented showing the sites of cores, excavated faces and grab sampling locations. The location of cross-section A-A1 is marked along with the extent of deposition (run-up) for each event.

To attain an idea of the dynamics involved in the washover deposits high resolution particle size analysis was completed using the Malvern Mastersizer 2000 instrument, a laser-diffraction based instrument that has a analysis range of 0.04 –2000  $\mu\text{m}$ , thereby covering the entire size range of clay through to sand under the sizes defined by the Udden-Wentworth scale (Udden, 1914; Wentworth, 1922). The technique is limited by several factors in analyzing mud sized particles but is particularly applicable to sediments where the main constituents are sub-rounded to well-rounded sand-sized particles that are relatively abrasion resistant. The rounded predominantly quartzose

nature of the sediments studied makes them good candidates for analysis using the equivalent sphere techniques associated with diffraction methods. A review of the use of laser-diffraction particle size analysis in the earth sciences with particular reference to beach and estuarine sediments was provided (Lario *et al.* 2001). This review outlines much of the early literature on the technique, its basic principles and development over the last 15 years.

### **6.5 Stratigraphy, lithology and deposit characteristics**

In vertical profile the washover deposits consist of a characteristic sequence of layered sands to which the layered appearance can possibly be attributed to variations in heavy minerals and shell hash. Dominated by sand-sized particles, the washover deposits form distinct sedimentological units separated by slightly muddy sands that record periods of low energy estuarine deposition. Although only intersected at the base of core ABBP3, it is likely that much of the washover/estuarine sequence is underlain by a slightly mottled dark brown muddy sand that overlies bedrock and is possibly of Pleistocene age.

#### **6.5.1 Generalised embayment stratigraphy**

The generalised stratigraphy of the sequence is presented in cross-section A-A<sub>1</sub> (Figure 6.7) and shows a vertical sequence of three storm deposits that are separated by lenses of muddy sand with small amounts of organic material (Figure 6.8). In some places (offset from stratigraphic transect) the upper deposit (July 2001) is separated from the underlying older sequence by soil development due to the smaller run-up of the March event not covering the poorly developed soil.

Bedding surfaces observed in excavated faces along the central transect of the estuary (Figure 6.9) infer evidence of both subaerial vertical and subaqueous landward accretion with foreset bedding developed as the washover reaches the estuary and subaqueous deposition is instigated. Although evident in both excavated faces and unit morphology, this feature was hard to distinguish in cored samples.

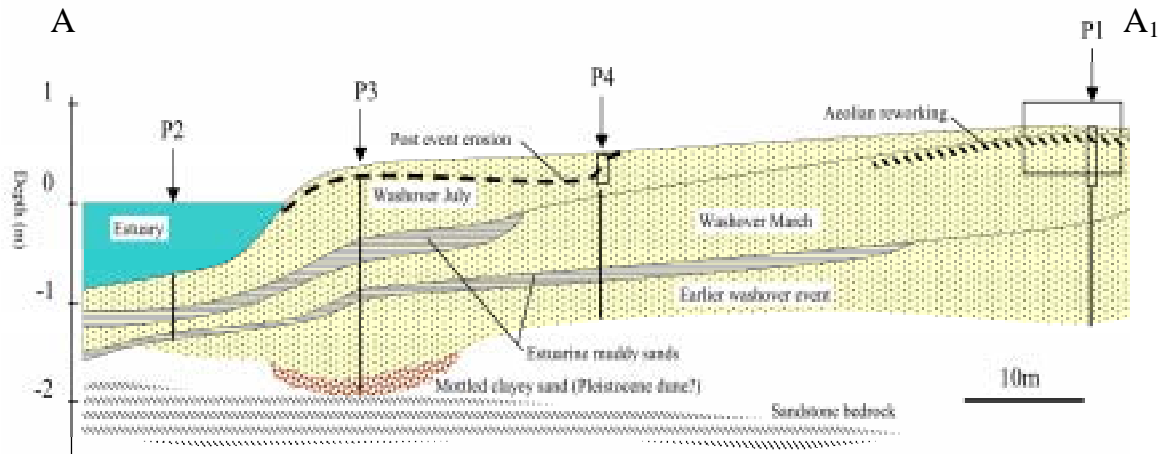


Figure 6.7 Cross section A-A<sub>1</sub> showing the shallow subsurface stratigraphy of the embayment and the presence of two recent storm washover deposits that overlie corresponding estuarine muds. A schematic log for core P3 is presented in Figure 6.8.

## 6.5.2 Facies characteristics

Four facies are assigned based on sediment analysis outlined in Section 6.4.3. The storm deposits are then subdivided further into facies under the scheme of Sedgwick and Davis (2003) wherein the stratified sands are further divided into three microfacies associated with individual sequences within the unit.

### 6.5.2.1 Basal clayey silty sand

The basal clayey sand is a dark coloured unit that contains up to 26.3% mud (23.9% silt, 2.4 % clay) and is found only in core ABBP3. In places the unit appears mottled and partly lithified although still friable. The samples collected share many of the characteristics of 'coffee rock' a common rock unit formed in coastal dunes that is thought to form where iron oxides and organic matter, which have leached through the soil profile, are precipitated at or above a fluctuating watertable.

### 6.5.2.2 Estuarine slightly muddy sands

Periods of estuarine sedimentation are recorded by a relative increase in very fine sand and mud (Figures 6.7 and 6.8) in sediment cores. The sedimentary unit appears in cores as darker coloured fine muddy sands with small amounts of organic debris and a relative increase in very fine sand deposited by aeolian processes. It is important to note here that some of the sand sized sediment is likely to have been transported to the estuary after erosion of the sandstone dominated catchment.

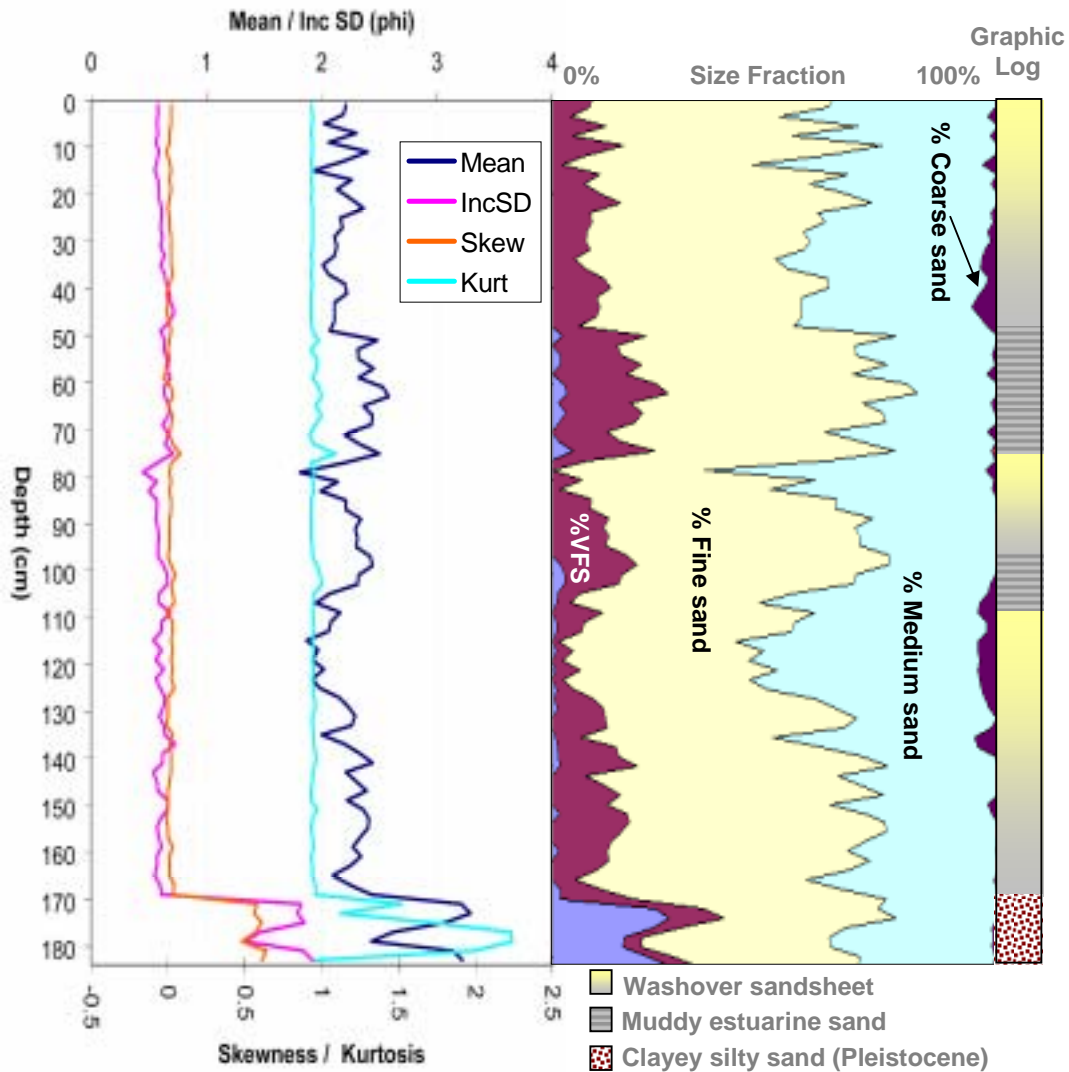


Figure 6.8 - Schematic stratigraphy present in core ABBP3 as demonstrated by laser diffraction particle size analysis on core samples taken at 2 cm intervals throughout the core. A sequence of estuarine muddy sand and clean marine sand lenses is evident.

#### 6.5.2.3 Washover sands (sub-aqueous)

In contrast to the slightly muddy fine sands of the estuarine units, the washover sands contain an abundance of fine-, medium- and coarse-grained sand (Figure 6.8). These units, when intersected, generally exhibit a fining upward in particle size due to preferential sorting in suspension in the estuary (Figures 6.8 and 6.11). This difference in sorting contrasts with the subaerial facies mentioned below.

#### 6.5.2.4 Subaerial sandy washover facies

The subaerial facies, that is those above the water line of the estuary, are observed in excavated faces and consist of a series of low angle ( $<5^\circ$ ) landward-dipping beds that

exhibit laminar stratification. This unit is dominated by fine- to medium- grained quartz sand with minor amounts of mature heavy minerals, carbonate shell and organic debris. Organic debris such as woody matter and seaweed was also found rafted at the margin of the deposit (Figure 6.9).

#### 6.5.2.5 Internal laminations and graded microfacies

Inspection of excavated faces highlighted a sequence of thin horizontal laminae in the mid parts of the deposit, which is consistent with the description of washover deposits from southern United States (Figure 6.10; Sedgwick and Davis, 2003). The base of each layer is usually characterized by darker coloured quartz sand and relatively abundant heavy minerals although at no times do the heavy minerals exceed 3%. This grades to a quartz sand with little heavy mineral content that grades further to a quartz sand with shell hash, a layer that is often absent possibly a result of erosion by the succeeding wave pulse (Figure 6.11).

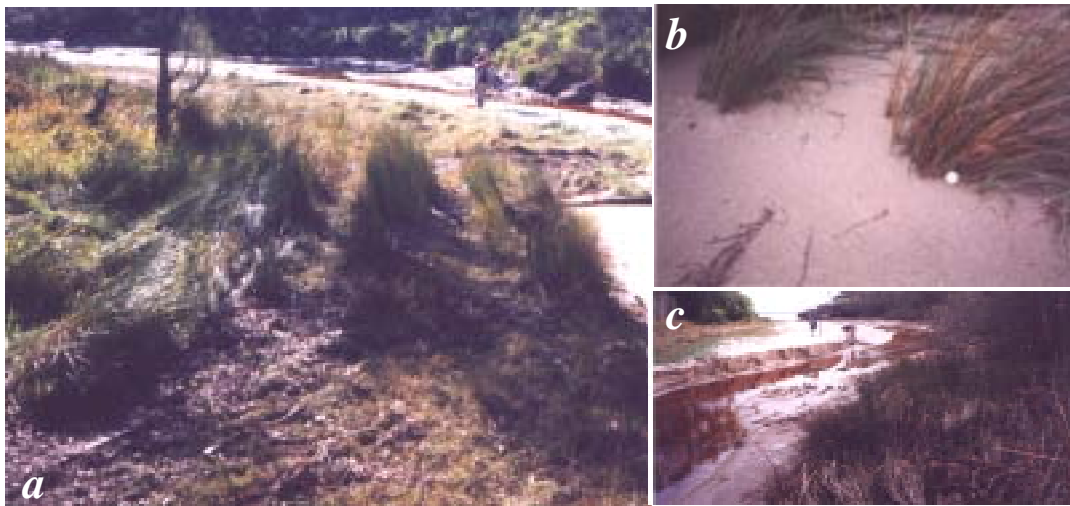


Figure 6.9 – Photographs of a) Rafted organic debris (foreground) found at the margin of the deposit. The debris consists of numerous small logs, twigs and seaweed. b) sand overlying reed beds on the margin of the lagoon and c) eroded reed beds in the centre of the photo.

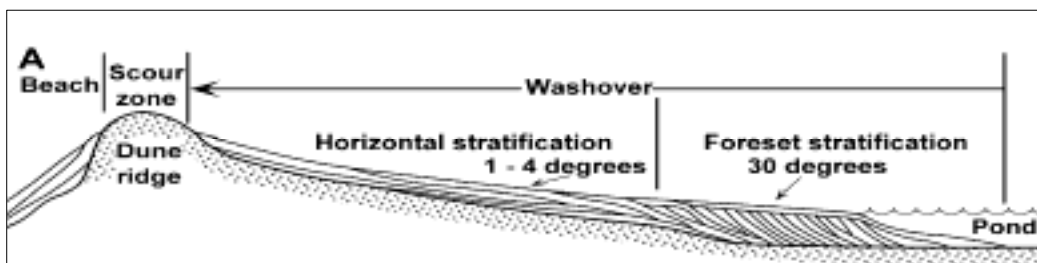


Figure 6.10 – Schematic model of washover stratigraphy from Sedgwick and Davis (2003).

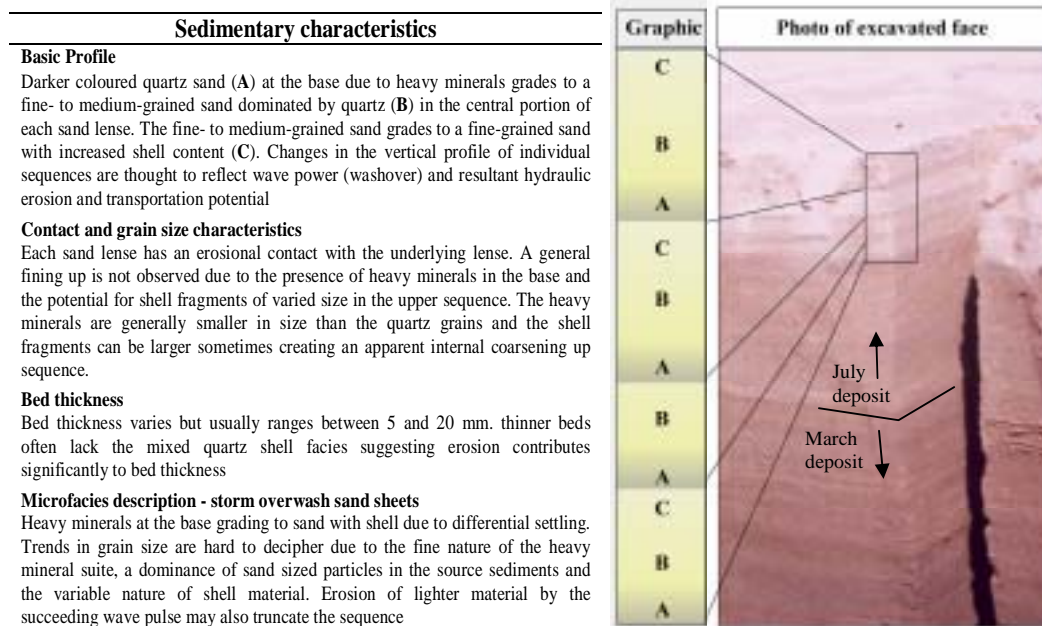


Figure 6.11 Analysis of the internal sedimentology of storm deposits from an excavated face (ASABBF1) at Abrahams Bosom Beach. Apparent fining-up sequences are not defined in elementary measures from the raw samples (mean, std deviation, skewness etc) but can be defined from changes in the population of sand classes (Figures 6.8; 6.12). The microfacies is defined as containing three sub facies labeled A, B and C and described in the text.

### 6.5.3 Microfaunal associations

Very few microfauna (maximum of 3 tests in ~6 g) were found in any of the washover unit samples and is most likely indicative of the source sediments being obtained from the relatively high energy nearshore, shoreface, beach and dune (barrier) environments. This hypothesis is supported by the broken and rounded appearance of the few tests recovered along with the sandy quartz dominated nature of the sediments found in each unit. Often washover deposits characteristically contain very little information the use in faunal associations (Davies and Haslett, 2000) and are dominated by sandy beach face material which is usually composed of sandy sediments with no or broken microfaunal assemblages. This concept also suggests that any population study will be tainted by selective destruction of particularly fragile tests conserving a record of only the most robust of fauna. The estuarine mud units contained no calcareous microfossils but did contain a number of pollen grains (cf. *Acacia* sp.) most likely derived from the catchment. In some samples organic remains of leaves and reeds were apparent although these were unidentifiable within the core-sampled medium.



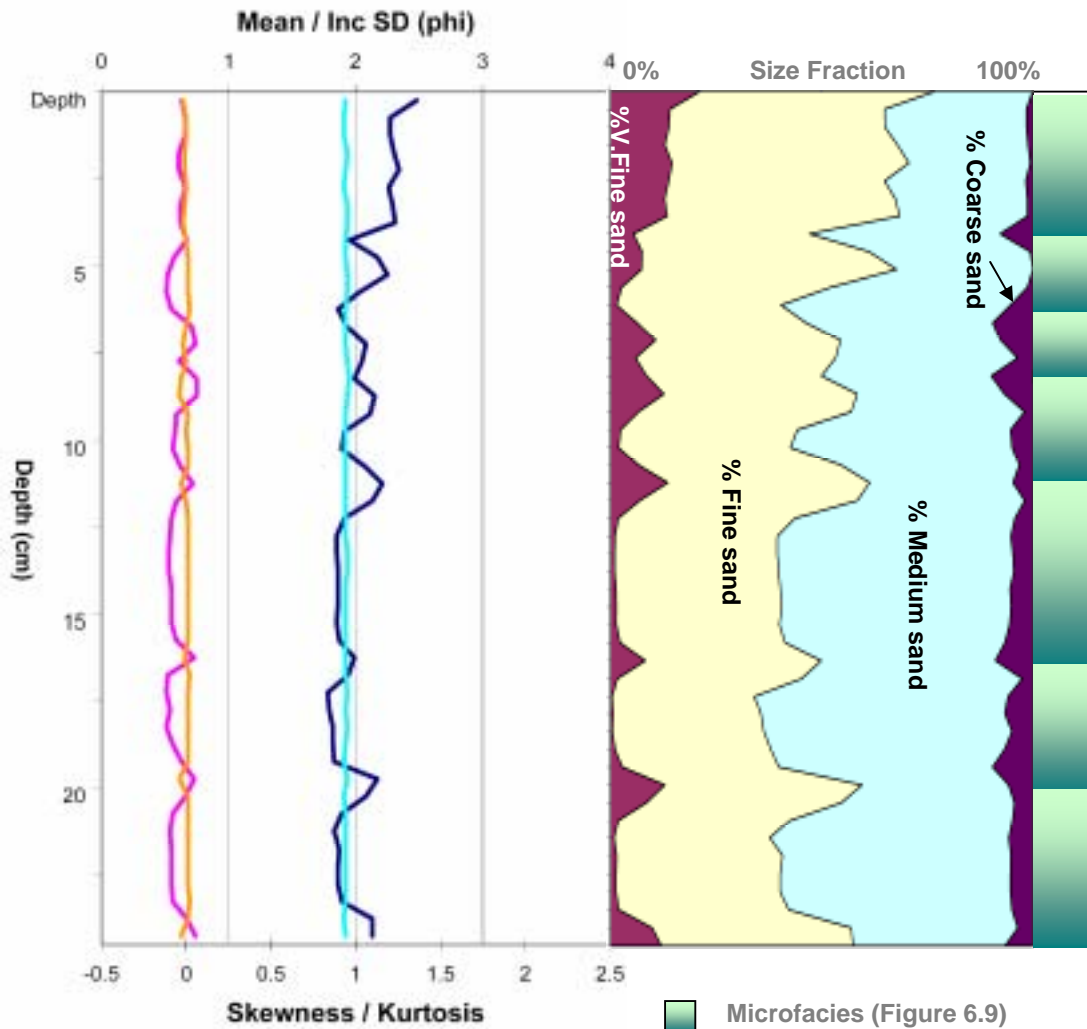


Figure 6.12 – High-resolution particle size analysis (5 mm intervals) of the July storm deposit from core ASABBP2 (starting at 15 cm depth). The grading is not clearly observable from mean grain size or sorting values. The grading is observed in the plot of sand fractions where coarse basal lenses are observed to grade up to fine sand.

#### 6.5.4 Heavy mineral analysis

Six samples from the washover sand deposits (3 subaqueous and 3 subaerial) were inspected under a binocular microscope to examine the heavy mineral suite of the sediments. Heavy mineral analysis identified a mature suite of heavy minerals dominated by zircon, rutile and tourmaline with approximately 5-15% carbonate. This heavy mineral suite is similar to that identified by Hareddy (2003) and Switzer *et al.* (in press) as indicative of barrier spit and shoreface sediments in the Minnamurra embayment approximately 30 km to the north.



### 6.5.5 Statistics

Basic statistical analysis was conducted using the JMP V5.0 statistical program with the analytical sedimentology results from all samples. Sediments from the washover sandsheets exhibit a particle size distribution dominated by fine-, medium- and coarse-grained sand that contrasts with the separating estuarine slightly muddy sand facies that contains a small mud sized population dominated by silt (Figures 6.8, 6.12 and 6.13).

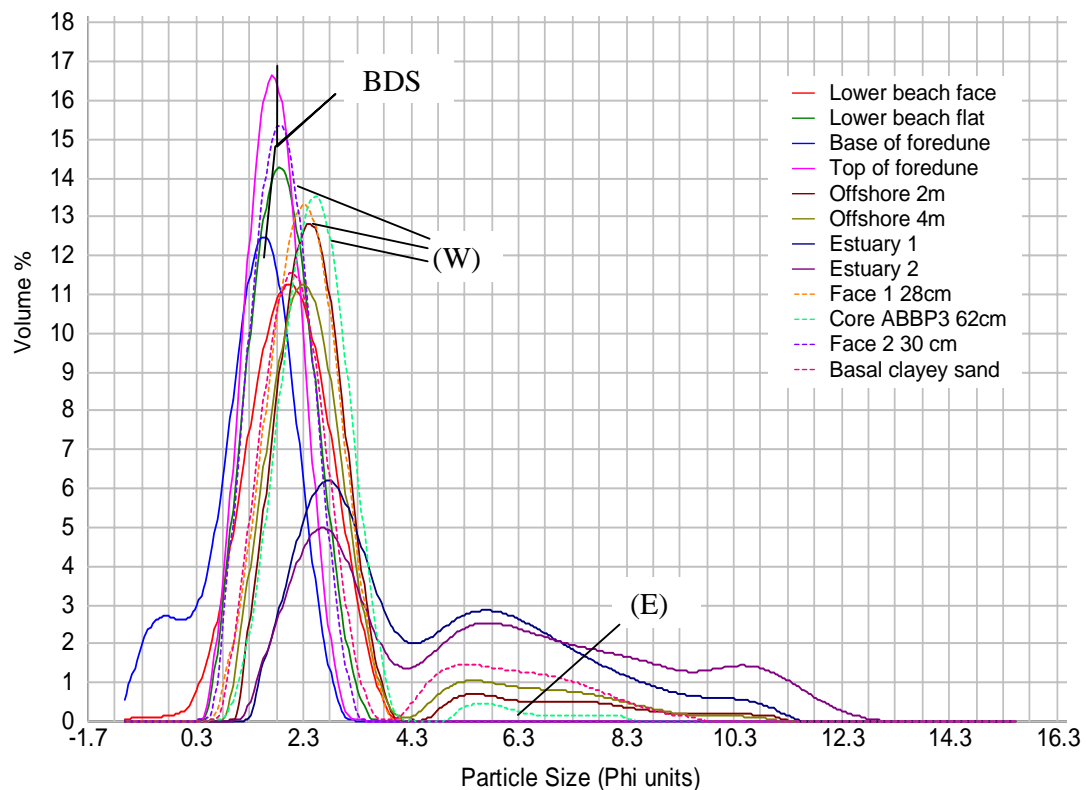


Figure 6.13 Plot of particle size distributions from a range of environments at Abrahams Bosom Beach note that the washover deposits labeled (W) are more poorly sorted than the seaward dune, beach and shoreface (BDS) samples. The estuarine samples (E) are differentiated by a small peak in mud sized material

#### 6.5.5.1 Bivariate plots and cluster analysis

The bivariate plots, plotting mean grain size versus standard deviation (sorting; Figure 6.14) shows that almost all washover sandsheet samples plot in a two well-defined clusters that also contain the grab samples collected from the beach flat and beachface. Note that many of the samples overlie each other on the plot as more than 300 samples are plotted in this figure. The clusters highlighted in Figure 6.13 failed to show a clear distinction between the estuarine deposits and those of the sandsheets.

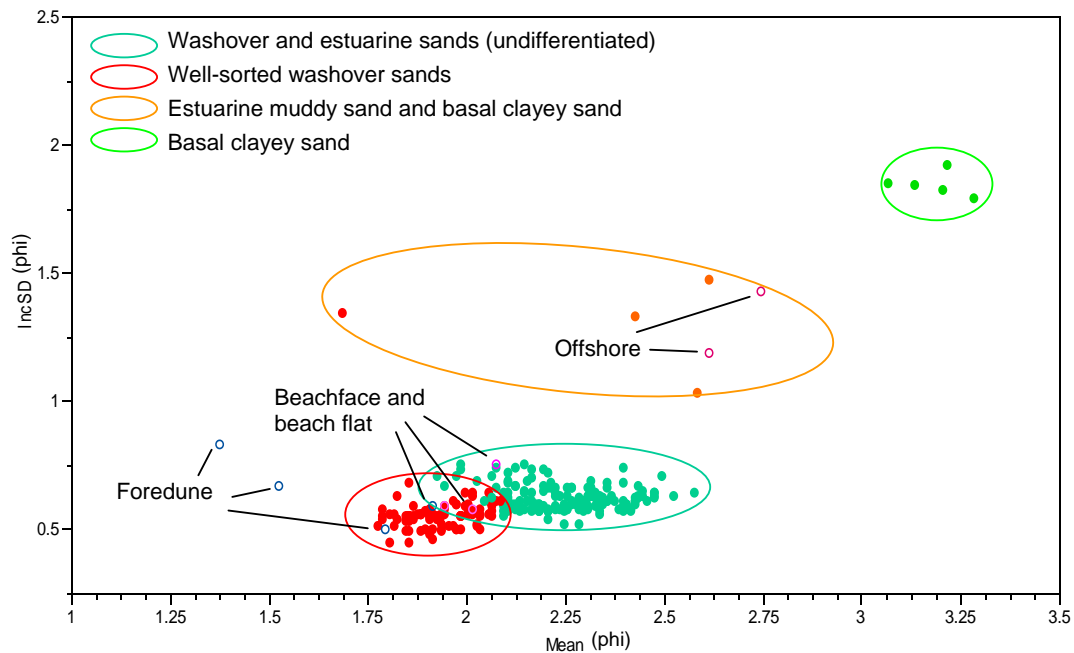


Figure 6.14 Bivariate plot of mean particle size against sorting (*Inc SD* = inclusive standard deviation) showing distinct clusters based on Ward clustering (Appendix 6.1) of all samples from Abrahams Bosom Beach. Also plotted are grab samples from the foredune, beach face, beach flat and offshore. It is hypothesized that much of the material incorporated in the washover sand sheet is obtained from the shoreface and beach flat along with a small percentage from the offshore zone.

## 6.6 Sediment sources

A comparison of particle size distributions and sediment characteristics with grab samples from the estuary dune, beach face and offshore zone (Figure 6.13) suggests that sorting demonstrated by the washover facies is most likely due to the incorporation of fine material (<63 $\mu$ m) from offshore and not from the estuary as the washover deposits lack the organic-rich, silty characteristics of sediments collected from the estuary. The fine nature of the offshore samples is most likely related to the predominantly low wave energy of the embayment. The longevity of these sediments is undetermined but it is likely that sediment composition would vary significantly in relation to variations in runoff and wave energy. The fine nature of the sediments may be a product of the high run-off, low wave energy environments that preceded the collection of the samples and may not be truly indicative of the average sediment size of this environment.

## 6.7 Depositional model for storm washover deposits behind a sandy dune system at Abrahams Bosom Beach.

The storm deposited sediments found at Abrahams Bosom Beach reveal a series of unique characteristics that allow the development of a depositional model for storm

washover deposits from the southeast Australian coast. Before outlining the depositional characteristics of the deposit it is important to reiterate the equilibrium concept outlined in Chapter 3.

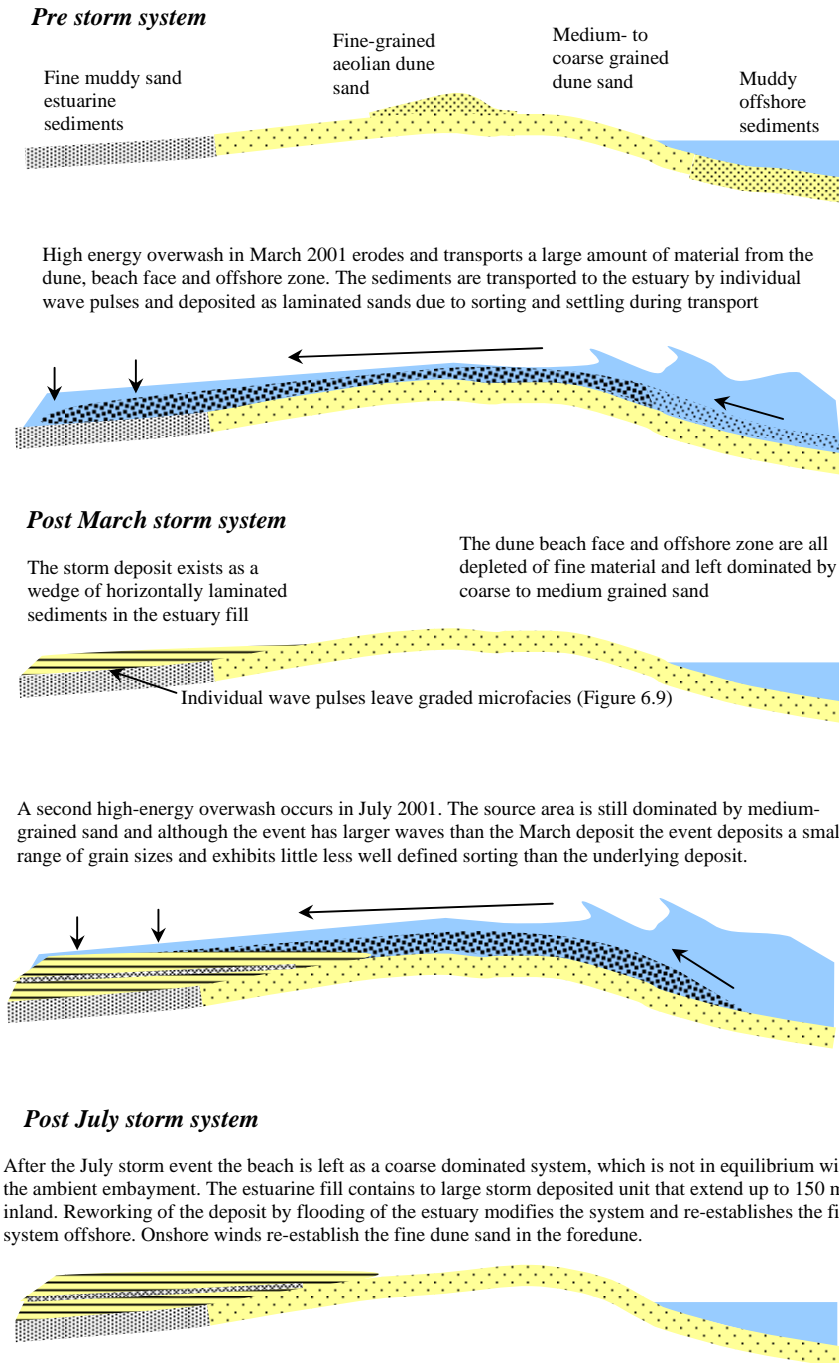
Abrahams Bosom Beach is a predominantly a very low-energy environment that experiences low wave energy that often results in a build up of fine material offshore, particularly after periods of heavy rain that flushes the small estuary. Large storm events, such as those of March and July 2001 generate large swell from the east to northeast causing high energy conditions that are in disequilibrium with this ambient environment. Sediments are mobilised during these higher energy events and very large events such as those identified in this study can breach the small dune system and carry sediments into the estuary. It follows that the internal sedimentology of any washover sediments deposited into the estuary will, at least in part reflect the conditions of the embayment immediately preceding the depositional event.

These inherited sediment characteristics are apparent in the two storm deposits studied here. Figure 6.15 shows a depositional model for both events. Although both deposits exhibit many similar characteristics in grading, extent and composition the second (July) deposit is slightly more well sorted than the first (March) deposit. The March deposit is finer grained and exhibits more well-defined laminae due to the presence of a wider range of grain sizes incorporated from offshore, back beach, dune environments. The July event is hypothesised to have eroded material of a much smaller range of grain sizes as considerably more beach face material was eroded and the resulting deposit exhibits grading that is considerably less well defined than that underlying sequence.

#### **6.7.1 Fine-grained storm deposits from high-energy coasts**

This study indicates that periodic storm-generated swells that strike the coast from the north to northeast are not in equilibrium with the ambient setting of north-facing embayments on this coast. Therefore such embayments should be considered the most likely to record a depositional signature of storm events on this coast. The ambient setting of the Abrahams Bosom Beach embayment is the product of the dominant southeast swell and associated beach set-up and it is implied here that such embayments are likely to be breached during episodic high-energy events due to the low energy nature of the dune and beach systems. The fact that many coastal communities, such as

the nearby community of Currarong, are located on small beach ridge systems characteristic of the southern end of embayments makes such embayments vulnerable to washover from large events from the northeast to east. It is likely that such low energy sites would be very likely to suffer damage during large storm swells.



Figurer 6.15 Depositional model for storm washover at Abrahams Bosom beach. The March event eroded and deposited significantly more fine material than the July event due to the low energy characteristics of the embayment at the time. The second (July) deposit contains a much smaller range of grain sizes and reflects significantly more erosion of the beachface and nearshore.

## 6.8 Synthesis

This project provides a unique opportunity to study the sedimentary characteristics of washover sedimentation in an estuary from the southeast coast of Australia that may provide a modern analog to assist in the characterisation of washover sand sheets identified in Holocene cores taken from estuaries along the southeast coast. The storm deposits of Abrahams Bosom Beach are characterised by a series of well-defined graded microfacies with low angle to horizontal bedding that grade landward to steep angled foreset bedding produced during subaqueous deposition. This structure is recognizable in both cores and excavated faces. It is also apparent that source material for this deposit is the beach face and frontal dune sequence as the washover deposits contain only sand sized particles with minor shell hash and very little heavy minerals along with an absence of microfauna (Figure 6.12). One would expect that storm deposits from other estuaries that rest behind small dune systems in low energy embayments along this coast would share at least some of the characteristics of this deposit.

## 6.9 Conclusions

- This study presents the first study of the internal sedimentology of fine-grained storm washover deposits. The study provides a modern analog for the analysis of plaeostorminess on high-energy siliclastic coasts.
- The washover deposits are dominated by sand and exhibit small graded microfacies indicative of repeated pulses of energy that is thought to be representative of individual waves entering the estuary.
- Deposition of the graded facies follows the depositional model of Sedgwick and Davis (2003) with horizontally laminated beds observed in terrestrially exposed faces and steeply dipping foreset bedding (poorly defined in cores) occurring in the estuary.
- The sediments of the washover deposits are more poorly sorted than grab samples from the shoreface, beach flat and dune. This is indicative of the range of particle sizes incorporated from different environments.

## Chapter 7.

### Killalea lagoon – Large-scale washover sedimentation in a freshwater coastal lagoon (ICOLL)

#### Introduction

Killalea Lagoon lies near Bass Point (Figure 7.1). The lagoon is predominantly a freshwater swamp that is only rarely and temporarily inundated by storm conditions at its seaward margin. A sequence of estuarine and back barrier lagoonal clays and peats occurs to depths of ~25 m and records Quaternary sea level fluctuations in the small embayment. A Holocene barrier system onlaps the sequence to the south and is composed of clean beach and aeolian sand.

A thin, laterally extensive sandy deposit exists in the upper embayment fill of the lagoon sequence and is thought to represent a large-scale, late-Holocene washover event. Coring of the sandsheet deposit suggests it extends continuously up to 600 m inland and tapers landward rising to ~1.6 m AHD.



Figure 7.1 Location of Killalea Lagoon. The lagoon is located on the southern side of Bass Point and is open to high-energy swell from the southeast. The lagoon has a very small catchment with little fluvial input of sediment.

The sandsheet deposit sharply overlies the upper part of the peaty lagoonal sequence and consists of fine- to medium-grained sand with some organic material dominated by fragments and rootlets of *Spinifex* grasses. In places the sand is overlain by accumulations of organic-rich silt that contain charophytes suggesting re-establishment of lagoon conditions. Microfaunal investigation identified a general lack of carbonate microfauna throughout the cores, most likely the result of dissolution due to the

presence of organic acids associated with the freshwater lagoonal environment. Investigation of two cores identified large populations of charophyte flora at various intervals throughout the upper embayment fill. Charophytes remains were absent throughout the sandsheet deposit but occurred both above and below it indicating a return to lagoonal sedimentation.

### **7.1 Lagoon evolution (ICOLLS)**

Killalea Lagoon (Figure 7.2) is a mature estuary that can be considered an end member of the estuarine model popularized by Roy and others (Roy, 1984; Roy *et al.*, 1994, 2001). New South Wales estuaries can be classified into three categories based on their entrance conditions (Roy 1984; Roy *et al.*, 2001): drowned river valley estuaries; barrier estuaries; and saline coastal lakes. Under this system Killalea Lagoon falls into the category of ‘saline coastal lakes’. Roy (1984) defined saline coastal lakes as small features located in coastal valleys where shallow mud basins and muddy fluvial deposits are the dominant sedimentary environments, with relative fluvial input characteristically very small.

These estuarine systems can also be classified as either ‘permanently open’ and ‘ephemeral’ or ‘intermittent’ based on their entrance characteristics. Killalea Lagoon fits in the latter class to which there are two sub-classes: intermittently closing and opening lakes and lagoons (ICOLL) and seasonally open tidal inlets (SOTI) (Kjerfve, 1994). Both of these estuarine systems are open, either by natural or artificial means, to the ocean at irregular (ICOLL) or regular (SOTI) intervals. ICOLL’s and SOTI’s are coastal lagoons, which occupy 13% of coastal areas globally and are broadly defined (Kjerfve, 1994) as a ‘shallow coastal water bodies separated from the ocean by a barrier, connected at least intermittently to the ocean by one or more restricted inlets, and usually oriented shore-parallel’.



Figure 7.2 a) Panoramic view of Killalea Lagoon looking northeast showing the small barrier system and the back barrier lagoon. The red arrow marks the landward extent of the sandsheet along the eastern margin of the lagoon. b) Topographic map of Killalea Lagoon and Bass Point. Killalea Lagoon is orientated to the southeast and receives consist high wave energy from the southeast. The lagoon lies in a small depression that has minimal fluvial input from the low (<50 m) surrounding hills of latite bedrock. (Map from LPI, 2002)

Under most conditions lake waters are saline to brackish but non tidal. Winds cause mixing and some transport in larger lakes. Normal freshwater inputs are accommodated by evaporation and percolation through the porous sand barrier. Fresh water conditions accompany heavy rains at which time inlets may be breached by super-elevated lake waters and storm waves. The lake then becomes saline and tidal for weeks to months until open ocean processes reform the beach berm across the inlet.

ICOLL's often occur in microtidal, wave-dominated coastal environments where strong seasonal changes of littoral transport and/or rainfall are experienced. They are closed to the ocean due to the formation of a sand bar at the inlet entrance when the streamflows are low and/or longshore transport is high (Roy, 1984; Hodgkin and Clark, 1988; Gordon, 1990; Wikramanaike and Pattiaratchi, 1999). High river discharge can erode the sand bar and thus open the inlet to the ocean. Many other ICOLL's exist along the New South Wales coast Roy *et al.* 2001). Most of the lakes and lagoons lie behind a barrier system that onlaps a sequence of estuarine and back-barrier lagoonal clays. The



barrier is usually composed of clean beach sand and is topped can be topped by large accumulation of fine aeolian sand that exists as a series of transgressive dunes.

### 7.1.2 Action of storms on Killalea beach

Killalea is open to the dominant storm derived swell from the southeast (Section 2.4). Very large swells, in excess of 4 m are generally erosional in this system. Erosion of the incipient foredune results in deposition (accretion) in the nearshore zone (Figure 7.2). Lower wave energy after storms results in accretion on the beach face and the reformation of the incipient dune. Repeated storm attack can cause severe erosion in the form of an erosional scarp due to an insufficient time frame to re-establish the beach face.

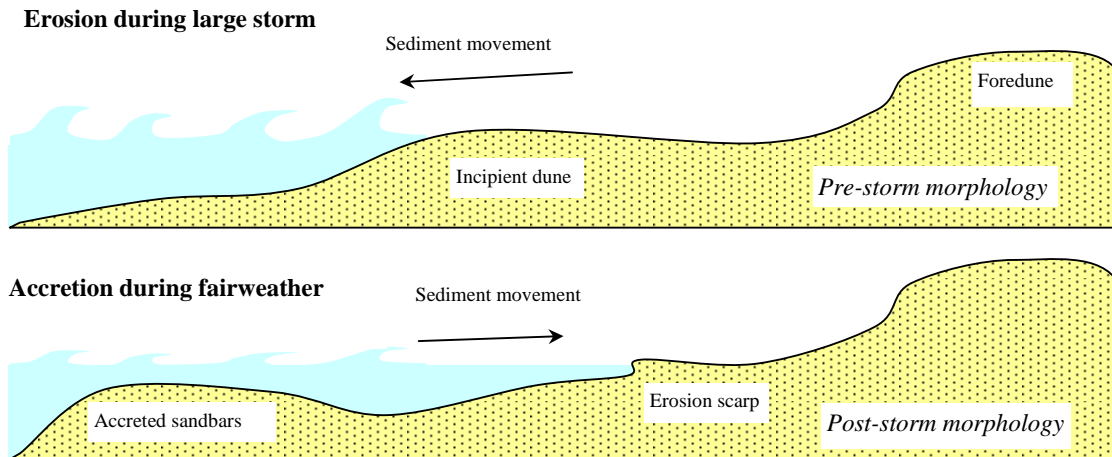


Figure 7.2a Generalised schematic diagram of the action of storms on high-energy beaches based on (Short and Wright, 1981). Storms in consistently high energy systems like that of Killalea Lagoon are generally erosional and contrast with the depositional features described for Abrahams Bosom Beach (Chapter 6).

Unlike the system studied at Abrahams Bosom Beach (Chapter 6), the system at Killalea is in equilibrium with high-energy conditions. This means that large storm waves generally have little noticeable affect on the beach. Local historical records, although subjective and fragmented, suggest that the lagoon is very rarely breached. A local fisherman suggested that the most recent time the lagoon was breached was in the storm of May 1974. This is supported by the near surface stratigraphy of the lagoon entrance, which suggested very few inundation events.

## 7.2 Lagoon sediments

Water depths in the lagoon are rarely more than 1 m and samples taken from the organic-rich lagoon floor suggest that the major components are reed fragments. The most common identifiable remains within the lagoonal sediment are the reproductive bodies and fragments of freshwater algae (charophytes) and seeds, with rare ostracoda (Figure 7.3).



*Figure 7.3 Photograph of the lagoon bottom showing abundant organic material including small lilies, algae, reeds and grasses.*

### **7.3 Coring program**

A three-stage program was implemented to investigate the stratigraphy of the embayment with a focus of obtaining cores to investigate the lateral extent and stratigraphic contact of the marine sand lense in the upper part of the sequence (Figure 7.4). The first stage of the drilling program involved revisiting existing core logs from B.G. Jones and I. Eliot that focused on the southern part of the lagoon with the aim of investigating the Quaternary evolution of the embayment. Coring in this early study identified a marine sand lense in the upper fill of the embayment which Jones (1996) provisionally interpreted as a storm deposit.

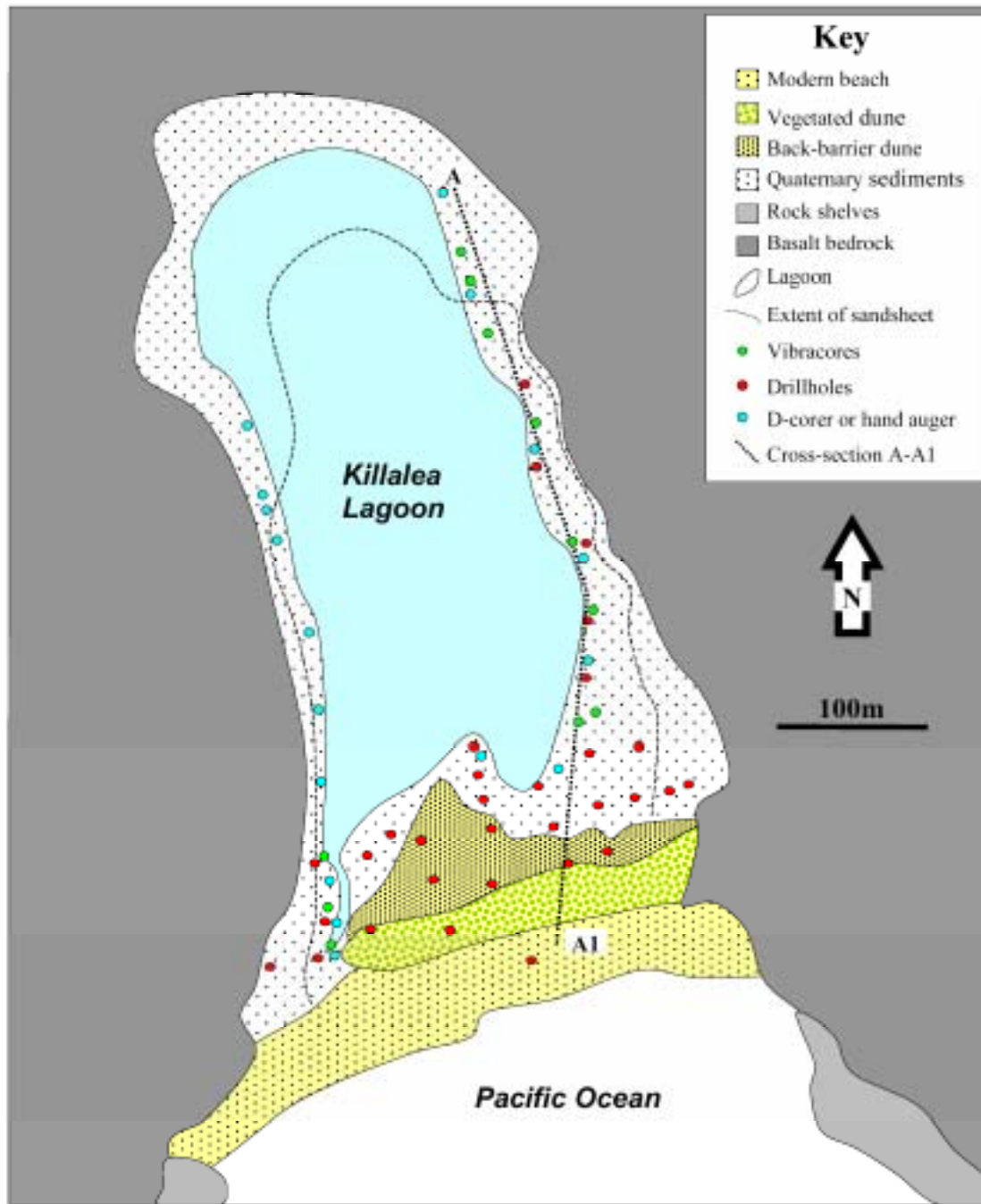


Figure 7.4 Map of Killalea Lagoon showing morphological units along with locations of drillholes and the extent of the washover sandsheet. Also marked is the location of the cross-section A-A1. The chief area of investigation was the eastern margin of the lagoon. This area was selected as only limited opportunity was available for drilling and the drilling could focus on the previous research (drillholes in red) of B.G. Jones and I. Eliot.

Analysis of logs and cross-sections provided by Jones (pers. comm., 2000) allowed the development of a strategically targeted, shallow, low impact subsurface drilling

program. A well-planned drilling program was required as Killalea Lagoon is a State Recreation Reserve. Initial enquiries to the Reserve Board of Directors indicated that drilling would be limited to the lagoon margins and that no drilling could be conducted within the lagoon due to environmental concerns as the lagoon supports populations of several endangered animals including the Green and Golden Bell Frog (*Litoria aurea*) and is protected under the State Environmental Planning Policy No 14 (Coastal Wetlands).

A drilling program involving hand auger, D-corer and limited vibracoring was proposed and presented to the board of Killalea State Park in September 2001. The board of Killalea State Recreation Park agreed to a slightly modified drilling program on the 17 October 2001. Permission was granted to investigate the eastern margin of the lagoon (a priority area highlighted in the proposal) as it would complement the most landward extent of coring by the B.G. Jones and I. Eliot during 1979-1981.

Low impact techniques of hand augering and D-coring were used to delineate the extent of the deposit on the western margin and to investigate the geological record of lagoon breaches in the southwestern corner of the lagoon. Subsequent amendments to the agreement were put to the board through email with the Park Manager. An example of this involved the granting of permission for ground penetrating radar (GPR) investigation (Chapter 9) of the dunes and back-dune environment.

Complementing the coring program was a grab sampling program (Figure 7.5) of the morphological units identified in Figure 7.4. Grab samples were obtained from modern environments including the hillslopes, lagoon, aeolian dunes system, foredune, beach face and nearshore zone. These samples complemented samples from offshore obtained for the study of Hareddy (2003) where samples were collected to depths in excess of 60 m (Figure 7.5). These samples were collected to compare modern sedimentary environments with the sediments forming the sandsheet and its confining units.

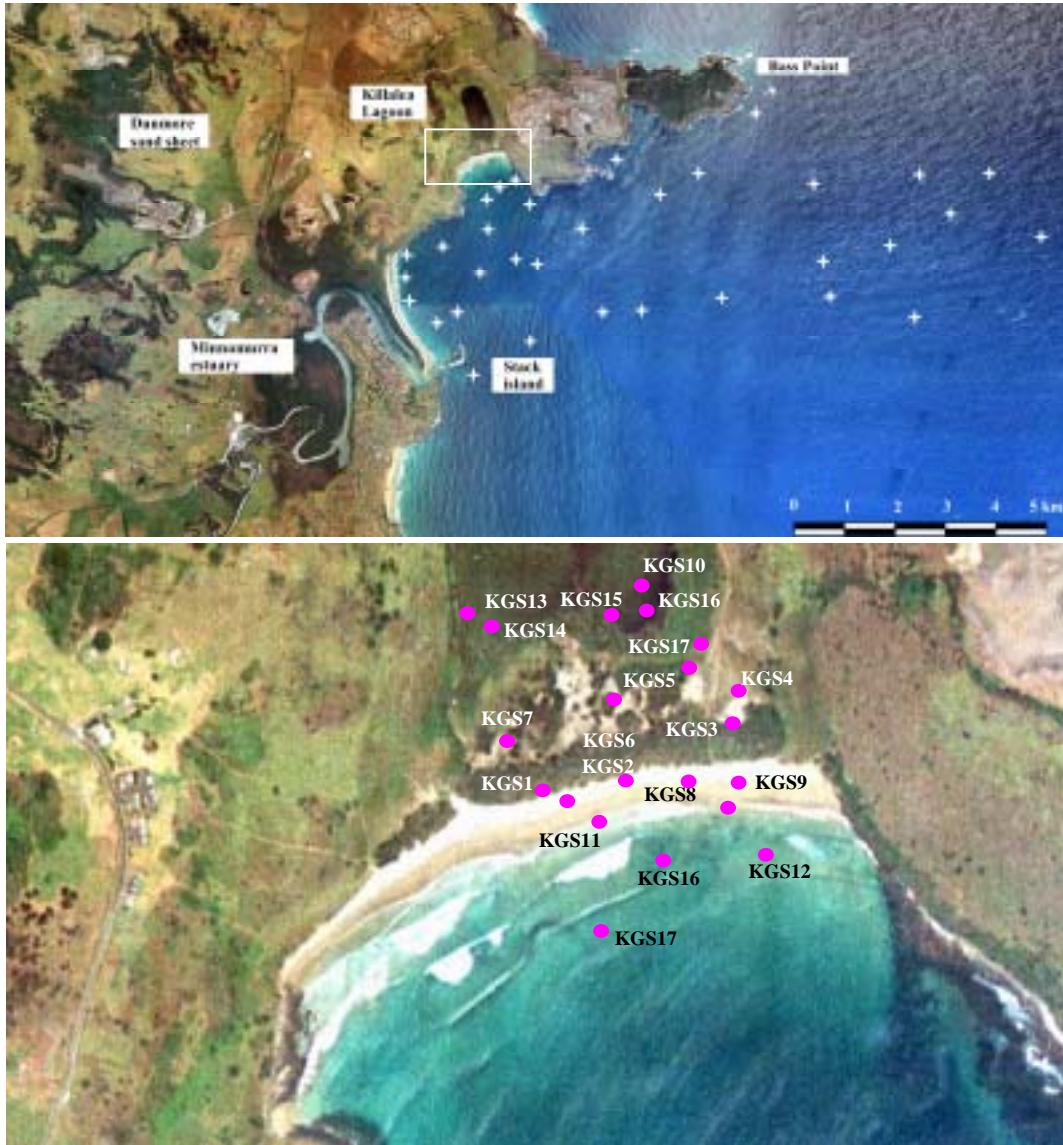


Figure 7.5 a) Location of samples collected for sediment and heavy mineral analysis by Haredy (2003). These offshore deposits were compared to the heavy mineral suite from the sandsheet (reproduced from Switzer et al., in press). b) grab samples collected from morphological units around Killalea Lagoon. The sampling program focused on the sediments of the dune and beach system as they are hypothesized to be the major source of sediments in the sandsheet.

### 7.3.1 Sampling

Initial sediment sampling was conducted on cores and grab samples using the techniques described in Section 5.5. Samples were collected at a minimum of 5 cm intervals through the cores, with extra samples taken across stratigraphic contacts and in areas of key interest including the washover sandsheet.

Sub-samples were also collected from key cores ASKVC3, ASKVC4, ASKVC5 and ASKVC6 for micropaleontology including charophyte flora and the preliminary analysis of diatom fauna. Two large sub-samples were also taken for detailed heavy mineral analysis. The sampling program for the deposit is summarised in Figure 5.6. Samples of sandy sediments were generally obtained by splitting dried samples using a riffle splitter. In many cases these sub-samples were then wet sieved at the appropriate sieve size in order to obtain representative samples with specified grain sizes. Sub samples were then prepared for each technique as outlined below. Obtaining representative sub-samples from peat and organic silty clay horizons involved taking between 6 and 15 small sub-samples from clean cut faces at random locations around the 1-5 cm slices of sediment (Figure 7.7). These small sub-samples were then combined to give a representative sample of the organic-rich sediments.

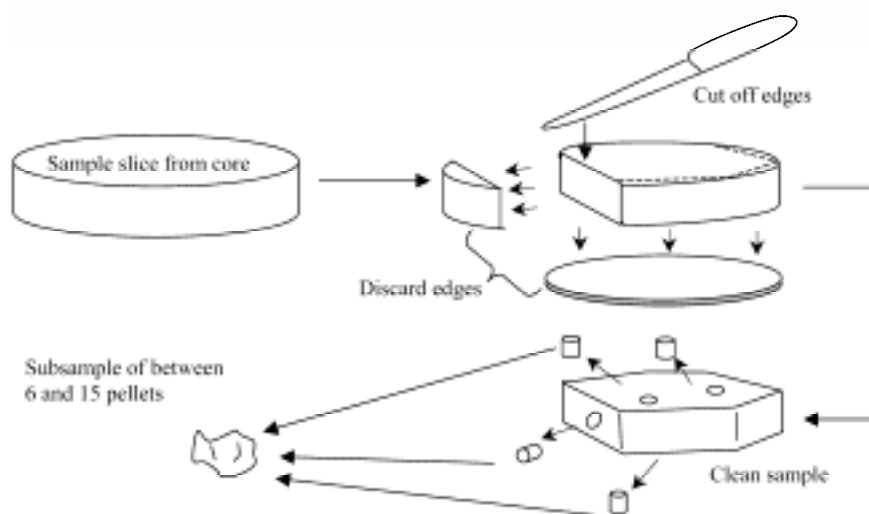


Figure 7.6 Schematic representation of the sampling program for obtaining representative sub-samples from peat and organic clay sediments from core samples collected at Killalea Lagoon

## 7.4 Sediment Analysis

Basic sediment analysis was conducted using techniques of particle size and elementary mineralogy as outlined in Section 5.6. Samples were prepared using hydrogen peroxide to remove organic material. Carbonate removal was not required as less than 5% carbonate was found in all samples with no visible carbonate observed in the sand samples. This is hypothesised to be due to organic acids moving through the groundwater system causing dissolution of any carbonate material. Testing of groundwater samples obtained from within the sandsheet during hand augering



indicated that pH of the groundwater was slightly acidic with readings of between 5.7 and 6.8 obtained from ten samples tested using a field pH meter.

## **7.5 Sedimentological techniques**

Particle size analysis, sediment composition, textural analysis, heavy mineral analysis and micropalaeontology were used as proxies to characterise the sediments of all geomorphic and stratigraphic units. Different techniques were often applied to particular units to develop an understanding of within unit variation and further characterise the depositional environment for particular units.

### **7.5.1 Particle size analysis**

Average particle size distributions for geomorphic and stratigraphic units obtained using the Malvern Masterizer are compared to highlight fundamental differences in sediment composition. This was conducted using comparative distributions, bi-variate plots of derived parameters (using inclusive graphic parameters) and cluster analysis. The inclusive graphics technique was previously outlined in Figure 5.6.

Percentage of sand, silt and clay along with inclusive graphic mean, inclusive graphic standard deviation, and graphical skewness and kurtosis were used as parameters for cluster analysis on grab samples and cores from the eastern transect in order to identify stratigraphic units and to identify sub-facies within the sand sheet deposit.

### **7.5.2 Sediment composition and textural analysis**

Sediment composition was characterised using particle size analysis and derived parameters along with inspection of selected sub-samples using a binocular microscope. Notes were made on individual sediment samples before compilation of results to form facies and landform descriptions. Units of particular interest, including the sand sheet and its confining peat, were further divided into sub-facies hypothesized to be indicative of subtle changes in depositional environment.

### **7.5.3 Heavy mineral analysis**

Microscopic inspection by the author identified the presence of metastable to ultrastable heavy minerals in the sandsheet deposit. Two samples were obtained from the sandsheets and compared to a study of the provenance and spatial distribution of heavy

minerals in the Minnamurra estuary, sandsheets of the Dunmore embayment and the adjacent shelf (Haredy, 2003). The heavy mineral assemblages in the fine sand fractions (63-250  $\mu\text{m}$ ) of 124 sediment samples were assessed using microscopic, EDAX and microprobe analyses by (Haredy, 2003). In addition to the dominant opaque minerals, twelve translucent heavy minerals species were identified. This was particularly relevant to the present study as the heavy mineral assemblage of the inner part of the outer shelf had previously been identified as occurring in overwash sand sheets found in the Dunmore embayment some 4km to the west (Switzer *et al.* in press).

#### 7.5.4 Micropalaeontology

Initial inspection of subsamples (>63  $\mu\text{m}$ ) collected from the sandsheet and its confining peat deposits by wet sieving indicated a relative absence of identifiable carbonate microfauna. Few ostracods were found in the modern lagoon samples and the uppermost sediment horizons. Small often-pitted shell fragments were found in some samples from the lagoon but are generally confined to the southern end of the lagoon and were possibly transported into the lagoon by aeolian processes. Very low concentrations of partially dissolved, often broken carbonate microfaunal material found in the sandsheet and underlying peat were unrecognizable at the species level.

The lack of or unrecognizable partially dissolved state of many shell fragments and calcareous microfaunal tests in the subsurface stratigraphy is most likely the result of dissolution due to carbonic acids within the groundwater. This hypothesis is supported by acidic pH found in the groundwater of the sand sheet (section 7.4) and the found in the subsurface stratigraphy.

Samples were subsequently collected for an initial investigation of the diatom fauna and charophyte flora from the sandsheet and confining peat beds. Samples for diatom analysis were sent to DIATOMA at the University of Adelaide where Dr John Tibby undertook the analysis using the method outlined below.

The samples (1  $\text{cm}^3$ ) for diatom analysis were taken from various intervals throughout cores ASKVC5 and ASKVC3. The samples were digested in 10 % hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) and 10% hydrochloric acid (HCl). The remaining material was diluted by a measured amount of distilled water and mounted with Naphrax. Counts were



undertaken on Olympus BH-2 and Zeiss Axioskop microscopes with differential interference contrast.

Subsamples from ASKVC5 and ASKVC6 were taken for charophyte analysis. Pre-soaking in water was required to soften and separate the numerous sub-samples from the cores prior to sieving, as they were composed mainly of fine silty sediment. The samples were then wet sieved with water, through 1000  $\mu\text{m}$  and 250  $\mu\text{m}$  mesh sieves respectively, in order to separate and remove materials not required as part of the study.

The samples were dried in small aluminium trays, in an oven at 50°C. With the aid of a Lieca MZ 12.5 stereoscope, all charophytes, and other organic and inorganic remains were sorted from each subsample using a 00 brush, and stored on slides.

Classification of each specimen was then carried out using a stereomicroscope. Identification of the specimens at genera and species level was carried out using Yassini and Jones (1995) for foraminifers and ostracods, and Garcia *et al.* (2002) for charophytes. Dr Adriana Garcia also assisted with the classification.

As the finer sieve size used in the wet sieving process was 250  $\mu\text{m}$ , it is possible that some taxa of charophytes were removed since the size of adult charophytes ranges from 200-1000  $\mu\text{m}$ .

## 7.6 Results

Analyses of core samples and grab samples from modern environments allowed direct comparison and interpretation of the subsurface stratigraphy of Killalea Lagoon. This was conducted in order to describe the Quaternary evolution of the embayment and to focus on the depositional environments of a thin laterally extensive sand sheet found in the upper fill of the lagoon sequence.

### 7.6.1 Stratigraphy

The general stratigraphy can be described as an onlapping highstand barrier sequence where a Holocene barrier system onlaps a sequence of estuarine and back-barrier lagoonal clays. The barrier is composed of clean beach sand and is topped by a large

accumulation of fine aeolian sand with a contemporary surface expression of a series of small well-vegetated transgressive dunes. The sandsheet in the upper fill of the lagoonal sequence is confined by lagoonal peat deposits with marked contrasts in internal sedimentology. The evolution of the barrier is discussed in Switzer *et al.* (2004b) and summarised schematically in Figure 7.7.

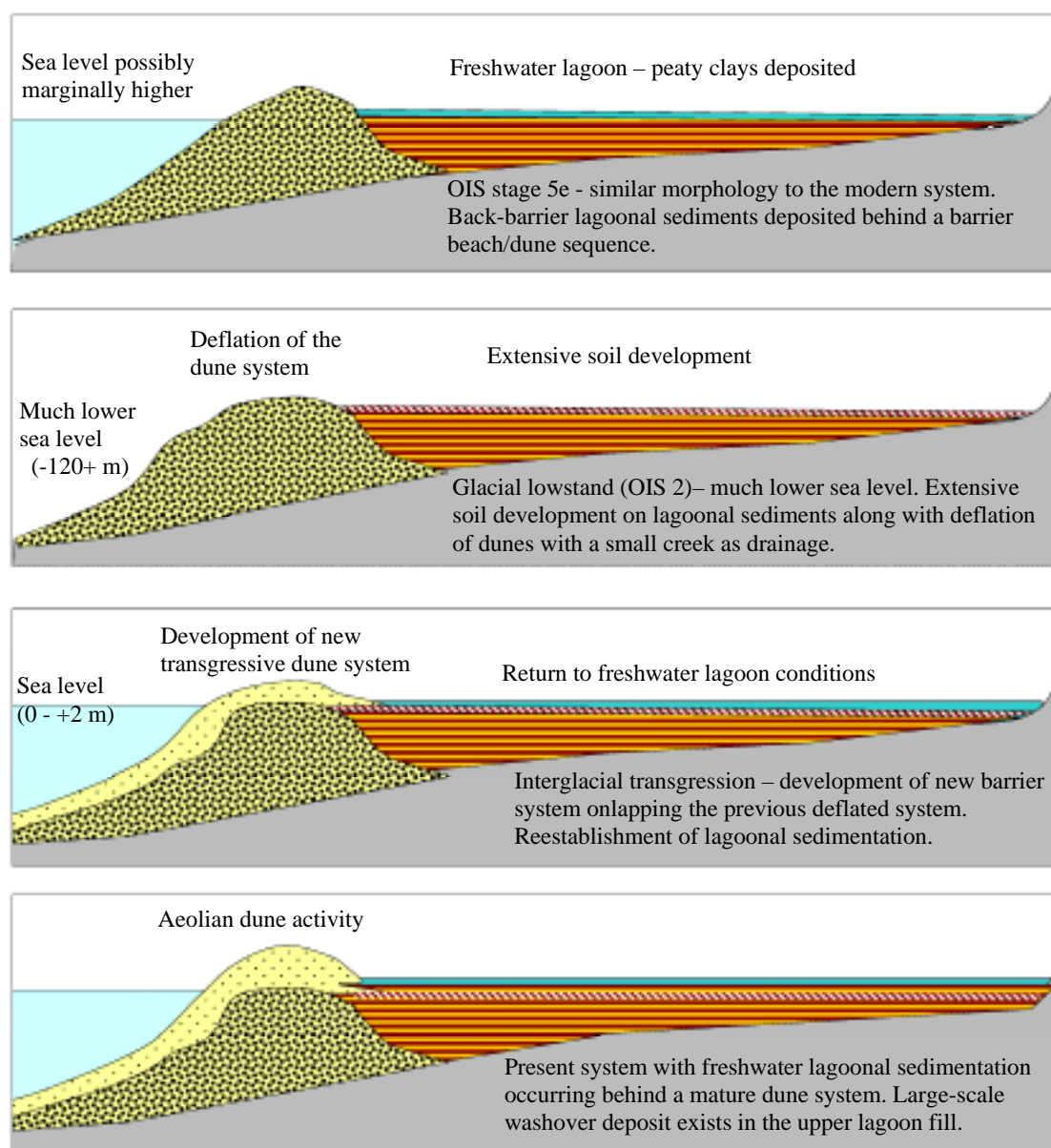


Figure 7.7 Schematic model of the morphological evolution of the Killalea system over the last glacial cycle. The presence of a Pleistocene barrier and Pleistocene lagoonal clays that underlie a well-developed soil profile indicate that the Pleistocene (OIS 5e) system was similar to the modern system of today.

### **7.7 Sediment characteristics of the sandsheet and confining peat deposits**

The fundamental aim of this research is to investigate evidence for large-scale washover deposition in the late Holocene. To this end the focus of the investigation at Killalea is the internal sedimentology of the thin sandsheet deposit identified in the upper fill of the back-barrier lagoonal sequence. It is reiterated here that the sandsheet is spatially and sedimentologically unique in its appearance and spatial distribution. As discussed in Section 3.1 the deposit is not likely to be the result of higher Holocene sea-level as it exists as a confined thin (<90 cm) lense and lacks evidence of wave attack or regressive beach ridge formation. Further evidence to negate the sea level change hypothesis lies in the dating results which indicate that the deposit is approximately 500 years old (Chapter 10). The marine nature of the clean sandy sediments suggests also that the deposit is not the result of fluvial or sheetwash deposition as any such deposit would be contain little quartz since the catchment is predominantly composed of latite bedrock and volcanic breccia that have characteristically low quartz contents.

#### **7.7.1 Sediment descriptions.**

Sediment descriptions for all units shown in stratigraphic cross section A-A1 (Figure 7.8) are provided in the following text. Of particular interest are the sediments of the confining peat deposits and the sandsheet (Figures 7.8 and 7.9), which were investigated in detail using high-resolution particle size analysis and microscopic techniques. The sediments of the sandsheet are then compared to those from the dune sequence and offshore zone with the aim of defining a source for the sandsheet deposit.

##### **7.7.1.1 Confining peat deposits**

The peat deposits that confine the sandsheet are characteristically fine grained (silty) and composed of the decaying organic remains of reed fragments including *Juncus* sp. and *Triglochin striata* along with the fragmented remains of freshwater algae and other aquatic plants. The silty peat deposits (Figure 7.9) also contain minor amounts of fine aeolian sand (particularly nearer the barrier system) and dominate the Holocene sedimentary fill of the lagoonal sequence. In some places an increase in fine sand may be indicative of periods of strong onshore winds, low water levels (drying) of the system or dune instability. The presence of soil particles in some horizons may indicate flooding or sheetwash deposition.

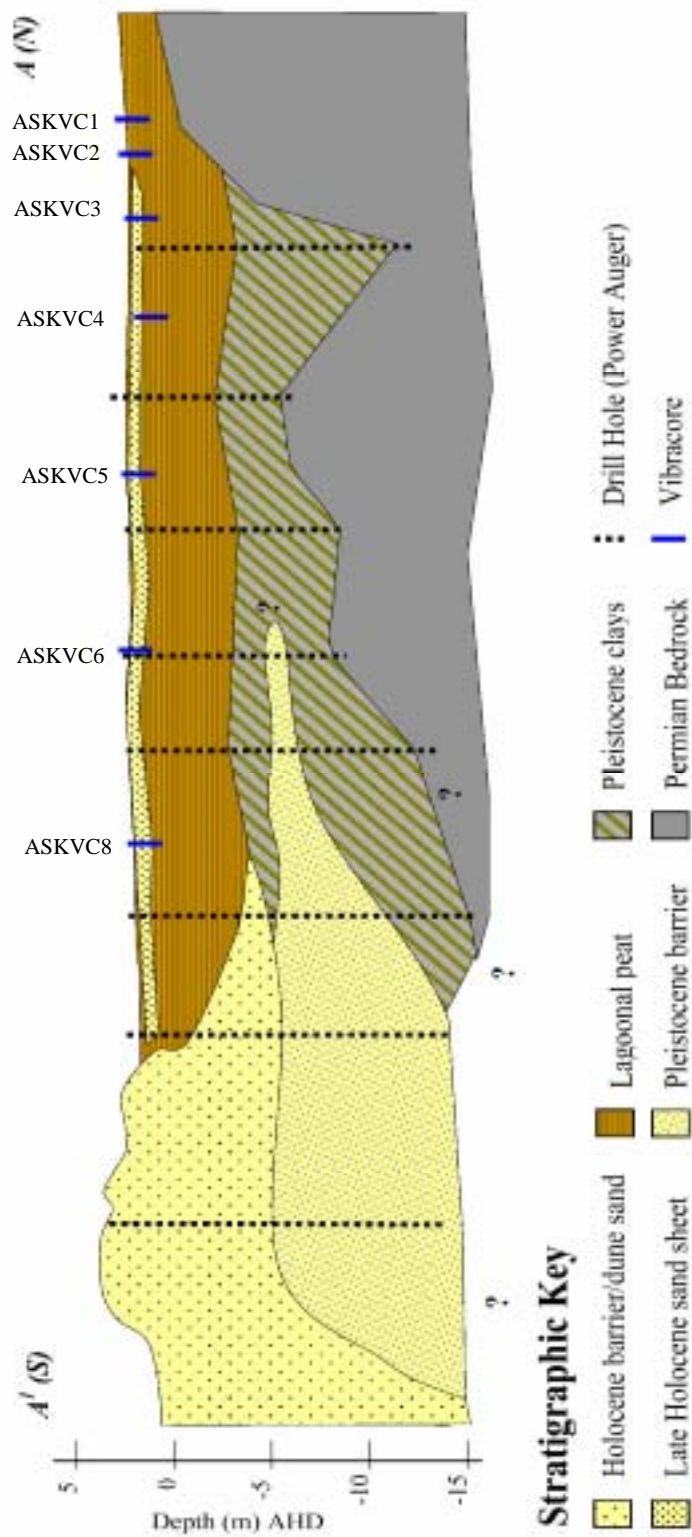


Figure 7.8 Cross-section A-A' showing a Holocene dune system overlying a deflated Pleistocene dune system. Holocene back-barrier lagoonal sediments overlie a similar Pleistocene system and are separated by a soil profile. An extensive sandsheet up to 90 cm thick, is found in the upper fill of the lagoon sequence and its genesis forms the focus of this chapter.



Figure 7.9 Photographs of vibracores ASKVC4 (a) and ASKVC5 (d). Inset (b) shows the graded nature of the contact between the sandsheet and the overlying organic sandy silt. Several organic clasts are also clearly visible at the top of the sandsheet deposit. (c) Shows the extremely sharp contact between the peat deposit and the overlying sandsheet. Photo (d) shows the upper two-thirds of core ASKVC5. The upper part of the core (e) shows the organic nature of the sediments. The dark silty sediments contain charophyte remains that are indicative of a return to freshwater conditions following the deposition of the sandsheet. An inset taken from the central part of the sandsheet (f) shows the sandy nature of the sediments along with the presence of organic rootlets and spinifex grass. A sharp contact between the underlying peat and the overlying sandsheet is also noted in this core (g).

### 7.7.1.2 Sandsheet

The sandsheet deposit is composed of two facies, (Figures 7.10) the first facies consists of near-symmetrical fine sand and the second is a slightly fine-skewed fine sand that has a small (<5% by volume) silt component. Microscopic textural analysis indicates that the sandsheet is composed of sub-rounded to well-rounded quartz sand with minor heavy minerals. Ultrastable heavy minerals including zircon, tourmaline and rutile dominate the heavy mineral suite (see below).

### 7.7.1.3 Heavy minerals in the sandsheet

A total of 10 different translucent heavy mineral species were identified according to their optical properties (as defined by Kerr, 1977; Rothwell, 1989; Deer *et al.*, 1992; Mange and Maurer, 1992), in the sand fraction (63-250µm) of two samples taken from the sandsheet. The assemblage includes both ultrastable minerals (zircon, rutile and tourmaline) and metastable minerals (pyroxenes, hornblende, epidote, garnet, andalusite and chlorite). Generally samples from Killalea lagoon were very mature with an average ZTR index of 59.

Zircon is very common in the heavy mineral suites of Killalea Lagoon samples, ranging from 8-34%. Two main populations of zircon occur in all samples: (1) colourless irregular to equant subhedral grains; (2) rounded anhedral grains (common in Killalea lagoon). A very rare occurrence of euhedral zircon grains is present in one sample. Rutile is present in low amounts in comparison to other ultrastable heavy minerals (zircon and tourmaline).

Tourmaline is the most abundant ultrastable heavy mineral in all samples, ranging between 8-43%. Tourmaline occurs as several colour varieties including brown, greenish brown and rarely blue. Pyroxene group is the most abundant metastable translucent heavy mineral in Killalea lagoon samples, ranging between 17-25% and all samples have low values of hornblende (2-5%). Epidote occurs as yellowish to yellowish-green grains along with andalusite (colourless and pleochroic to pink) and very low abundances of garnet (colourless to pink) and chlorite (green) in some samples.

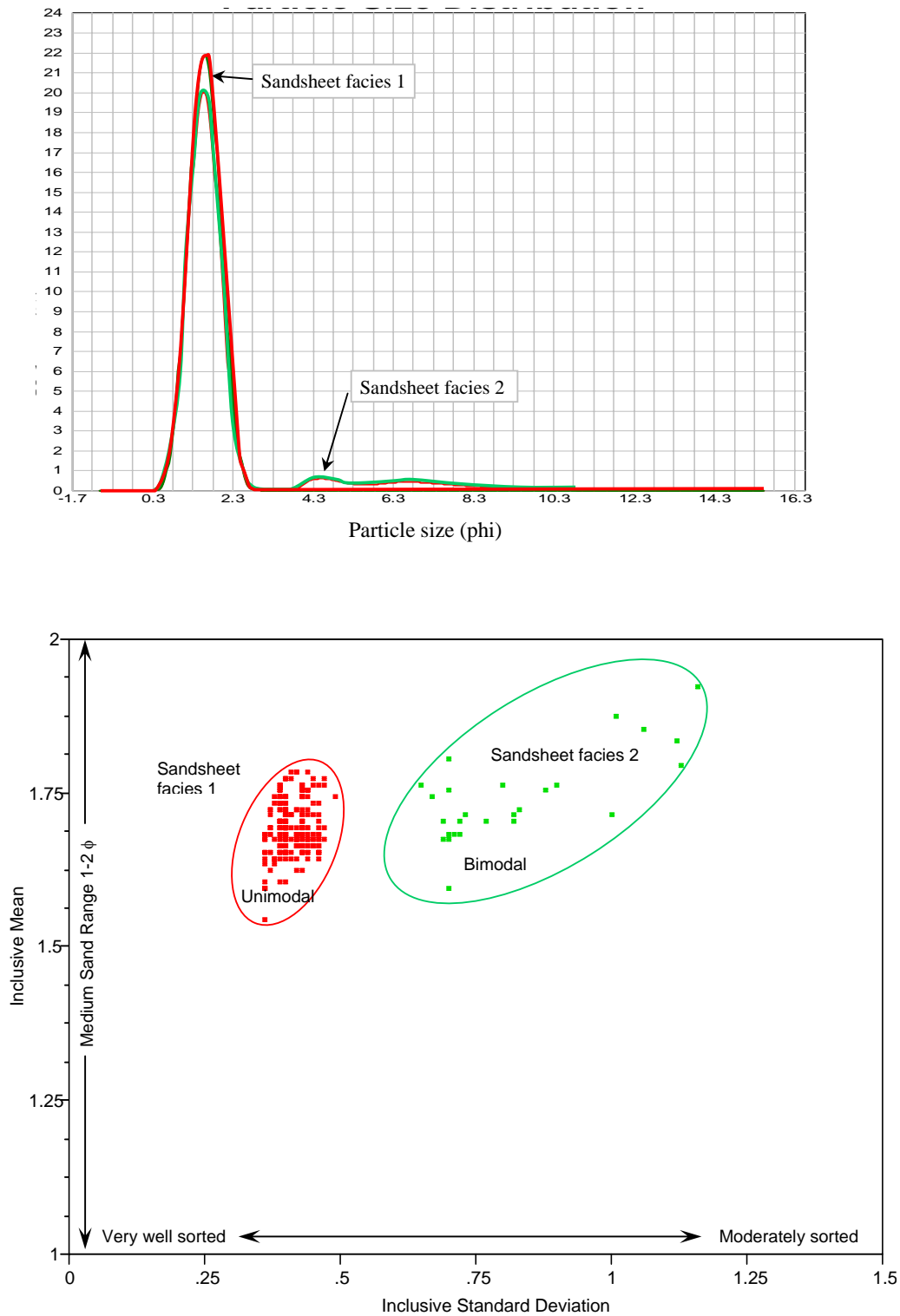


Figure 7.10 a) Average particle size distributions ( $N=30$ ) of the two facies identified in the sandsheet deposit at Killalea Lagoon. A silty peak appears in the second sandsheet facies. b) Bivariate plot of graphic mean ( $\phi$ ) against inclusive standard deviation ( $\phi$ ) shows that two well defined facies are present.

The heavy mineral populations identified in the Killalea samples are similar to those identified in the washover deposits of the Dunmore sandsheet (Switzer *et al.*, in press). The presence of metastable minerals such as chlorite is indicative of mass movement of material from the shelf into the embayments at Killalea and Dunmore. This hypothesis is supported by the comparative similarity of the depositional features found within the deposits including: the dominance of sand sized sediment; the direct contrast with the underlying stratigraphy and surrounding bedrock; and the presence of organic debris and rip-up clasts.

Facies	CaCO <sub>3</sub>	Zircon	Rutile	Tourmaline	Augite	Titanaugite	Aegerine augite	Hornblende	Minor heavy minerals *
A	9.3	29.7	13.4	13.1	32.1	1.1	1.2	5.7	3.4
B	8.3	32.7	3.6	19.7	25.8	1.4	2.5	7.2	6.2
C	5.1	18.0	1.7	15.8	33.0	4.1	17.7	5.9	3.3
D	26.5	18.2	3.3	18.5	39.3	1.6	1.2	11.7	4.4
E	29.0	11.1	1.5	23.2	23.3	1.6	0.5	20.8	3.6
D-Av	7.8	28.6	2.9	18.8	24.7	1.2	1.9	4.8	4.9
K1	<2%	34.19	2.57	30.51	16.54	0.37	ND	2.94	6.16
K2	<2%	8.77	1.17	42.69	23.98	1.17	ND	3.51	9.94
Facies	Biotite	Chlorite	Weathered	Heavy min. %	(G. Mean Phi)	Inc G. SD (Phi)	% Sand	% Silt	% Clay
A	0.1	0.1	6.4	25.0	1.7	0.5	100	0	0
B	0.3	0.7	9.7	5.3	1.5	0.5	100	0	0
C	0.2	0.3	14.5	4	1.6	0.9	95.3	3.7	1
D	0.7	1.0	9.2	3.1	1.8	0.6	99.9	0.1	0
E	10.2	4.2	16.1	1.6	4.1	1.8	58.8	33.0	8.2
D-Av	0.2	0.4	10.1	3.2	1.3	0.7	99.1	0.8	0.1
K1	ND	0.00	6.25	1.86	1.65	0.45	100	0	0
K2	ND	0.00	7.60	2.01	1.60	0.50	100	0	0

\* = epidote+andalusite+garnet.

Table 7.1 Heavy mineral assemblages from Killalea Lagoon (K1, K2) compared to the facies identified by Hareddy (2003); Switzer *et al.* (in press). An average from the Dunmore sand sheet is presented for comparison with the Killalea samples. Both samples cluster with sediments from the inner part of the outer shelf as defined by Hareddy (2003).



#### **7.7.1.4 Evidence for internal grading**

The deposit contains little evidence of internal grading and contrasts with the storm deposits described in Chapter 6. Although many subtle changes exist in sediment populations obtained from cores (Figure 7.11), there are no discernable statistically significant grading trends obtained from core data. The sandsheet deposit does not appear to show evidence of significant vertical fining within cores or lateral fining between cores.

Mean grain size and sorting (inclusive graphic SD) were plotted in for all samples in Figure 7.10b where two clusters were identified. The two clusters (facies 1 and 2) respond to pure sand samples and a second cluster that contained a small percentage of silt (Figure 7.10a). These facies are identified in Figure 7.11 and are shown to exist randomly throughout most cores including ASKVC5 (Figure 7.11a). The exception comes from the most landward core that contains the sandsheet (ASKVC3; Figure 7.11b), which shows a concentration of facies 2 at the base and the top of the sandsheet.

The concentration of the more poorly sorted sediments at the top and base of the deposit in ASKVC3 may be indicative of erosion of lagoonal sediments during the initial overwash that is recorded in the sediments at the base of the deposit. The concentration of finer material in the upper part of the deposit may be due to fine material settling out of suspension after deposition and during the re-establishment of lagoonal sedimentation.

#### **7.8 Micropalaeontology**

As stated above, the analysis of carbonate microfauna such as foraminifera and ostracods from the sandsheet and confining peat was complicated by the apparent dissolution of carbonate tests by the acidic groundwater conditions. Investigation was then focused on the silicic remains of diatoms and the organic remains of charophyte oospores. This investigation complemented the study of sporadic seeds and organic debris. The organic remains of several charophyte oospores were found in peat samples indicating freshwater to brackish lagoon conditions.

### 7.8.1 Charophyte flora and organic debris

Charophyte floras were investigated from two cores ASKVC5 and ASKVC6 at selected intervals including across the upper and lower contact of the sandsheet. Micropalaeontological analyses of the peat samples revealed abundant charophytes (Figure 7.12), which indicated freshwater conditions and were used as a proxy to study subtle changes in salinity for the palaeoenvironmental reconstruction (Saini *et al.*, 2004). Charophytes were represented exclusively by organic remains (oospores) of those taxa that typically calcify, i.e. *Lamprothamnium* spp.

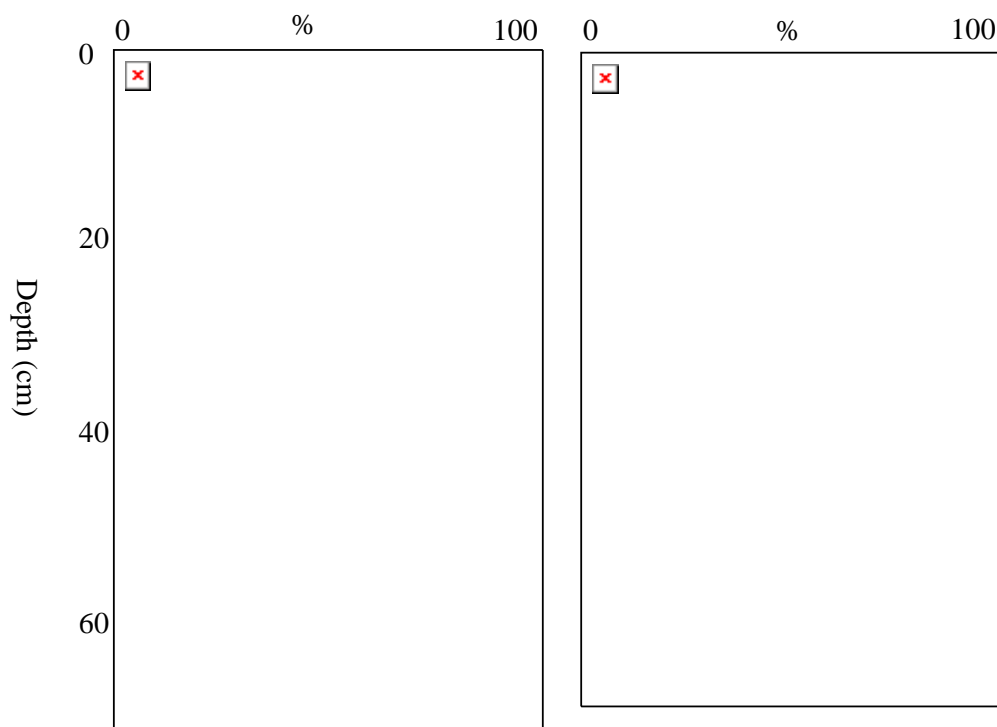


Figure 7.11 Graphical representations of size fractions from a) ASKVC5 and b) ASKVC3. Note that sandsheet facies 2 is identified in the sand sheet by a small percentage of mud sized material (silt).

Both cores exhibited successions that began with a population of *Lamprothamnium succinctum*, indicating an environment of changing salinity conditions, probably a water body connected temporarily to the sea. Above this there is a slow change to a dominance of freshwater taxa of *Chara fibrosa*, *C. australis*, *Nitella congesta* and *Nitella* sp.

Figure 7.13 shows the interpretation of Saini *et al.* (2004). It is important to note that in its broadest sense the presence of charophytes above the sandsheet is indicative of a

return to lagoonal conditions. The slight increase in abundance of freshwater taxa may be due to geomorphic adjustment after the deposition of the sandsheet.

### 7.8.2 Diatom analysis

Diatom analysis yielded no statistically significant counts. The presence of marine diatoms has been noted in many storm and tsunami deposits (Hemphill-Haley, 1996; Davies and Haslett 2000) as indicative of marine inundation. Interim analysis of samples taken from cores ASKVC4 and ASKVC5 (Table 7.2) indicated that the confining peat deposits contained few freshwater diatoms and that samples from the sandsheet yielded very few diatoms all of which were freshwater. At no time were marine diatoms encountered.

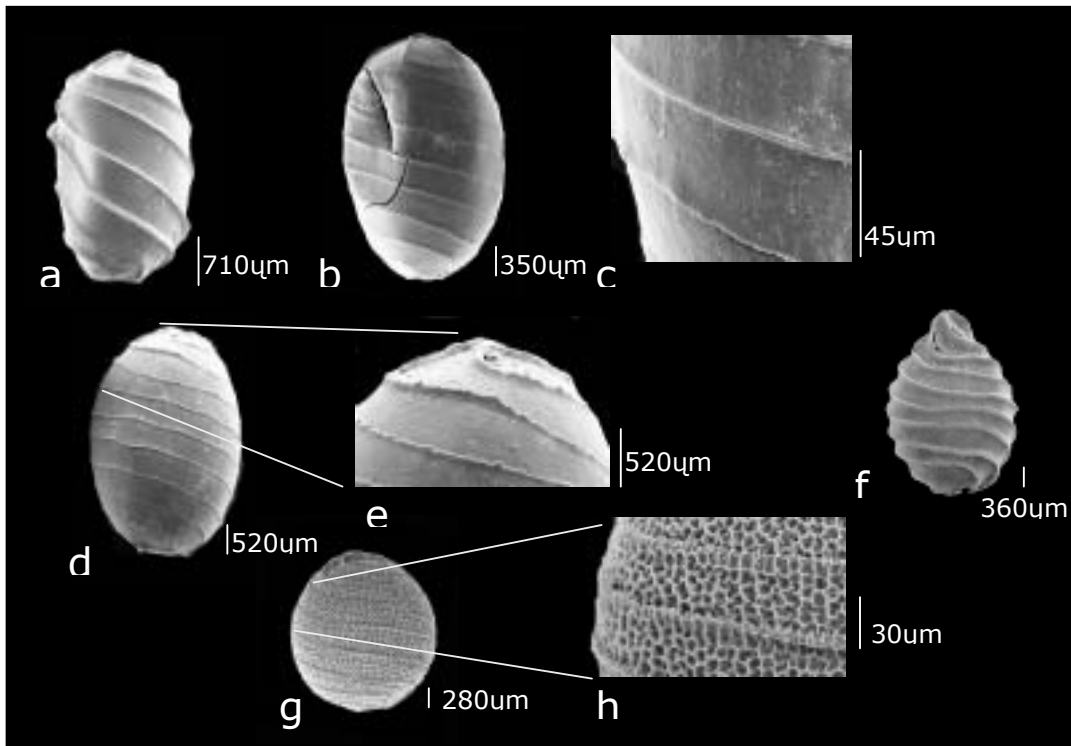


Figure 7.12 Images of charophyte oospores recovered from ASKVC-5. (a) *Chara australis* (b) *Chara fibrosa* (c) *Chara fibrosa* striae detail, (d) *Lamprothamnium succinctum*, (e) *Lamprothamnium succinctum* striae detail, (f) *Nitella congesta*, (g) *Nitella leptostachys*, (h) *Nitella leptostachys* striae detail.

This investigation was not expanded to full population counts. The presence of freshwater diatoms both above and below the sandsheet does, however, support the

inference that lagoonal sedimentation resumed soon after deposition of the sandsheet into what was a freshwater environment at the time of deposition.

### 7.9 Depositional characteristics of the confining lagoonal sequence and washover sandsheet

The direct contrast between the confining lagoonal deposits and the sandsheet is best indicated by looking at the grain size characteristics and sediment size populations through one of the central cores (Figure 7.14). Subtle up core variation throughout the lower organic-rich silty sequence is clearly indicated from 68-200 cm. At 68 cm there is a sharp shift to sand-dominated sediments associated with the sandsheet deposit. Little variation in sediment character exists in the sandsheet which spans the interval from 7-68 cm. Overlying the sandsheet is another silty sequence from 0-7 cm. This upper silty sequence shares similar sediment characteristics with the lower sequence indicating a return to low energy conditions.

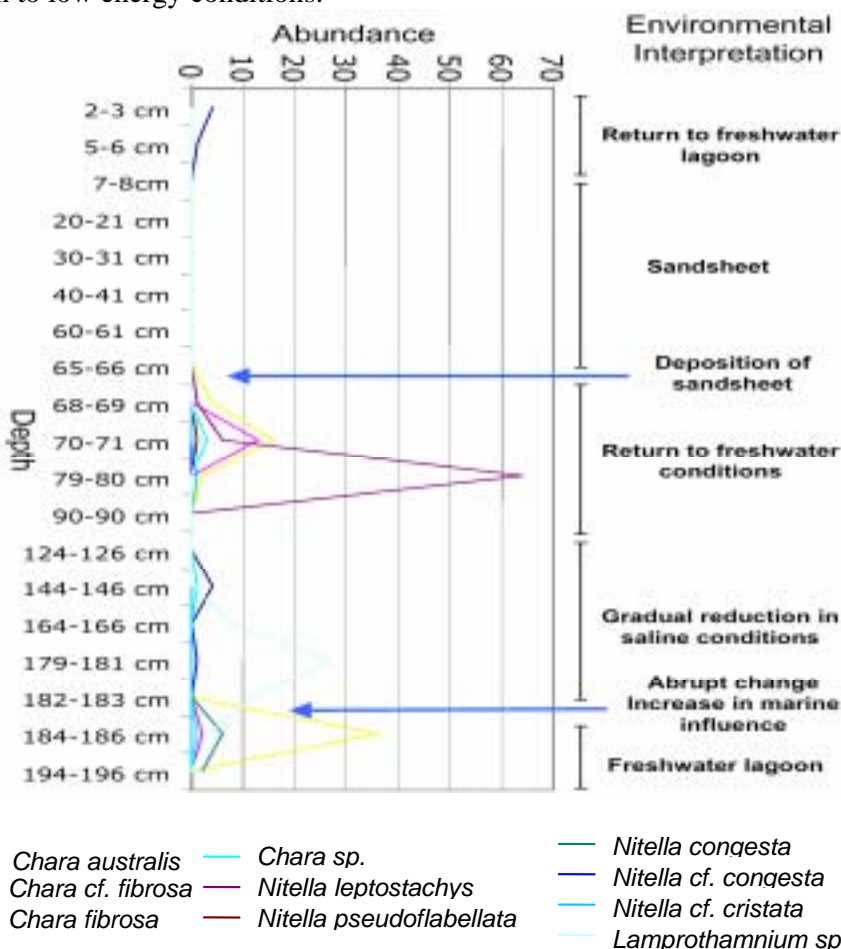


Figure 7.13 Environmental reconstruction of Saini et al. (2004). The sandsheet is indicated by a lack of charophyte remains and is overlain by a thin veneer of sediment rich in the organic remains (oospores) of the diverse flora indicative of a return to lagoonal conditions after deposition of the sandsheet.

ASKVC-5	ASKVC-4
3 cm: Freshwater diatoms (more alkaline)	0 cm: Freshwater diatoms
10 cm: Freshwater diatoms (possibly acidic)	3 cm: Freshwater diatoms (not highly abundant)
28 cm: Few/no diatoms	15 cm: Few/no diatoms
55 cm: Few/no diatoms	44 cm: No diatoms
77 cm: Freshwater diatoms (possibly acidic)	74 cm: Few/no diatoms
149 cm: Fresh-possibly brackish (non-marine) alkaline	94 cm: Some freshwater acidic forms
	96 cm: Few/no diatoms
	155 cm: Few/no diatoms

*Table 7.2 Interim diatom results from DIATOMA at the University of Adelaide. Full counts were not conducted as early results indicated that counts would be very low and difficult to relate to modern environments. The presence of freshwater diatoms above and below the sandsheet indicates a return to lagoonal conditions after deposition.*

### 7.9.1 Deposition of the peat deposits

Organic-rich clayey silt sediments that are the product of very low energy, fresh to brackish lagoonal conditions, dominate the lagoonal sediment sequence at Killalea. The sediments are a product of sheet wash from the volcanic-rich catchment, in situ production and aeolian sand deposition from the seaward dunes.

Drilling by Jones and Elliot indicated a Pleistocene system similar to that of the modern system at depths to 25 m. The Quaternary evolution of this barrier system is reviewed in Figure 7.8. At depth a lagoonal sequence of silty clays underlies a well-developed soil profile (~ -8-12 m) that Jones and Elliot suggested was the result exposure of the lagoon floor during the last-glacial lowstand of sea-level.

Lagoonal sediments containing charophyte oospores, abundant reed matter and freshwater diatoms confine the sandsheet deposit. The main sedimentary characteristics including grain size, organic content and elementary composition of this facies are indistinguishable from modern sediments collected from the lagoon during this study. Minor differences, such as a lack of carbonate in older sediments, are attributed to decomposition of organic matter resulting in acidic conditions in the subsurface.

Fluctuations in sediment size (Figure 7.14) found in the lower organic-rich silt facies are most likely related to fluctuations in rainfall, lagoon levels and aeolian input from onshore (SE) winds. Microscopic analysis of the sand fraction collected from random intervals throughout the sequence indicate that the sand fraction is dominated by very fine- to fine-grained, well-rounded (often pitted) quartz sand with a few sand sized grains of weathered latite derived from the catchment.

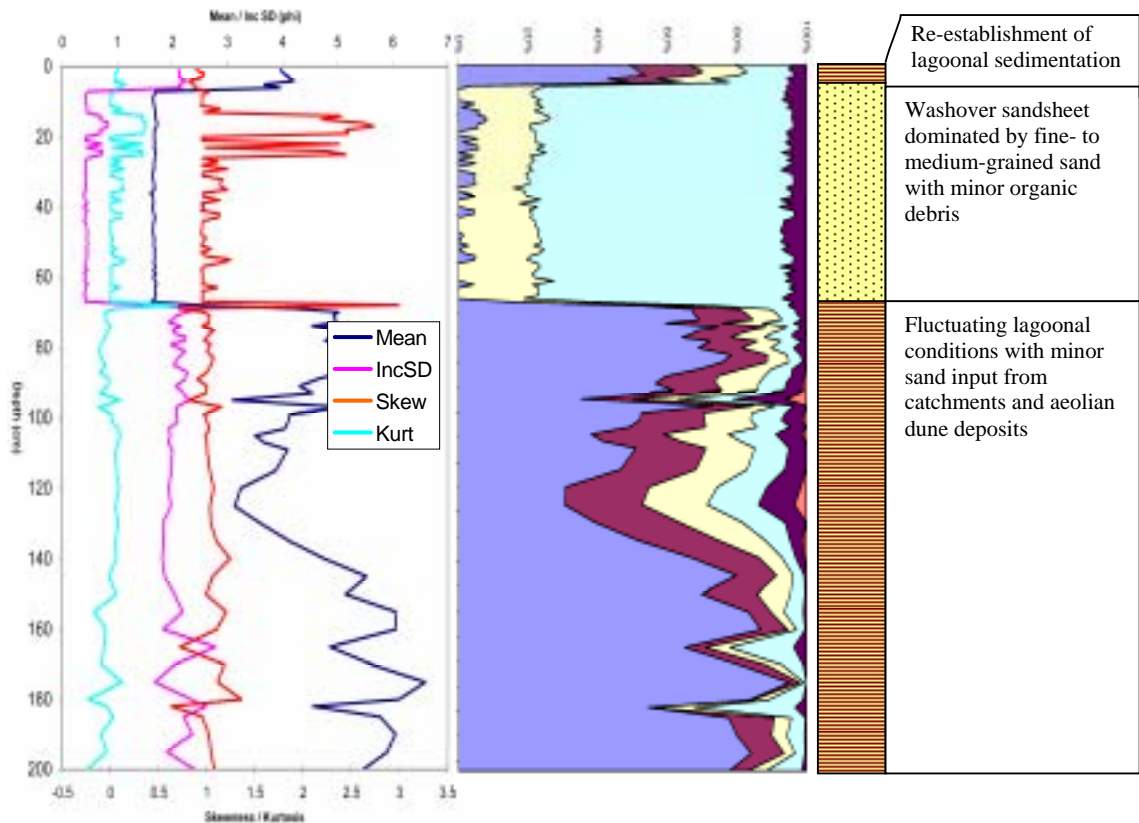


Figure 7.14 Sediment characteristics of core ASKVC5. The contrast between the particle size characteristics of the sandsheet and confining lagoonal deposits is clearly visible.

### 7.10 Depositional characteristics of the sand sheet

The sedimentary characteristics of the sandsheet contrast directly with the organic silt units that lie above and below the deposit. The sandsheet exists as a distinct continuous lens up to 90 cm thick that extends more than 600 m inland of the present high water mark. Assuming the deposit has an average thickness of 60 cm and a conservative area of 350x100 m<sup>2</sup> the volume of the sandy deposit is in excess of 21,000 m<sup>3</sup>. This deposit contrasts directly with the storm deposits from Abrahams Bosom Beach presented in

chapter 6. The storm deposits are all less than 50 cm thick and extend less than 150 m into the estuary. The larger upper storm deposit (July, 2001) has a maximum volume of  $1125 \text{ m}^3$  based on dimensions of  $150 \times 25 \text{ m}^3$  an average thickness of 0.3 m. This comparison is based on several basic assumptions that assume at very basic principles; the same source volume of available sediment; the same resistance to the event by the onshore morphology; and identical hydraulic behavior of waves in each event type. For example, on basic principles, a washover deposit of  $15000 \text{ m}^3$  is only possible if an equal volume of sediment is available in the source area (see below). Nevertheless, the Killalea deposit is more than ten times greater in dimension than the upper storm deposit at Abrahams Bosom Beach.

There are no readily discernable trends in grading within the sandsheet either within cores or between cores. As discussed in Chapter 3, the identification of graded sediment units in washover deposits can assist in distinguishing them as storm or tsunami deposited. This is discussed below with reference to the limited grain size range of the potential source sediments.

The presence of organic debris including rip-up clasts of peat (usually found in lower parts of the sandsheet) and blades of *Spinifex* sp. and other unidentified twigs and woody debris indicates the depositional event stripped considerable vegetation from the seaward dune system. Much of this material is in a state of partial decomposition, which is indicated by organic staining of the surrounding sediment.

### **7.11 Comparison of sandsheet sediments with seaward landforms: source materials?**

The major size fraction (by volume) found in the sandsheet is fine- to medium-grained sand and comparison of the particle size distributions from the sandsheet, beach face, nearshore, foredune and barrier (Figure 7.15) suggests that the majority of the sand in the sandsheet may be derived from the barrier, beachface and foredune.

Large-scale washover of the beach and dune system would cause significant erosion of the sandy system. Such large scale erosion would result in significant geomorphic modification to the dune system including the stripping of large amounts of dune vegetation such as *Spinifex*. It is important to note here that the majority of the organic

clasts in the sandsheet deposit are found toward the base of the unit. The removal of the dune vegetation would expose large areas of unconsolidated, unvegetated sandy dunes that would easily be entrained by any following waves.

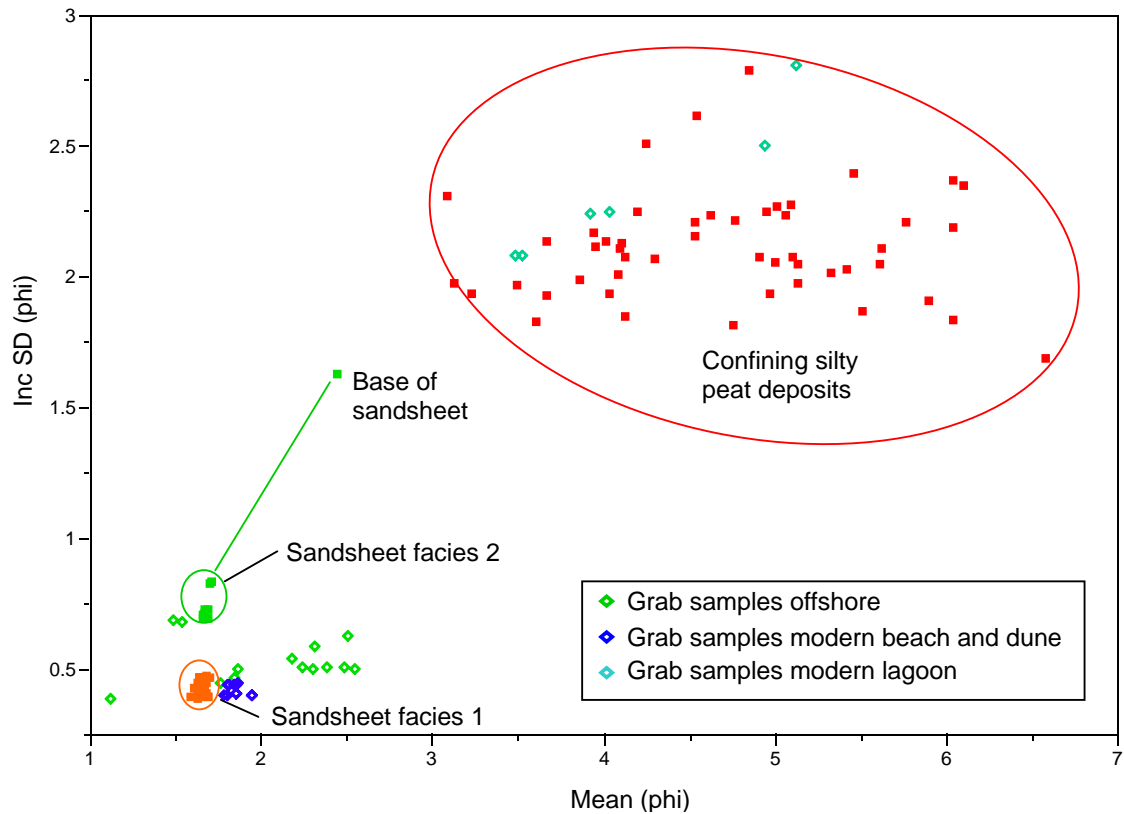


Figure 7.15 Comparison of mean and sorting for all samples from ASKVC5 identifying three facies (see Figure 7.14) along with grab samples from the seaward beach and dunes, and samples from offshore (including nearshore and shelf). Also presented are grab samples from the modern lagoon that cluster with the lagoonal sediments that confine the much coarser sandsheet.

Of much more complexity is the silt population characteristic of sandsheet facies 2. As presented by Switzer *et al.* (in press), it is hypothesised that this material is at least partly representative of sediment stripped from the shelf during the large-scale washover event.

### 7.12 How was the sand sheet deposited: tsunami or exceptionally large storm?

The volume of the Killalea sandsheet is more than 10 times that of the modern storm deposits studied in Chapter 6. Furthermore the deposit lies in an elevated position (up to +1.6 m AHD) in sheltered lagoon behind a high-energy barrier-beach system with modern dunes up to 4 m high.



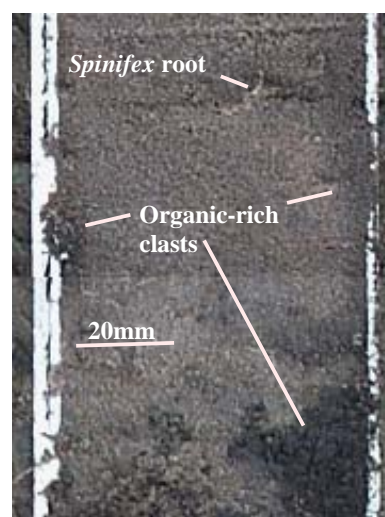
Historical evidence and local accounts suggest that the storm of May 1974 (waves over 15 m high) breached the lagoon at its entrance but very little sediment was carried into the lagoon. Coring of the entrance indicated a number of undated lenses of fine- to medium-grained sand none of which extended farther than 20 m into the lagoon system. The 1974 storm is one of the biggest storm events of the last 100 years suggesting that very large storms are not likely to carry large volumes of sand into the lagoon.

As stated in Chapter 3, many diagnostic criteria (Table 3.5) have been forwarded in global literature to distinguish between the deposits of storm and tsunami (Scheffers and Kelletat, 2003; Goff *et al.*, 2001, 2004). Many of these criteria merely indicate the marine nature of the sediments (e.g. the presence of marine microfauna or diatoms) but several key characteristics were identified in Chapter 3 (Table 3.6) as indicators of deposit genesis. What follows here is a discussion of these five criteria and their implications for the deposition of the Killalea sandsheet.

The first criterion is the contact with the underlying sediments and the possible inclusion of intraclasts (Goff *et al.*, 2001; Kortekaas, 2002) - in this case of the organic-rich lagoonal facies. Intraclasts of material eroded from the underlying sediments are often reported as being incorporated in tsunami deposits (Nanyama *et al.*, 1993; Shi *et al.*, 1995; Goff *et al.*, 2004; Gelfenbaum and Jaffe, 2003). This criteria is considered diagnostic for tsunami since although in rare cases erosional basal contacts have been reported for storms, the presence of intraclasts has not (Kortekaas, 2002). The presence of intraclasts is recorded in cores ASKVC4, ASKVC6 and ASKVC8 where they are all found in the bottom 10 cm of the deposit (Figure 7.16).

The presence of the organic-rich clasts suggests that the depositional event was capable of breaching the barrier with enough force to erode the organic-rich sediments of the lagoon. The semi-consolidated, very fibrous, nature of these sediments suggest an extremely high energy event would be required to breach the barrier and then erode material from the lagoon.

Figure 7.16 Organic-rich intraclasts found at the base of the sandsheet in ASKVC4. The irregular shaped organic-rich clasts often contain rootlets and are indistinguishable by sediment characteristics (mean grain size, sorting and composition) from the underlying peat deposits. Also present in this photograph is a piece of organic rootlet identified as *Spinifex* sp.



Similar facies were identified in the Dunmore embayment some 4 km to the west (Switzer 1999; Pucillo, 2000; Switzer *et al.*, in press). Here clasts of the underlying estuarine mud were found in a sandsheet deposit attributed to a tsunami at least 2000 years old.

The second criterion involves the identification of sediment sources. For storm deposits, such as those described in Chapter 6, the washover deposit is often composed of beach and nearshore sand material derived from a limited range of environments (Sedgwick and Davis, 2002). In contrast tsunami deposits are often composed of wide range of material from inner shelf to terrestrial debris (Goff *et al.* 2004; Switzer *et al.*, 2004b). Extensive erosion by these large scale events allows incorporation of material from a wide variety of environments.

The identification of meta- and ultra-stable heavy minerals in both the Killalea deposit and the Dunmore deposit (Switzer *et al.* in press) that are not found in the modern beach facies or nearshore sediments provides evidence of a secondary source of material. The heavy mineral assemblage in the sandsheets clusters with the heavy mineral assemblage of the inner shelf and it is hypothesised here that this indicates the incorporation of material from below storm wavebase (Haredy 2003; Switzer *et al.* in press). The internal petrology contains a dominance of quartz sand with minor heavy minerals and when combined with the evidence from the intraclasts mentioned above, indicate that

the event was capable of eroding material from the inner shelf, nearshore, beach, dunes and lagoon.

The third criterion suggested as diagnostic for storm or tsunami deposition is the degree of sorting identified in the deposit. It should be reiterated here that both this criteria and the previously mentioned factor of source area are inherently source dependent. For example it would not be possible to expect boulders in a storm or tsunami deposit if no boulders were available in the run-up area of the event. Storm deposits are generally composed of poorly to moderately sorted material with a uni-modal particle size distribution (Sedgwick and Davis, 2003). In contrast tsunami deposits are often reported to be composed of poorly sorted sand, clasts and debris often showing a bi-modal particle size distribution (Shi *et al.* 1995; Goff *et al.* 2004).

The Killalea deposit contains facies that exhibit both uni-modal and bimodal size distributions, a characteristic that is most likely a product of the high-energy sand dominated coastal system. The dominant sediment type identified in nearshore areas in this study and in offshore areas by Haredy (2003) is composed of fine- to medium-grained sand. It is not until water depths of greater than 15 m that the silt content of the samples exceeds 5%. Due to these sediment types in potential source area, any washover deposit, no matter what the type would be expected to exhibit a dominance of sand-sized particle and, therefore, as in the Killalea sandsheet exhibit a well-sorted sediment population. Analysis of the 63-250  $\mu\text{m}$  heavy mineral population suggests a significant component of fine sediment in the sandsheet is a product of erosion of the inner shelf environment. In contrast to the deposits studied by Goff *et al.* (2004) and Tuttle *et al.* (2004) the large extensive Killalea washover deposit presents as better sorted than that of the storm deposits identified in Chapter 6. This is most likely a product of the different source areas for the deposits. The Killalea event eroded and transported material from a high energy system dominated by sand, which contrasts with the embayment off Abrahams Bosom Beach where sediments collected from depths of 2 and 4 m offshore exhibited significant silt fractions (Figure 6.14). It is also likely that fine material in the estuary mouth of Abrahams Bosom Beach would be more easily entrained than the back-barrier lagoonal sediments of the Killalea system.

The fourth and fifth criteria outlined in Chapter 3 relate to graded beds and evidence of bidirectional flow. Many authors have noted that storm deposits contain numerous then graded beds that are the result of individual waves during a storm washover event (Leatherman and Williams, 1977; Sedgwick and Davis, 2003; Nott, 2004; Tuttle *et al.* 2004). The model of Sedgwick and Davis (2003) shows that storm beds are recorded as thin horizontal laminations in terrestrial environments and foreset beds in subaqueous systems (Figure 6.10).

The Killalea deposit does not exhibit any discernable grading and contrasts with the well-defined layering of the storm deposits at Abrahams Bosom Beach. The only real evidence of grading in the Killalea deposit is found in the presence of a fine silt component in the lower and upper parts of the sandsheet identified in core ASKVC3. This was hypothesised by Pucillo *et al.* (2001) and Switzer *et al.* (in press) to be the result of the finer nature of the poorly developed dune soils and exposed aeolian sands at the time of inundation. Evidence for this hypothesis was found in the Dunmore deposit (Switzer *et al.* in press) but little evidence exists in the much more sand dominated system at Killalea. There is also little evidence for bidirectional flow in the Killalea deposit. Such evidence is best obtained from extensive trenching (Nanyama *et al.*, 2000; Kortekaas, 2002) and this was not allowed at this site.

### 7.13 Synthesis

The Killalea system is a predominantly freshwater lagoon system (ICOLL) that is enclosed by a sandy seaward barrier system (Figure 7.7). The open nature of the beach means the system experiences a dominance of high-energy ocean waves as it is open to the dominant swell regime from the southeast.

The barrier system consists of a narrow beach and offshore bar system (medium- to coarse-grained sands) and a small sandy barrier dominated by fine- to medium-grained sand that exist up to ~4 m (AHD) topped by partially vegetated aeolian dunes. Modern dune vegetation consists of dune grasses and low shrubs. It is important to note that the dominant vegetation of the dune system is now *Chrysanthemoides monilifera* an introduced species that has only been present on this coast since the late 1940's. Prior to this, historic photographs indicate that the dominant vegetation was coastal wattle (*Acacia* sp.) and dune grasses, such as *Spinifex*.

Modern lagoon sedimentation is the result of decomposition of organic debris in the lagoon with minor input of sediment from the catchment by sheetwash during floods. This results in a sequence of very fine-grained organic-rich sediments that range from peat to organic silt. The other minor sediment input into the lagoon is the fluctuating levels of very fine- to fine-grained sand that is brought into the system by aeolian transport from the seaward dunes during high-energy onshore winds.

Storm activity on Killalea Beach usually results in small-scale erosion of the incipient dune and rarely results in breaching of the lagoon entrance (Figure 7.2). Coring in the back-barrier lagoon indicates that the barrier has only been breached twice. The first resulted in deposition of a small sand lense some 4 cm thick (ASKVC8), less than 60 m behind the barrier. The second event is much younger and larger and is the focus of this Chapter. Dating of both of these deposits is presented in Chapter 10.

A transect of vibracores collected from the eastern margin of the lagoon (Figures 7.4 and 7.10) identified a large sandsheet up to 90 cm thick that is found in the upper fill and is confined by a lagoonal facies of organic-rich silt, clay and peat. The sandsheet deposit contrasts in composition with the confining lagoonal facies and is composed of two well-defined facies (Figure 7.12) containing a dominance of fine- to medium-grained sand. Sand sheet facies 1 is a unimodal, well-sorted, fine- to medium-grained sand with a near symmetrical particle size distribution and contrasts with sandsheet facies 2 that is bimodal and contains a second fine population of silt-sized particles. Although the two facies are easily separated using Ward cluster analysis and bivariate plots (Figure 7.10b) there is no discernable trends within or between cores.

It is extremely unlikely that the sandsheet deposit at Killalea is a storm deposit. Such a storm would have to be several orders of magnitude greater than any storm in recorded history for this coast. The deposit is more than ten times greater in volume than a modern storm deposit formed during swells in excess of 4 m. Furthermore this deposit lies behind an extensive beach and barrier system that is in equilibrium with very high energy conditions.

The deposit was tested against the criteria outlined in chapter 3 for distinguishing tsunami and storm deposits. The results are compelling and indicate a very large washover event from the southeast that is most likely attributed to a tsunami. The deposit exists up to 700 m inland and up to 1.6 m (AHD) and contains a dominance of fine- to medium-grained sand that contrasts directly with both the confining silty organic-rich facies and the bedrock of the small catchment.

The deposit contains eroded clasts of organic debris, including evidence of dune vegetation and rip-up clasts of lagoonal sediment, and a heavy mineral assemblage that clusters with that of the inner (below storm wavebase) shelf and not the nearshore region. Although the deposit shows little grading it does contrast with the laminated and micrograded sediments of the storm deposits at Abrahams Bosom Beach. This contrast infers that the deposit is not the result of repeated pulses of unidirectional flow that allowed individual laminae to form.

The presence of freshwater diatoms and charophyte flora above and below the deposit also suggest that the marine sediments are the result of a short lived event, which, after deposition, were overlain by lagoonal sediments indicating a return to freshwater conditions.

#### **7.14 Conclusions**

- The Killalea deposit exists as an elevated laterally extensive marine quartz sandsheet in a freshwater lagoonal environment that exhibits an obvious contrast with the low-energy organic-rich lagoonal deposits that exist above and below the sequence
- The deposit exists up to 700 m inland and rises to a height of 1.6 m (AHD). A conservative volume for the deposit is more than 21,000 m<sup>3</sup> and it contrasts directly with the much smaller washover deposits presented in Chapter 6 that are less than 10% of this volume.
- The sandsheet deposit contains a dominance of clean fine- to medium-grained quartz sand. Rip-up clasts of the underlying stratigraphy are incorporated into

the lower parts of the deposit along with evidence for the removal of dune vegetation including *Spinifex* sp.

- Two facies are identified in the sandsheet deposit, the first a clean unimodal sand and the second a bimodal slightly muddy sand that is hypothesised to contain material from the inner shelf, as suggested by the presence of a distinctive heavy mineral assemblage.
- The Killalea deposit is the result of large-scale washover from the southeast capable of breaching the barrier and carrying very large amounts of sandy sediment into the back-barrier lagoon. The deposit lacks many characteristics of modern storm deposits and is most likely attributed to a late-Holocene tsunami.

## Chapter 8

### An elevated coarse shell-rich deposit in a pocket embayment on the margin of Batemans Bay

#### 8. Introduction

An elevated and unusual coarse shelly sedimentary unit is found in a sheltered beach ridge sequence in a pocket embayment on the northern bank of the Clyde River estuary at Batemans Bay (Figure 8.1). The shelly unit contrasts directly with the underlying beach sequence and overlying soil profile. The coarse sediments, along with the sheltered and elevated nature of the deposit, suggest that the deposit is the result of high-energy deposition. Initial hypotheses considered for the deposit are river flooding and higher sea level. The young age of the deposit <1000 years and the marine nature of the sediments suggest that neither of these initial hypotheses can adequately explain the deposit.

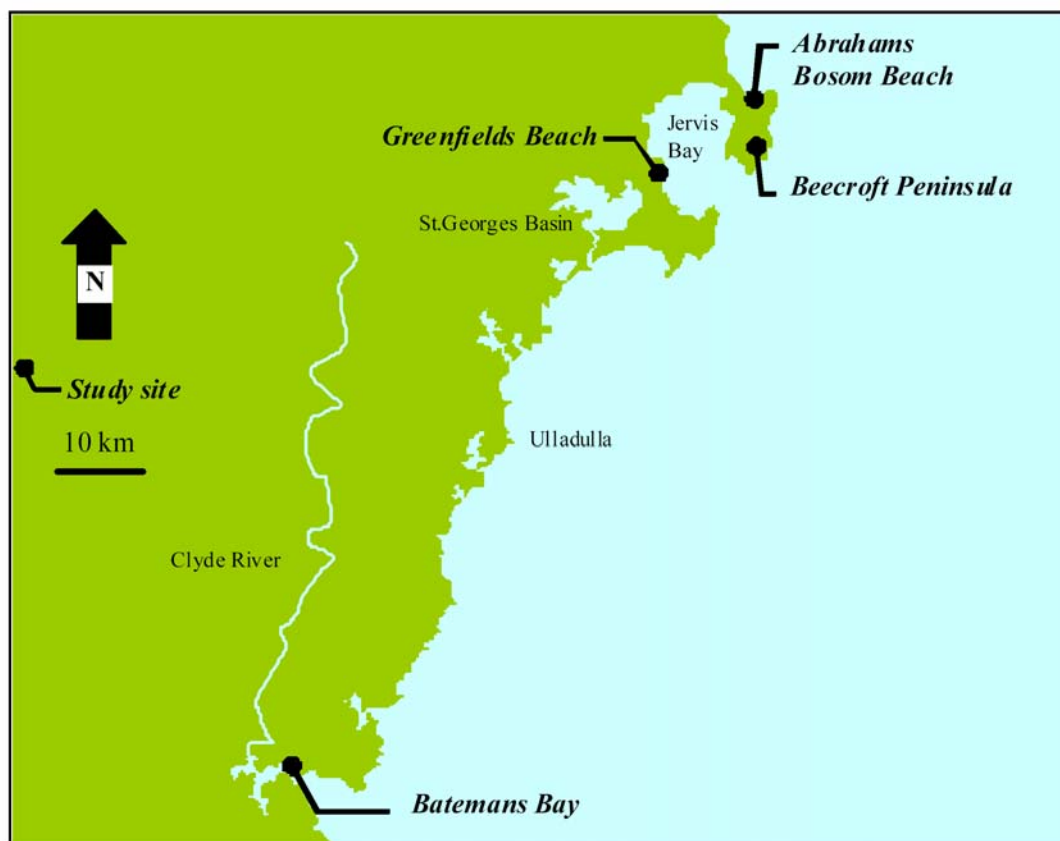


Figure 8.1 Location of Batemans Bay, the southernmost embayment studied. The Clyde River drains an extensive well-vegetated catchment and leads to the funnel shaped estuary of Batemans Bay. The study site is marked with a black dot and is landward of a large tidal delta (Figure 8.3) that shelters the site from open ocean swells.



### 8.1 Embayment characteristics

Batemans Bay is a steep-sided drowned river valley subject to fluvial influences of the Clyde River with a catchment of approximately 1,800 km<sup>2</sup> (May et al., 1996). The Batemans Bay estuary is about 12 km in length. The roughly V-shaped bay is over 30 km<sup>2</sup> in area from its ~ 6 km wide entrance to the bridge where it is some ~ 450 m across (Hennecke, 2004). The funnel shaped bay trends landward to the westnorthwest exposing much of the northern side of the bay to the predominant swell out of the southeast (Figure 8.2).

The estuary is up to 25 m deep in several sink holes in the mid reach of the estuary. A large marine sand body confines a channel along the southern margin of the estuary. The channel is of variable width (usually less than 300 m wide) and averages 8 m deep at the seaward end (Figure 8.3). Flood derived fluvial sands are interbedded with estuarine muds in the upper estuary. Occasional large floods breach the channel and flood across the deltaic sand body. Many small embayments drain into the outer bay from the north including Cullendulla inlet (Section 8.1.2). Grab samples taken from bayhead deltas indicate that the predominant sediments in such environments are silty muds (Figures 8.2; 3.16).

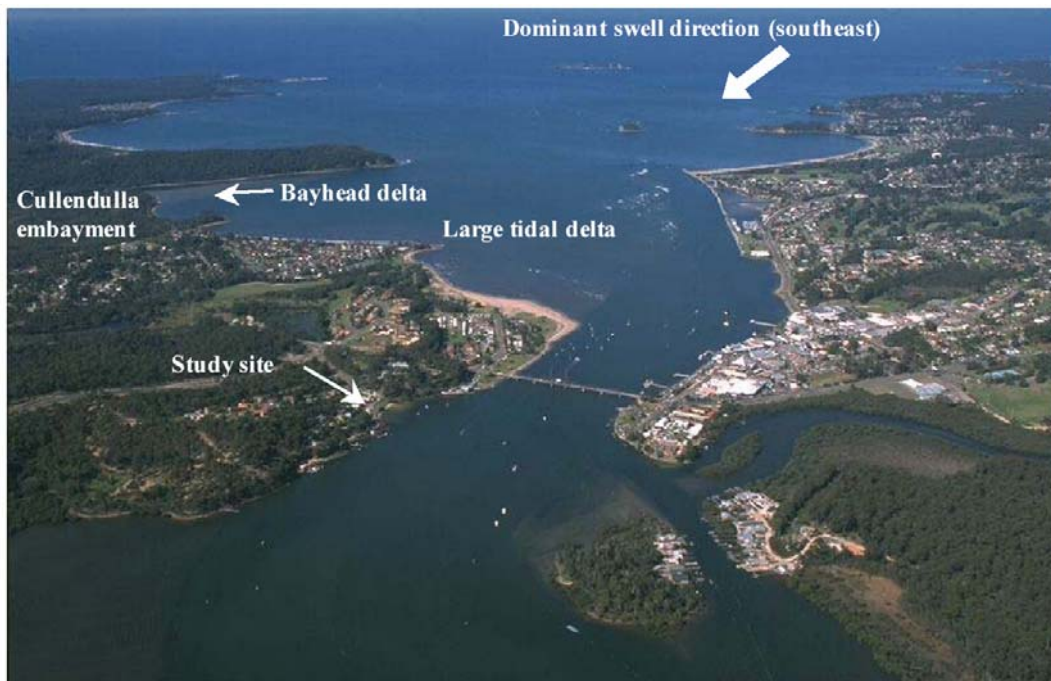


Figure 8.2 Photograph of Batemans Bay looking to the east. The sheltered study site is located in a small pocket embayment located on the northern bank west of the bridge. The large tidal delta minimises wave influence past the bridge as do the offshore islands located within the bay.

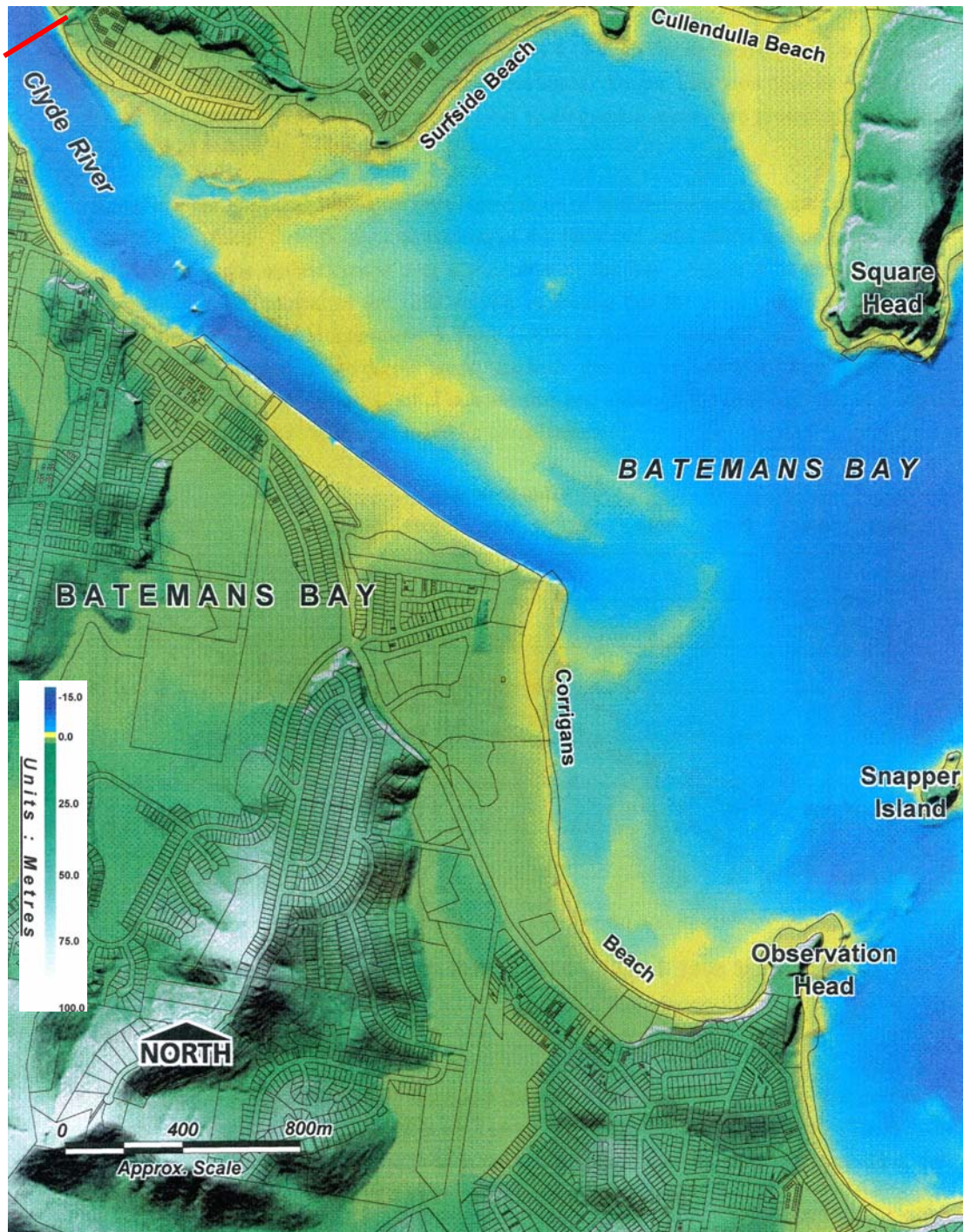


Figure 8.3 a) Digital Elevation Model (DEM) from WBM Oceanics, (2001) which highlights the confined tidal channel and the presence of a large marine sand body (tidal delta) at the estuary entrance found to the east of the study site. The study site is 150m to the northwest of the bridge highlighted in red at the top left of the image.



### 8.1.1 Geology and geomorphology

The geology of the Batemans Bay region is dominated by the moderate to highly deformed sediments and intrusive rocks of the folded Cambrian to Ordovician Lachlan Fold Belt. This system contrasts directly with the gently dipping sedimentary succession of the southern Sydney Basin that is found to the north.

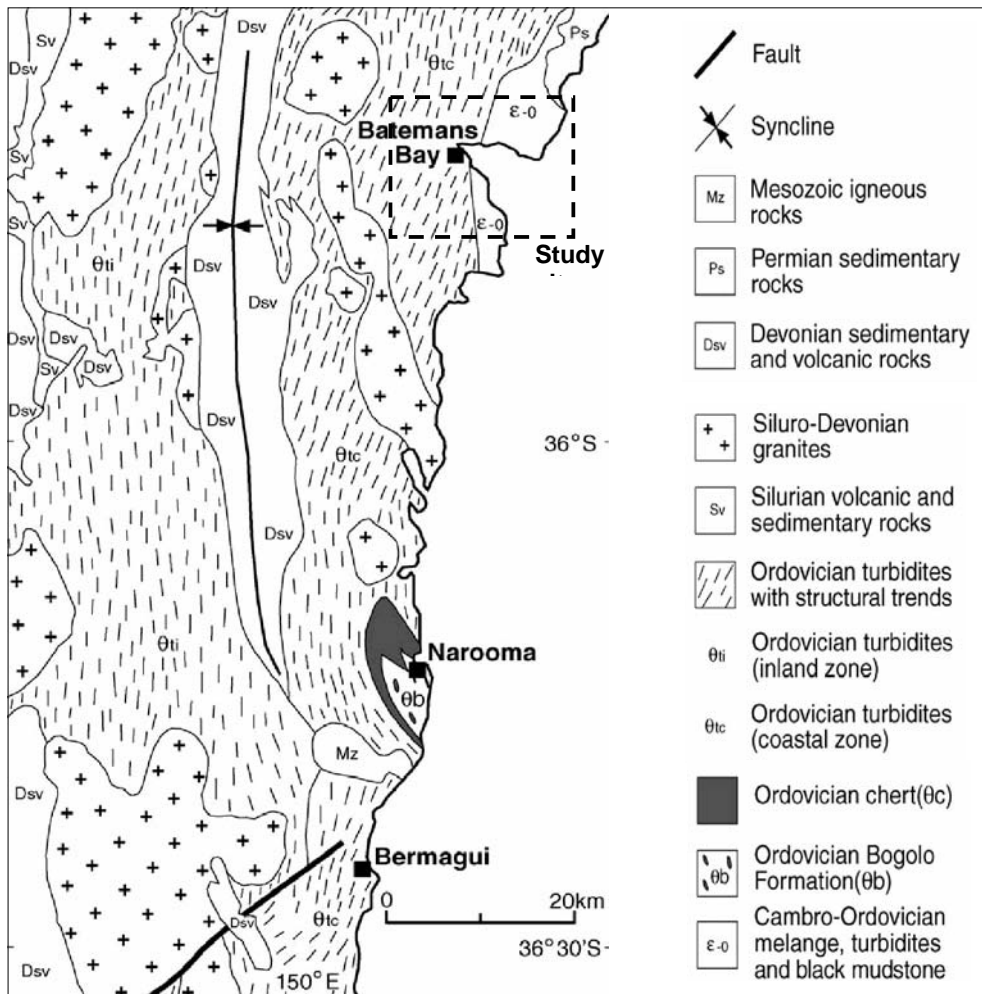


Figure 8.4 - Geological map of the eastern Lachlan fold belt (Fergusson and Frikken, 2003). This subduction complex is associated with significant tectonic deformation in the Ordovician to Silurian. The small pocket embayment at Batemans Bay (stippled box) is cut into the Ordovician turbidite beds (θtc). A sequence of older Cambro-Ordovician sediments (ε-0) outcrop to the east. The Sydney basin, a younger Permian to Carboniferous sedimentary basin (Ps) lies to the north and accommodates all other study sites.

### 8.1.2 Bathymetry and Holocene evolution

Batemans Bay has a mixed rocky and sandy shoreline (Figure 8.5) and an embayment of complex bathymetry particularly around the Tollgate Islands.

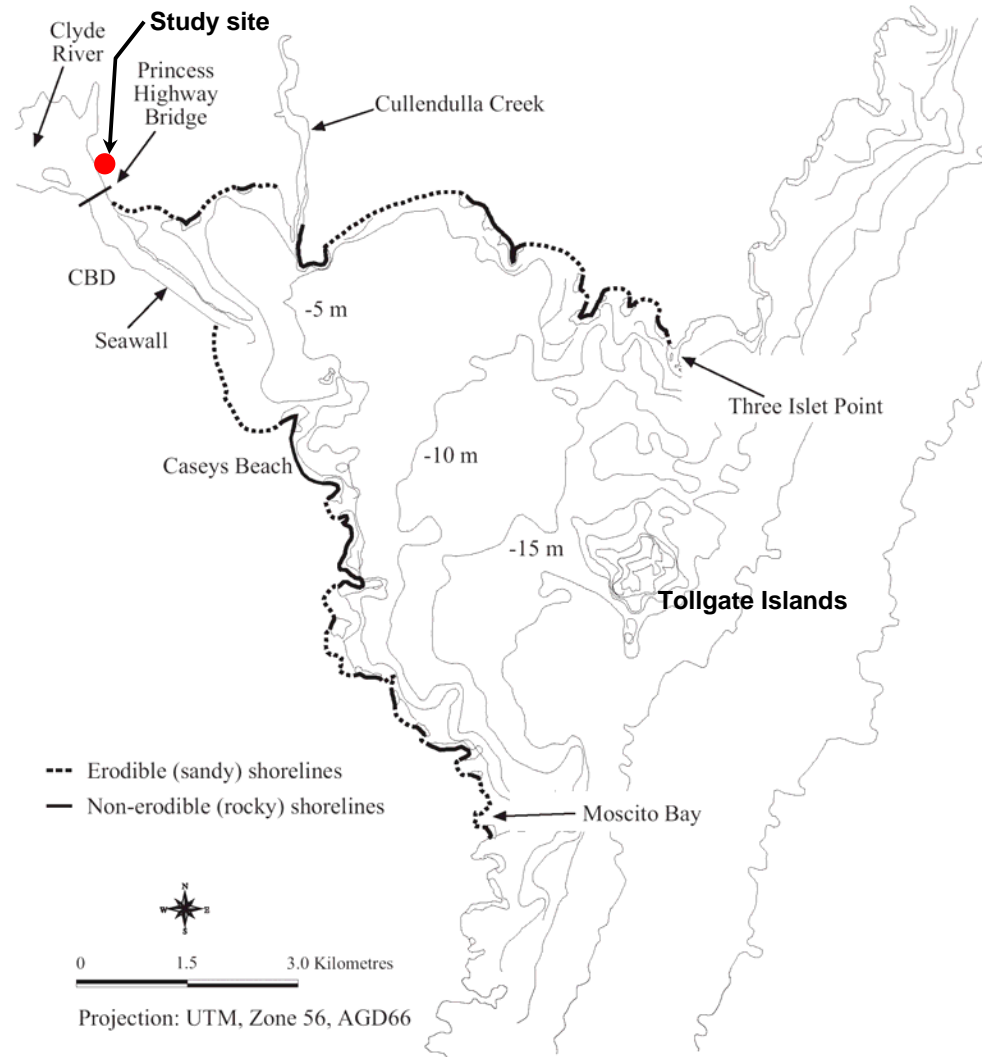


Figure 8.5 - Bathymetry of Batemans Bay based on the bathymetric map of Hydrographic Service of the Royal Australian Navy, 1985 showing erodible and non-erodible shorelines in Batemans Bay (Hennecke, 2004)

Little research has focussed on the broad scale Quaternary evolution of Batemans Bay (Wright and Thom, 1978). The embayment is most likely to have evolved in a similar fashion to other drowned river valleys (Figure 8.6; Section 2.8.1.2) such as Broken Bay and Port Hacking, these deeply incised valleys are partially filled by marine sediment during the Holocene transgression but unlike barrier estuaries they exhibit little attenuation of tidal ranges and are permanently open to the ocean. Flooding of these systems by the large river basins yields fine sediments that either accumulate in the

large mud basin or are delivered to the ocean through the small often-constricted entrance channel.

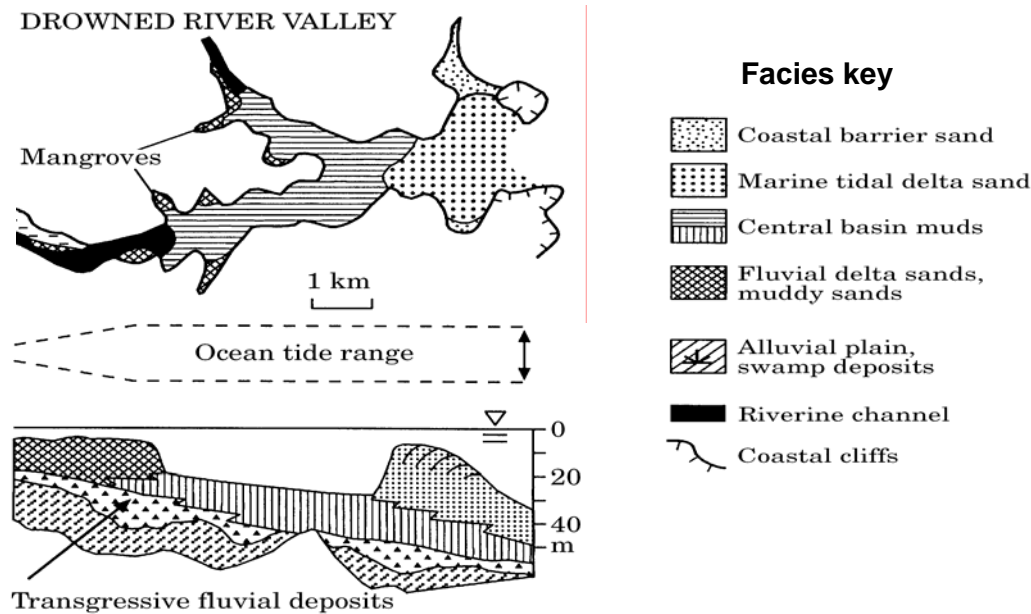


Figure 8.6 – Lithofacies distribution of an idealised drowned river valley estuary. Grab sampling of modern sediments in this study indicates that the lithofacies relationships found within Batemans Bay match this model. It is important to note that the flood tide delta in Batemans bay is significantly more confining than the model, thus attenuating the tidal range slightly.

### 8.1.3 Beach ridge formation and washover at Cullendulla

A chenier beach ridge sequence found at Cullendulla Inlet (discussed in Section 4.6.1) on the northern margin of Batemans Bay provides the only site of extensively published research into the Holocene geomorphic evolution of the embayment (Thom *et al.* 1981, 1986; Donner and Junger 1981; Bryant *et al.* 1992; Bryant, 2001). Here radiocarbon dating of a series of cheniers (some are beach ridges) shows a disjointed record of progradation that Donner and Junger (1981) related to a complex period of near shore shallowing and shoaling that caused an associated reduction in wave energy. Bryant *et al.* (1992) suggested that the ridges are geomorphic forms related to tsunami sedimentation pointing out that consistently young dates provided by radiocarbon can be explained by the incorporation of younger material into the ridge forms during large scale washover by tsunamis. It is hypothesised here upon review of the works of Thom *et al.* (1981, 1986); Donner and Junger (1981) and Bryant *et al.* (1992) that all hypotheses may in part be correct and that the geomorphic history of Cullendulla Inlet is one of prograding chenier ridges that were subsequently modified by large scale washover in the late Holocene. It is likely that such a large-scale event would cause considerable

modification or destruction of the seaward ridges. It is hoped that ground penetrating radar analysis of the most seaward ridge system may yield insights to test this hypothesis in the future.

#### 8.1.4 Grab sampling of the bay and Clyde River

Grab samples were obtained between the outer bay and the upper reaches of the estuary (Figure 8.7). This sampling was conducted with the aim of comparing samples from the beach deposits, mud flats and elevated shelly unit with modern environments within the estuary. Sampling both downstream and upstream of the study site allowed direct comparison of sediment composition and micro- and macrofaunal abundances.

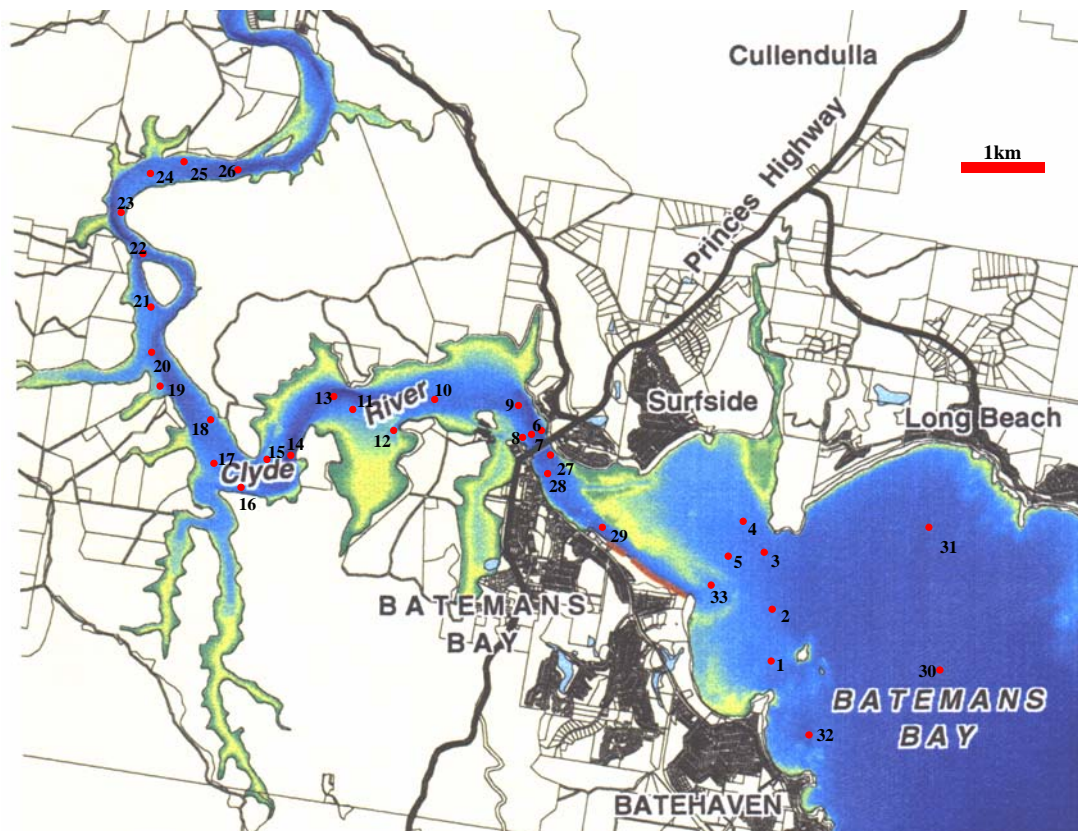


Figure 8.7 Map of grab sample locations from Batemans Bay. Sedimentological characteristics along with macro- and microfauna populations (Appendix 4) were compared in an attempt to identify the source environment of the shelly unit.

##### 8.1.4.1 Macrofaunal analysis

Macrofaunal analysis was conducted on dried ~20 g subsamples sieved at 2000  $\mu\text{m}$  (2 mm). The amount of material (rocks, cobbles, wood clasts and concretions) was



recorded as material >2000 µm. Macrofauna (Figures 8.8 and 8.9) were identified with the aid of the texts of Jensen (1995) and Beesley et al. (1998).

#### 8.1.4.2 Microfaunal analysis

Grab samples indicate that species diversity decreases upstream and out to sea with the most diverse macrofaunal populations identified in the channel and mid estuary (Figure 8.8; Appendix 4). Upstream (BBGS14-26) very few macrofaunal remains were identified. Samples from the inner bay exhibited considerably less diversity and were dominated by small gastropods and juvenile bivalves.

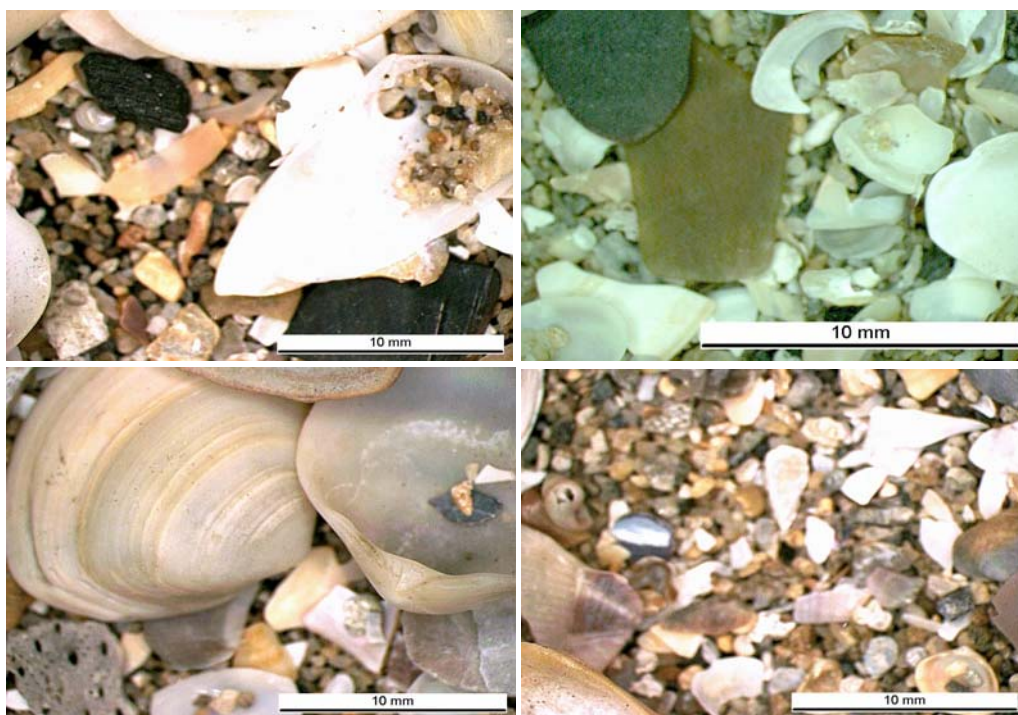


Figure 8.8 Photographs of BBGS29 a grab sample taken from the channel. The sample contains an abundance of shell hash and numerous small bivalves including abundant *Notospisula trigonella*.

## 8.2 History of oceanic flooding in Batemans Bay

The township of Batemans Bay lies on the low foreshores of the southern side of the bay at elevation of between 1.5 and 3 m (AHD). Consequently it has the potential to be flooded by elevations in the level of the Clyde River or oceanic water from the embayment. A study of oceanic inundation (Public Works Department, 1989) found a recurrence interval for marine flooding of 20 to 100 years at various sites around Batemans Bay.



Figure 8.9 Photograph of macrofauna collected from a beach face grab sample taken from the modern beachface to the east (Surfside) of the bridge (Figure 8.3). The sample contains an abundance of small bivalves including *Notospisula trigonella*.

Inundation of the foreshores of the bay by elevated ocean levels has been recorded to varied degrees since the 1940's. Estimates in 1989 indicated that a storm level of ~2.5 m (AHD) would have the potential to inundate nearshore developments worth in excess of \$50M (considerably more in 2005) causing potential damage in excess of \$5M (Public Works Department, 1989). The inundation study also indicated that the embayment has the potential to amplify storm surge to extreme levels that inundate the low-lying margins of the embayment. The oceanic inundation study (Public Works Department (1989) only looked at washover potential on the margins of the bay and no study was undertaken to the west of the bridge as very little wave energy was found to penetrate through the channel confined by the tidal delta. This observed dissipation is supported by the modelling of WBM Oceanics (2001) that indicates storm waves of 10 m from the east-southeast cause little wave action across the tidal delta or in the channel (Figure 8.7). Wave energy on the tidal delta and in the channel from storm events from the southeast were found to be considerably less.



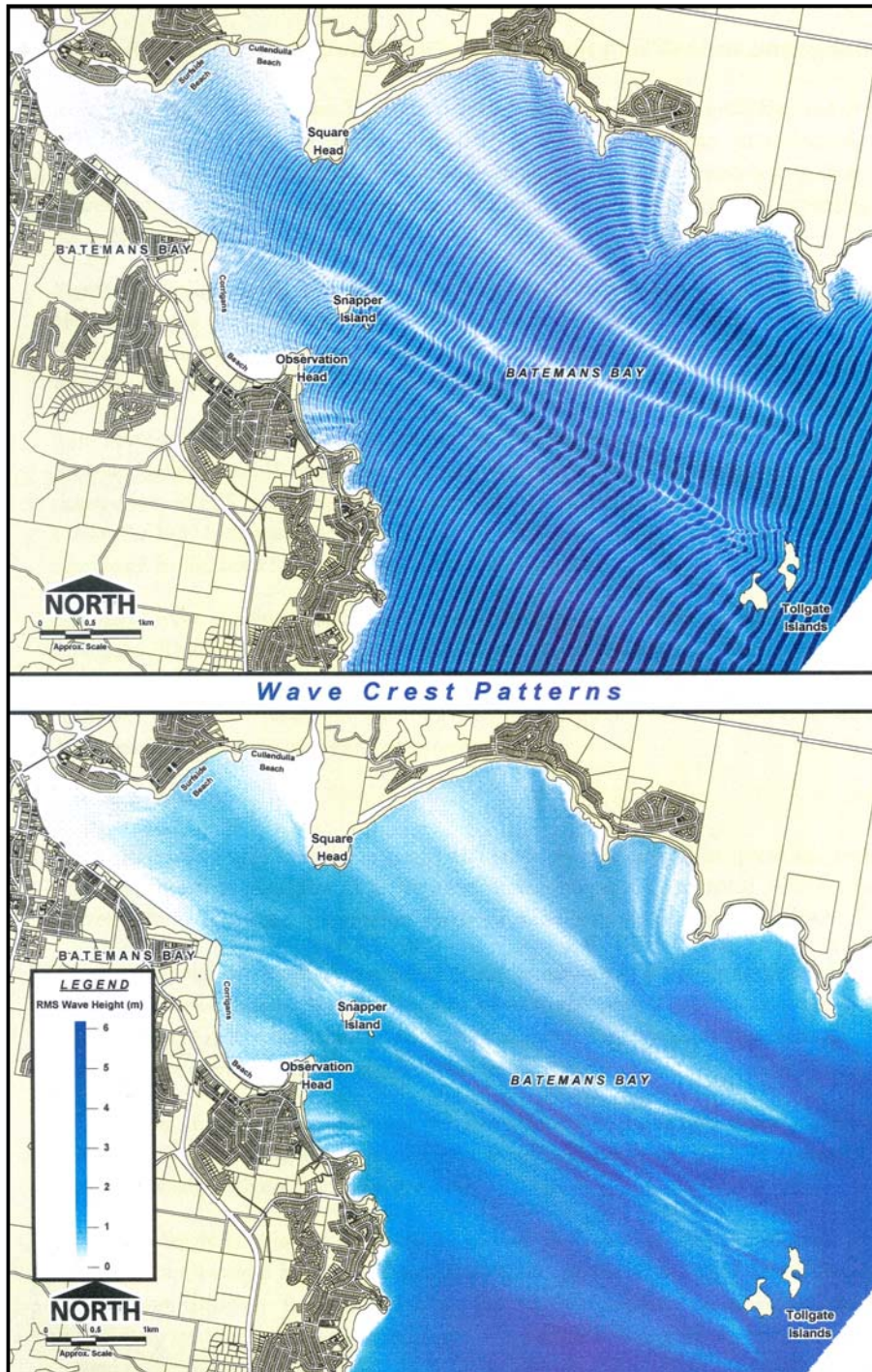


Figure 8.10 2-Dimensional wave propagation modelling of wave heights from a 10m swell from the east-southeast (WBM Oceanics, 2001) based on data from Lawson and Treloar (1989, 1996). Very little wave energy is shown to strike the tidal delta or channel with no wave energy identified at the bridge.

### 8.3 Study site – A sheltered pocket embayment

The study site is a small sheltered embayment some 150 m to the west of the bridge. The embayment is on the northern bank of the river where it broadens landward following the bedrock constriction of the bridge. A small pocket beach contains an

abundance of marine sand and shell with little fluvial sediment. The deposit is currently undergoing active erosion due to anthropogenic activity, burrowing fauna (wombats) and river floods.

The embayment is unusual in that it exhibits considerable evidence for accretionary beach activity that defies its sheltered contemporary location. The evolution of the beach facies is hypothesised in its most basic principles to be the product of higher energy deposition. Possible causes of the energy change are discussed in Section 8.9 and include higher Holocene sea level, changes in seaward morphology and a more open embayment.

#### **8.4 Study site morphology**

A morphological map of the study site is provided in Figure 8.11 along with a schematic cross-section of the deposit (Figure 8.12). The Quaternary sediments of the deposit lie in a small amphitheatre shaped basin that is incised into bedrock composed of heavily folded Ordovician metasediments. The basal part of the deposit was not studied in detail but the embayment is thought to contain little material of last interglacial age as ground penetrating radar (Chapter 9) indicates that the accretionary marine fill overlies bedrock that is located less than 10 m below the surface.

#### **8.5 Sampling program**

Samples were obtained using a series of vibracores, hand augers and excavated faces. The positions of cores obtained for this project are presented in Figure 8.9. As outlined in Section 5.3 coring of this deposit was problematic due to the shell-rich nature of the deposit. The ground penetrating radar analysis indicated that the deposit consisted of a series of accretionary beach deposits. As a result, planned drilling with a truck-mounted rig was then abandoned to focus on the genesis of the elevated coarse shelly unit hypothesised to be the product of large-scale marine washover deposition.

##### **8.5.1 Excavated faces**

Faces excavated into the bank of the river and modern beach allowed detailed analysis of the sedimentary facies associations in the beach deposit and the overlying elevated shelly unit and organic lenses. Inspection of the deposits in the field allowed elementary faunal and sediment analysis. Samples collected from the excavated faces were brought

back to the university in snaplock bags where they were analysed using a variety of sedimentological techniques including particle size (Section 5.6.1), mineralogy (Section 5.6.2), and macro- and microfaunal investigation along with organic and carbonate contents.

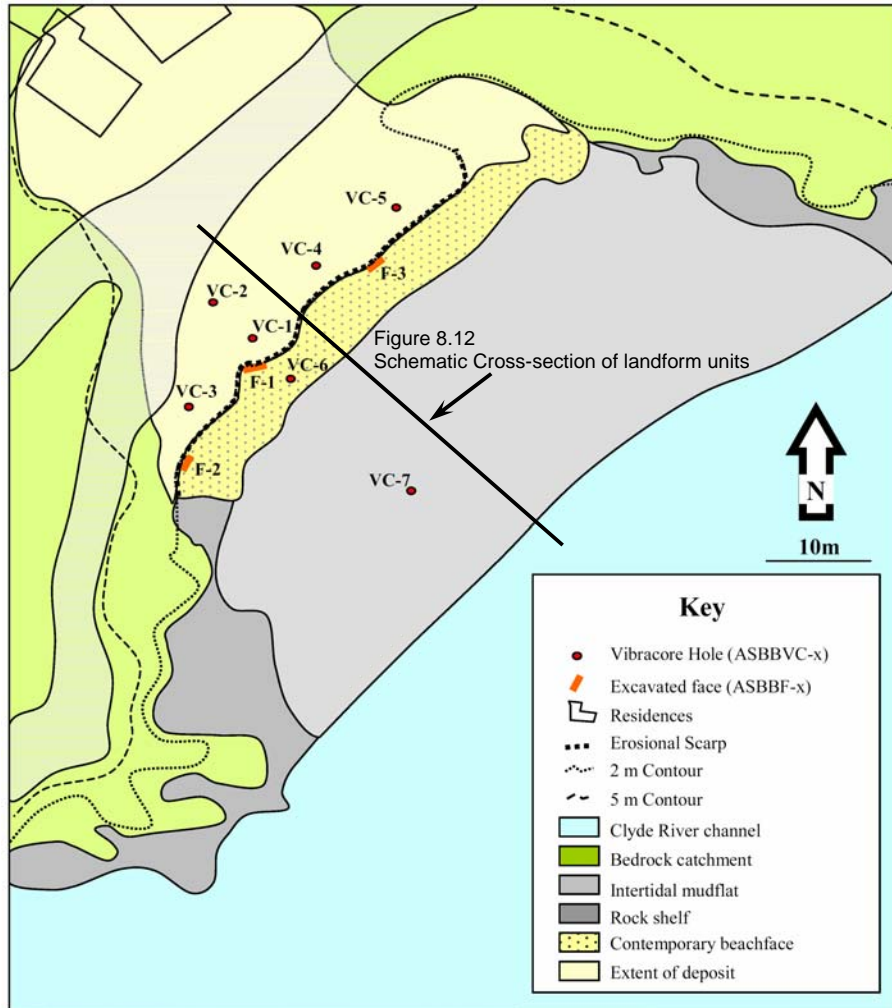


Figure 8.11 Schematic map of study site at Batemans Bay, showing locations of vibracores (ASBBVC- X) excavated faces, and facies associations. OSL samples were taken from Face 1(ASBBOSL1) and Face 2 (ASBBOSL) as outlined in Section 10.4.1.

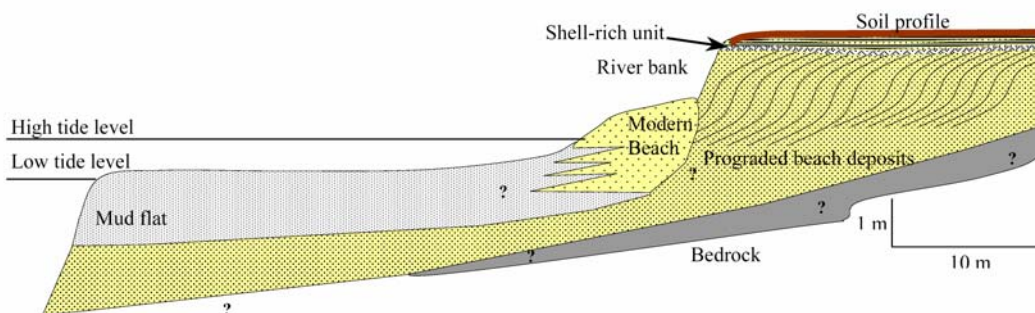


Figure 8.12 Schematic cross-section of landforms identified at the study site. Geological uncertainties are indicated with a question mark.



### 8.5.2 Coring program

The coring program was problematic due to the shelly nature of the deposit. The deepest vibracore penetrations were obtained from the beach face and mudflat. As outlined in Section 5.3.6 only shallow cores were obtained from the elevated part of the embayment. All cores penetrated the shelly unit and allowed investigation of the upper parts of the sequence. An expensive truck mounted coring program was planned for late 2003. This program was abandoned after GPR clarified the prograding nature of the deposit strongly suggesting that the lower sequence is the result of prograding beach activity in the early- to mid-Holocene most likely while sea level was 1-2 m higher between 7800 and 3000 yrs BP (Sloss *et al.*, in press).

## 8.6 Site specific analysis

Sedimentological techniques that are specific to the Batemans Bay study site centre on the presence of carbonate macro- and microfauna. Carbonate content in the prograded beach samples ranged from ~5–24%. The majority of this material was composed of *Notospisula* shells and shell hash with a small percentage of microfauna (almost exclusively foraminifers).

### 8.6.1 Macro- and microfaunal analysis

The majority of samples taken from the prograded beach sequence within the pocket embayment (Figure 8.13) were found to contain in order of abundance, *Notospisula trigonella*, *Tellina* sp. with rare *Anadara trapezia* and fragments of *Saccostrea glomerata*. It contains a similar assemblage to modern samples taken from the delta and surrounding beach (Figure 8.9).

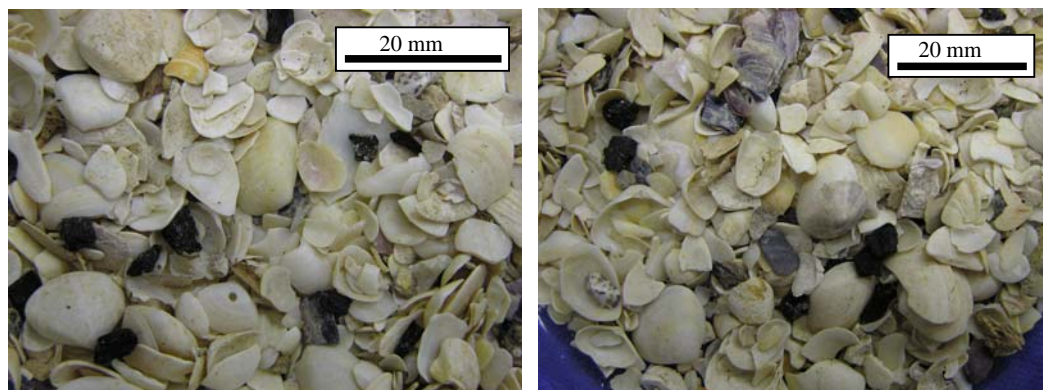


Figure 8.13 Macrofauna collected from sample BBF2 (2.25m AHD - coarse unit). Material in this photograph was sieved at 10 mm to remove several large shells including several articulated *Anadara* shells (Figure 8.18).

In contrast the large shell layer contains a dominance of *Anadara trapezia* and large or complete *Saccostrea glomerata*. It is also interesting to note that the shelly layer contains occasional articulated *Anadara* that were mainly filled with sand. The microfaunal assemblage of the prograded beach and coarse shelly unit consists of very few recognizable foraminiferal tests that are most likely a species of *Elphidium*. The tests appear badly affected by partial dissolution and or breaking.

### 8.7 Stratigraphy and facies relationships

The stratigraphy of the small embayment records fluctuations in wave energy throughout the Holocene. An organic-rich soil overlies prograded beach deposits that are now undergoing active erosion (See Chapter 9) and the latter are onlapped by a contemporary beach system mainly composed of sediments that appear to have been reworked from the older beach deposits. Onlapping the modern beach is a tidal mudflat that is composed of much finer sediments. The sequence is represented schematically in cross-section A-A<sub>1</sub> (Figure 8.14) and shows the relationship between the facies identified.

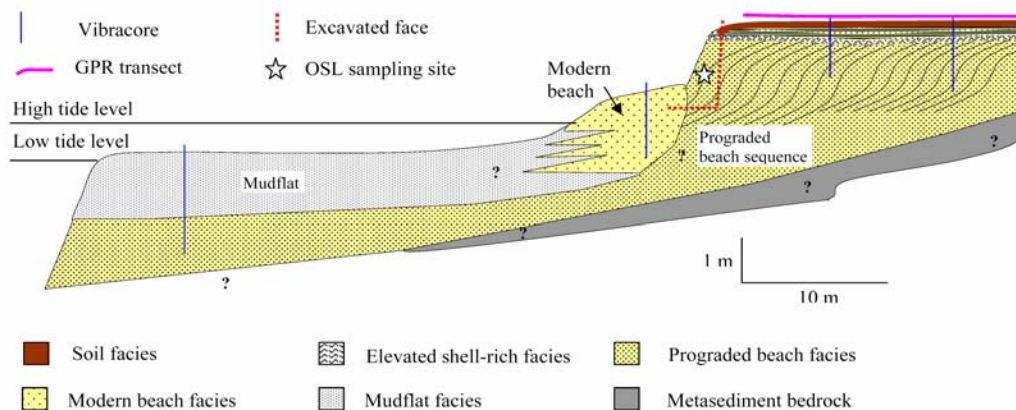


Figure 8.14 Stratigraphy of the pocket embayment deposit showing the stratigraphic relationship between facies and landforms along with the location of OSL sampling (Chapter 10) and the GPR transect (Chapter 9). Modern beach facies is reworked and shares many characteristics of the prograded facies and is not referred to as a facies in the text.

### 8.8 Sedimentary facies identified in excavated faces and cores

Three main landforms were identified in the small embayment. A prograded mid-Holocene beach cut into by a modern sequence beach that is onlapped by a modern mudflat. A soil profile developed on top of the older beach sequence has been modified

for development and cleared of most vegetation. Of principal interest in this study is the genesis of a thin, laterally continuous, coarse shelly unit that exists in the upper fill of the beach system.

Four facies were defined based on composition and sediment characteristics (the modern beach and prograded beach were inseparable on sediment characteristics and are therefore treated as one facies). Ward-based cluster analysis of samples separated four well-defined facies based on organic content, shelly fauna and sediment size characteristics. Each facies is clearly the result of very different landforms and depositional environments (discussed below). Seven vibracores collected from the sequence show the lateral extent and thin nature of the shell-rich unit and the surrounding facies (Figure 8.15). Figure 8.16 shows photographs of the physical characteristics of each of the four facies.

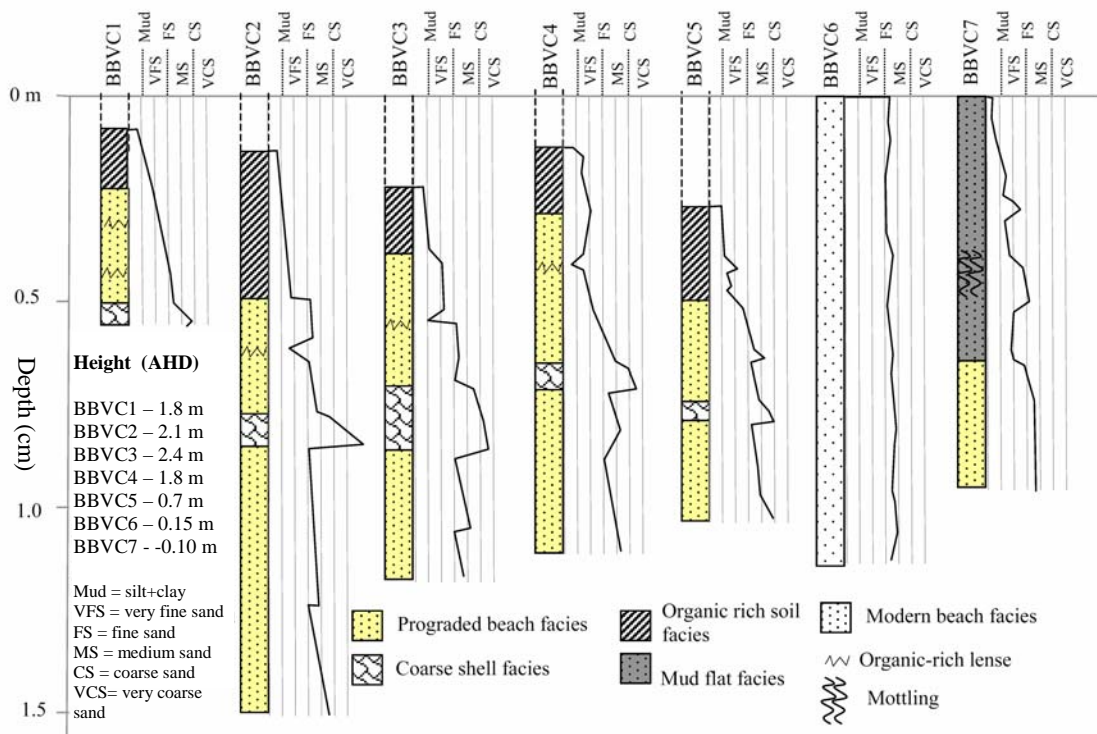


Figure 8.15 Graphic log and raw (sieved) grain size results for seven vibracores collected from the pocket embayment at Batemans Bay. Four main facies were identified in the system. The consistency of the stratigraphy in cores 1-5 indicates the extent of the shell-rich deposit.

The excavated faces allowed detailed analysis of the sandy shell-rich facies of the prograded beach sequence, the coarse shelly unit and the soil in both lateral and vertical detail. Figure 8.17 shows excavated face 2 and the interpretation of sedimentary features. The shelly sand nature of the beach facies is clearly visible, as is the shelly

unit. Like the modern seaward beach system, the sediments of this prograded deposit are most likely an expression of variable energy over time. It is noted on the modern systems that periods of low energy result in sandy sediment deposition whilst higher energy conditions leave coarser shelly sequences behind after the sandy material is eroded and reworked.

### 8.8.1 Two sandy beach facies

The beach facies of both the prograded beach sequence and modern beach are composed of clean- to shelly-sand deposits dominated by fine- to medium-grained quartz sand with a minor component of medium- to coarse-sand size lithic grains. Sand content of treated sediments in the prograded beach facies is consistently above 90% and contrasts with the organic rich facies and the mudflat. The source of the small mud component (Figure 8.18) in the prograded beach facies is undetermined but it is hypothesised that a significant source may be due to groundwater movement through the overlying soil that transports fine material down into the underlying system.

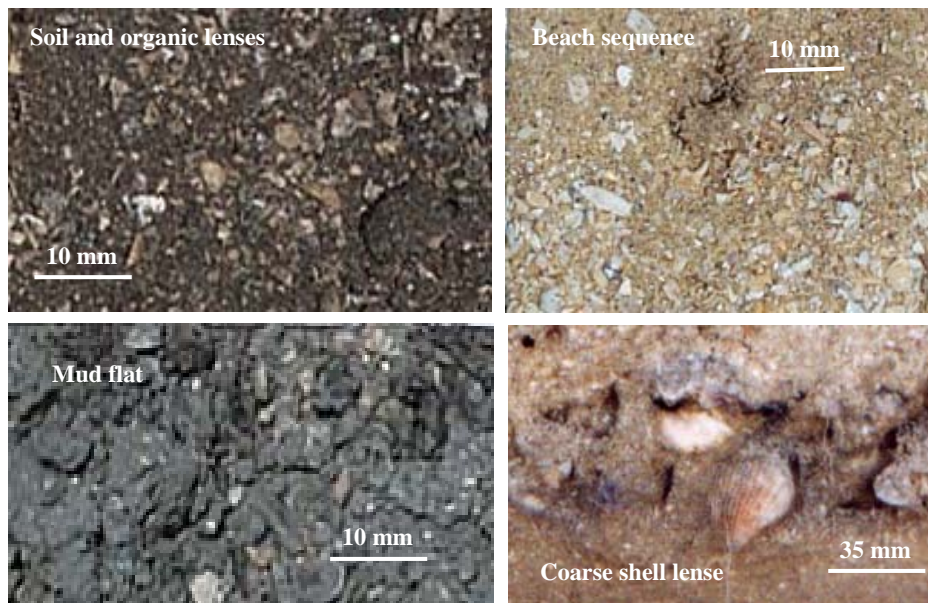


Figure 8.16 Facies identified in cores and excavated facies from the Batemans Bay study site

The prograded beach facies contains very few microfauna although few heavily weathered foram tests (possibly *Elphidium* species) were identified in the samples collected from excavated faces ABBF1 and ABBF2. The entire sequence is dominated by the small bivalve *Notospisula trigonella*, in places these small shells contribute more than 70% of the sample.



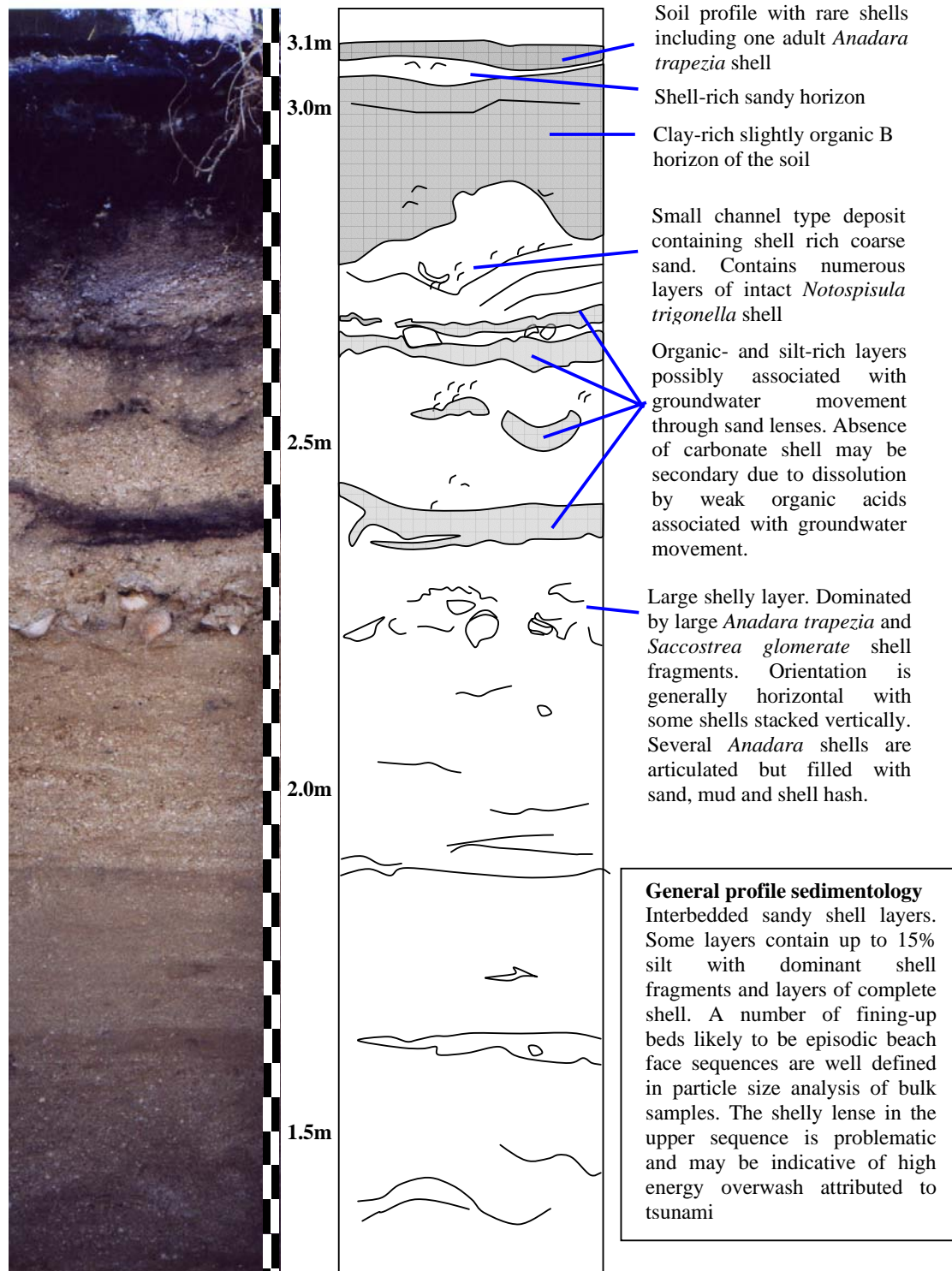


Figure 8.17 Interpretation and sedimentological characteristics of excavated face ASBBF2 at Batemans Bay. All heights are relative to Australian height datum (AHD). The lower sequence is most likely the result of a prograded beach sequences. The shelly lense in the upper sequence contrasts directly with the enclosing sediments.



### 8.8.2 Sedimentary characteristics of the modern mudflat facies

The mudflat contrasts with the beach facies that it onlaps. The muddy sediments are dominated by silt with a small component of quartz and lithic sand. Much of this sand has probably been reworked from the beach sequence that is currently eroding the prograded beach. The sand content increases with depth in cores (Figure 8.15) and the mottled nature of the sediment in the mid parts of BBVC7 in places may suggest the former presence of a mangrove community before removal for development in the 1950's. The mudflat facies also contains a small population of bivalves, gastropods and carbonate microfauna including *Ammonia beccari* and *Elphidium* sp. indicating a low energy environment.

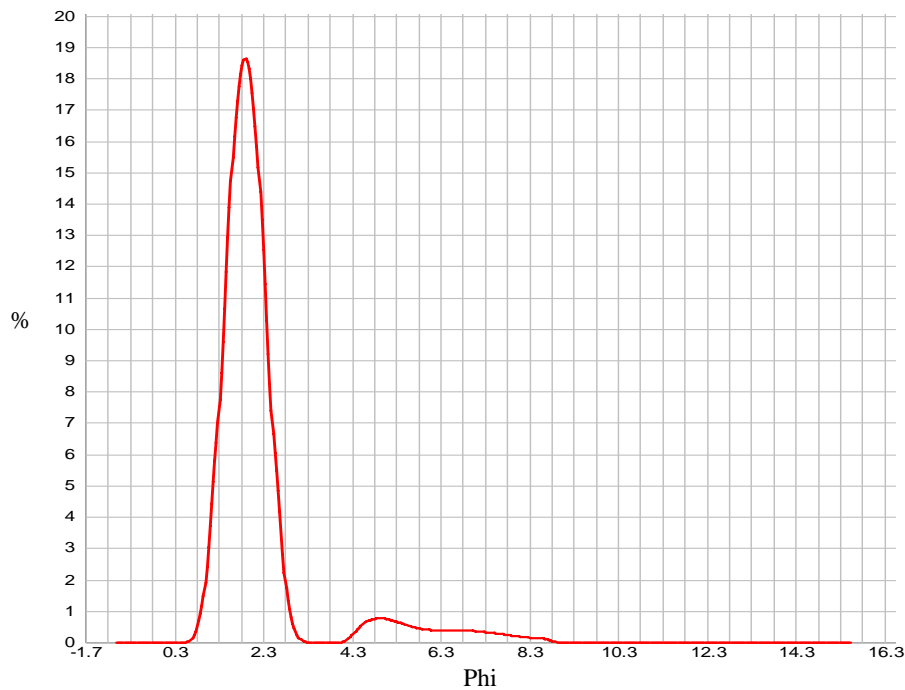


Figure 8.18 Grain size distribution of a treated sediment sample from the prograded beach facies at 0.50 m (AHD) in excavated face 2.

### 8.8.3 Organic rich soil and organic lenses

An organic-rich soil and several organic-rich lenses are found in both the cores and excavated faces and they overlie the sandy beach facies. The organic-rich facies is characterised by high silt and clay content (up to 50%) and the presence of dark organic debris and a minor component of fractured shelly debris. Sediments are composed of an organic-rich clay matrix with sub-angular to sub-rounded quartz/lithic fine-grained sand. Sediments grade down from the soil to a fine- to medium-grained shelly sand sequence with organic lenses. The genesis of the organic lenses is problematic but they

appear to be secondary and may be a result of preferential groundwater movement through the porous sandy units. An alternative hypothesis of settling after large-scale washover is discussed in Section 8.9.

#### 8.8.4 Thin elevated coarse shelly facies.

The coarse shelly deposit appears anomalous and exists as a thin extensive lense ranging from 0.7 m to 2.25 m AHD. Although dominated by fine- to medium-grained quartz sand (Figure 8.19), the shell-dominated lense is differentiated from the sandy prograded beach sequence by the presence of very coarse shelly fauna including abundant *Anadara trapezia* and *Saccostrea glomerata*. Of particular interest is the presence of several articulated *Anadara* shells (Figure 8.20a). These shells are randomly orientated through out the unit and were often found in a partially opened state, with sand and occasional small shells and shell hash inside the valves (Figure 8.20b). Few microfossils were identified in the shelly deposit and, like the prograded beach sequence, tests were limited to several heavily weathered *Elphidium* sp.

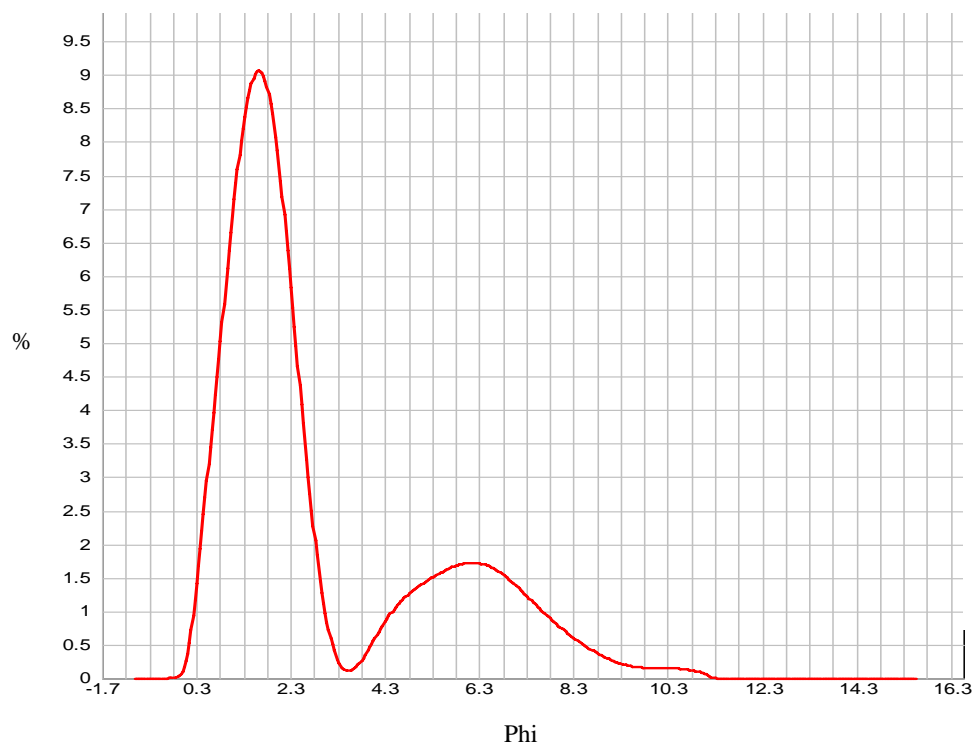


Figure 8.19 Grain size distribution of a sample taken from Face 2 at 2.25 m in the coarse shell unit. The sediments are dominated by fine- to medium-grained sand with a second mode of silt sized material.



Figure 8.20 Articulated *Anadara trapezia* from face 2 at 2.25 m. a) shows a large cleaned *Anadara* that was dated using amino acid racemisation (Chapter 10). b) shows the shell-rich facies in face 2 that the shell was extracted from.

### 8.9 Comparison of the facies

The sand fraction (treated to remove carbonate) of both the prograded beach sequence and very coarse shelly unit is composed of fine- to medium-grained quartz sand with a minor lithic component. Both facies contain little variation in grain size (1.7-2.2 phi). Major variation does occur in the presence of macrofauna. The beach sequence is dominated by shell hash and hundreds of the small bivalve *Notospisula trigonella*. Samples from cores, cut faces and grab samples were plotted in bivariate plots to identify contrasts between the facies and related to modern environments. Figure 8.21a shows a graph of mean (inclusive graphical mean) against sorting (inclusive graphic standard deviation) along with a plot of organic content (loss on ignition) against percent greater than 2000  $\mu\text{m}$  (Figure 8.20b) for 60 samples. Four groups are clearly defined by these two plots and the coarse grained shelly unit is noted to cluster with the modern samples collected from the channel for carbonate and organic matter and the beach for particle size parameters.

Comparison of grain size parameters including inclusive mean and inclusive standard deviation along with percent greater than 2000  $\mu\text{m}$  and carbonate and organic content identified four facies. The soil and organic lenses cluster with the fine-grained sediments of the modern tidal flat and are only separated by organic and carbonate content. Both facies are representative of low energy environments with the mudflat containing a slightly higher shell content and much greater organic content.

### 8.9.1 Depositional history of the beach sediments and mud flats

On basic sedimentological principles the beach sequence must be the result of a higher energy system than the tidal flat sequence. The genesis of such a high-energy environment is problematic. The high energy conditions required to produce the prograded quartz-dominated sequence would require the embayment to be open to much higher wave energy.

As outlined in section 2.5 considerable debate has continued over evidence for higher mid-Holocene sea-level (Flood and Frankel, 1989; Baker and Haworth, 2000a,b; Baker *et al.*, 2003, Sloss *et al.*, in press). Higher mid-Holocene sea levels (+1-2 m) may have contributed to an increase in wave energy in the small embayment (Figure 2.22).

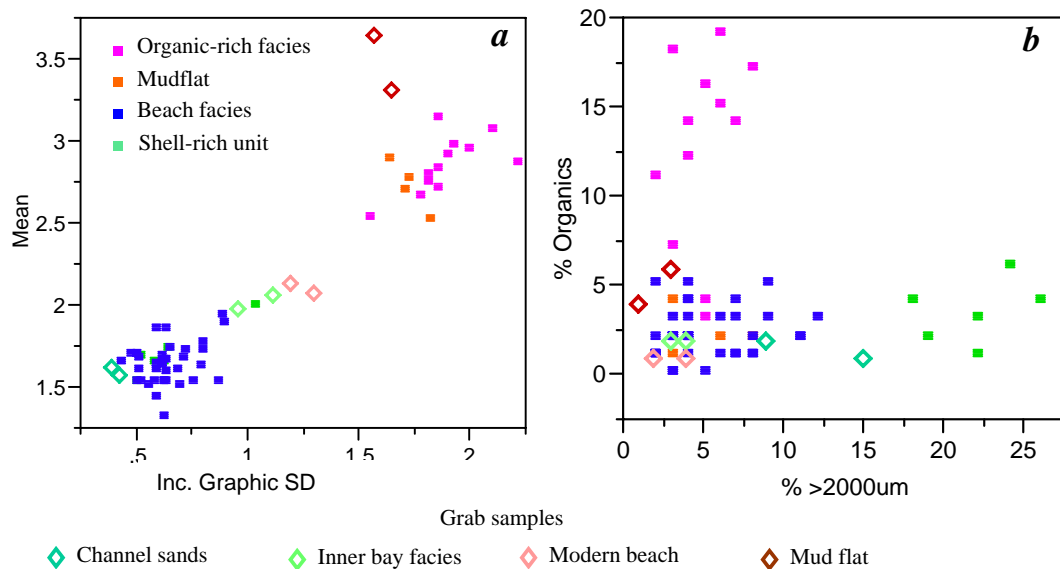


Figure 8.21 Bivariate plots of a) Inclusive mean vs sorting (inclusive graphical standard deviation) and organic content v % greater than 2000 um (sieved). Both the beach facies and the shell-rich unit have similar sediment size characteristics but are differentiated by differences in organic and shell content.

The genesis of the prograded sequence remains unresolved as little is known about the growth and development of the sand body at Batemans Bay township and the early growth of the delta to the east of the bridge. It appears likely that the sandy beach sequence is the result of higher energy experienced during both a period of higher sea level and an immature estuary with a more open embayment (Figure 8.22). This hypothesis is partially supported by dating of the beach sequence presented in Chapter 10, which provides several dates between 2500-4000 years. These dates correspond to the high stand period identified by (Baker and Haworth, 1997; Baker *et al.*, 2000a,b). It

is also likely that, although unstudied in the Batemans Bay area, the early Holocene would have seen this system experience a different more open morphology. It is, therefore, likely that as sea level fell and the present morphology of the eastern bay developed, the wave energy would be significantly dissipated stranding the beach sequence in the small embayment allowing the accumulation of the present low energy mudflat.

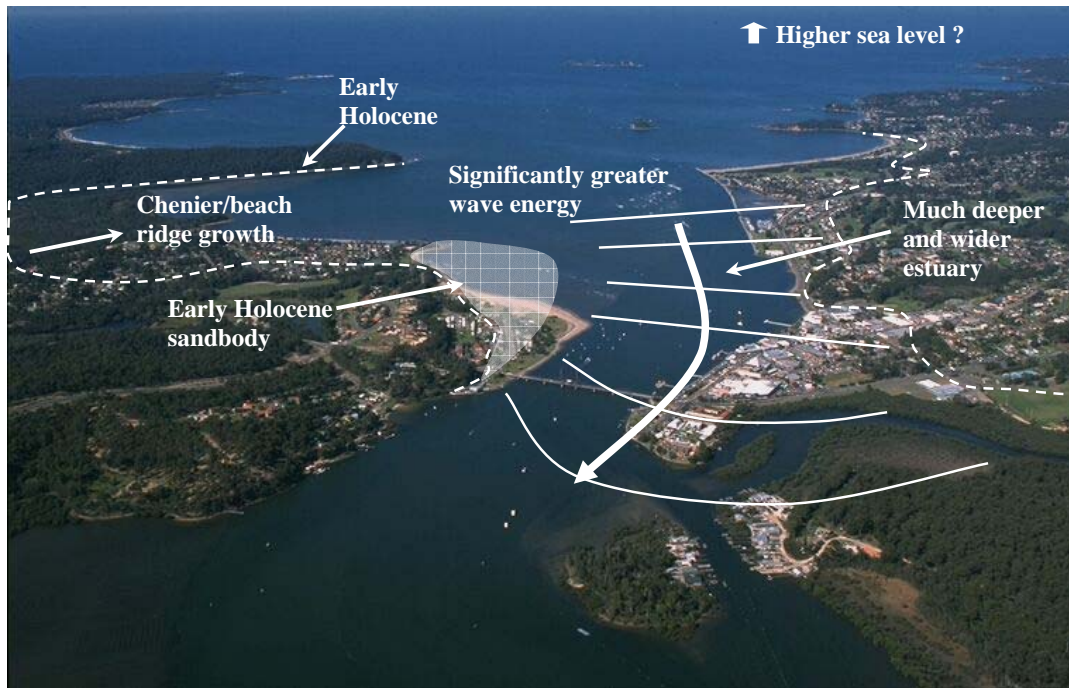


Figure 8.22 Schematic figure demonstrating the hypothesis of a more open embayment in the mid-Holocene. A more open embayment would account for the higher energy system indicated by the prograded beach facies. It is also likely that possible higher mid-Holocene sea levels (Sloss *et al.* in press) would increase wave energy in the small embayment.

The tidal mudflat deposit contrasts with the beach sequence and although undated is much more likely to represent the modern low energy sequence. Of interest is the mottled appearance of the lower parts of the sequence observed in core BBVC7. The mottling is likely to be representative of a mangrove community developed on the mudflat. This mangrove environment may have contributed significantly to the preservation of the beach sequence as it would dissipate floodwaters associated with flooding of the Clyde River. Clearing of the mangrove for development in the 1950's (Eurobodalla Shire Council) has led to contemporary erosion of the system to the morphology observed today.

### **8.9.2 Sedimentology and origin of the raised shell-rich unit.**

The coarse shell-rich unit exhibits very unusual sediment characteristics. Bulk samples are considerably coarser than the enclosing sediments due to the presence of large amounts of coarse shell (>2 mm). Analysis of treated (carbonate removed) samples suggests that the deposit matrix is very similar to the underlying beach facies and modern samples collected from both the seaward channel and beaches. Also unusual is the elevation and lateral extent of the deposit. The deposit exists in all excavated faces and vibracoring suggests that the deposit covers much of the embayment (at least back to the road) and exists from 0.7 m to 2.25 m in elevation.

The macrofauna identified in the coarse shelly deposit are representative of modern shells from rock platforms, modern beaches and the tidal channel suggesting the deposit is the product of erosion from several seaward environments. However, the presence of fragile and articulated shells (Figure 8.20) is also unusual because it suggests that the deposit was emplaced with little abrasive reworking. The presence of the articulated shells that are filled or partially filled with sand is indicative of post depositional infilling as the organic material of the shell decomposes. It is also important to note that several large well-rounded clasts of quartz and folded metasediments were found incorporated in the shelly unit.

One source of diverse large shelly fauna often found on the coast are aboriginal middens (Hall and McNiven, 1999). It is unlikely that this deposit is a midden as it is much more extensive than any midden found on the coast, contains no evidence of burning and contains several inedible shells. This deposit is different since it contains shells from different environments. A mixed assemblage of channel and beach material possibly indicative of large scale washover that is capable of incorporating, beach material channel sediments and depositing them in a flat lying laterally extensive deposit.

### **8.10 Synthesis**

The very coarse nature of the elevated shell-rich unit appears anomalous when related to the evolution of the underlying beach sequence. The presence of very coarse (cobble sized) shelly sediments with numerous rock clasts indicates deposition under very high-energy conditions.

Shell and cobble deposits have rarely been identified as evidence for washover deposition. Two notable examples include sediments attributed to large storms in the Netherlands (Jelgersma *et al.*, 1995) and northern Australia (Nott and Hayne, 2001; Nott, 2003). The examples from northern Australia (Figure 3.6) are from the carbonate dominated environments of the tropical Great Barrier Reef. In contrast to the coastal sediments of the study site, the shelly carbonate-rich deposits studied by Nott and Hayne (2001) and Nott (2003) contain little terrigenous sediment. The shelly carbonate ridges are the product of the source environment as the nearshore zone, beach and dune are composed of this material.

Jelgersma *et al.* (1995) identified a sequence of shell-rich beds that they attributed to the action of large mid-Holocene storms. The shell beds are found in coastal dune sequences and consist of beachface shells that are confined by accumulations of aeolian sand. Several notable similarities and contrasts exist between the deposits identified here and those of Jelgersma *et al.* (1995). In both sequences the deposits contain shelly faunas that differ from those of the confining sediments, and they are both composed primarily of shelly debris in a matrix of sand-sized sediment. The most peculiar characteristic of the coarse shell unit found at Batemans Bay is the presence of lithic clasts, oyster shell and single and articulated *Anadara* shells. Based on size alone the large (>50 mm) oyster shells indicate that the depositional event was capable of transporting very coarse clasts. Furthermore the presence of oyster shells may also suggest that the event was capable of removing the top valve of oyster shells from the surrounding rocky outcrops before depositing them in the elevated deposit. Unfortunately there are no modern examples of such erosion from this coast and this speculative hypothesis remains to be adequately tested.

The articulated *Anadara trapezia* shells may provide a valuable insight into the deposition of the shell-rich unit. *Anadara trapezia* are found in seagrass meadows on sandy substrates in many estuaries along the New South Wales coast (Jensen, 1995). Unfortunately no modern *Anadara trapezia* were obtained from the grab sampling program for this study but it is likely that they would come from a seaward direction as they rarely live in muddy substrates. The most intriguing characteristic of the shell-rich unit is the presence of articulated shells that are often half opened and filled with shelly fine- to medium-grained sand.



It is hypothesised here that the shells were transported to their elevated position by a depositional event with energy levels high enough to transport the material but not high enough to separate the valves the tightly closed vales of the live shells. To fulfill this hypothesis and deposit articulated and partially filled shells in an elevated position the depositional event would require a mechanism of transport that would not cause separation of the shells. It is unlikely that a storm surge or storm waves would do this as they are characterised by individual pulses of very-high energy associated with individual wave run-ups. The shells do open after the organism dies and the adductor muscles are no longer contracted. This happens in all systems and would explain the post depositional infilling with sand.

#### **8.11 Model for the deposition of the shell-rich unit.**

The sedimentary characteristics of the shell-rich unit show that it is composed of material derived from several environments that occur in a seaward direction of the deposit. Figure 8.23 shows a schematic model for the deposition of the shell-rich unit. The model provides an explanation for the erosion transport and deposition of all components of the facies along with the source area for each component.

As discussed above it is unlikely that this deposit can be attributed to a storm surge event. One mechanism that explains the transport of large amounts of material by both turbulent and laminar flow is deposition by tsunami (Bryant, 2001). A late-Holocene age of the deposit is inferred from dating the underlying sediments and it is hypothesised that this deposit is related to the washover event identified at Killalea lagoon.

Unlike large storm waves, a tsunami often occurs as a single surge that is capable of carrying large amounts of material in suspension considerable distances inland. This property may explain the presence of the large articulated shells found in the shell-rich unit. The shells may have been carried in suspension with little reworking before being infilled with sand.

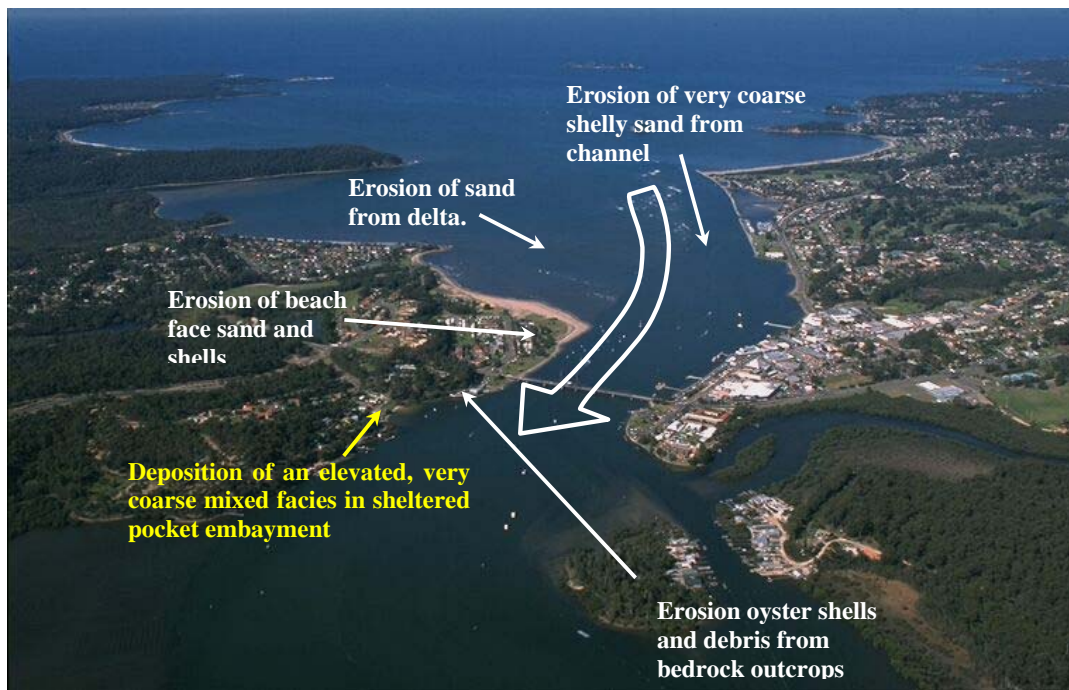


Figure 8.23 Schematic model for the erosion and deposition of the shell-rich unit by large-scale washover. The event was capable of eroding large amounts of material from the seaward environments and transporting it to the elevated position in the pocket embayment. The presence of articulated shells suggests that the event did this without significant turbulence that would have separated the valves of the shells. This event is attributed to a late-Holocene tsunami from the southeast.

The identification of this deposit indicates that large washover events have occurred in the past in the Bateman Bay area and that these events are considerably larger than those in recorded history. Regardless of the genesis suggested for the deposit the reoccurrence of this type of event would cause considerable damage to the low-lying communities that surround the bay.

## 8.12 Conclusions

- A sequence of fine- to medium-grained, shelly sands occurs in a shallow pocket embayment at Batemans Bay. The sequence is interpreted as a prograded beach sequence that is the result of a combination of a more open embayment and possible higher sea level during the mid-Holocene. Establishment of a mangrove community is recorded as mottled mudflat deposit that onlaps the beach sequence. Removal of the mangrove has now opened the embayment to considerable erosion during flooding of the Clyde River.

- A laterally extensive, flat lying, shell-rich unit is found in the upper fill of the embayment. The unit appears anomalous and contains large shells and rock clasts. Of particular note is the presence of articulated and fragile shells that indicate transport with little hydraulic reworking. Comparison of the sedimentary components of the shell-rich unit with grab samples from throughout the estuary suggests that the shell-rich unit is composed of material that occurs primarily in seaward environments such as the channel and the tidal delta.
- It is unlikely that the shell-rich unit is the result of storm waves due to the sheltered nature of the embayment, the presence of large articulated shells and rock clasts. The deposit is possibly the result of large-scale washover by tsunami in the late Holocene and may be coincident with the deposition of the sandsheet presented in Chapter 7. The tsunami is thought to have eroded large amounts of material from the channel, delta and surrounding rock shelves before transporting the material (with little reworking) to the elevated site of deposition.

## Chapter 9

### **Ground Penetrating Radar (GPR) - Identification of an erosional signature in the dunes of Killalea**

#### **Introduction**

The focus of this part of the study involves analysis of the geological record for an erosional signature within the dune system of Killalea Lagoon. One would expect that if the marine sand forming the sand sheet is the product of washover then the sandy barrier, would have experienced considerable erosion. Furthermore it is reasonable to expect that such an event would have caused considerable geomorphic change to the barrier and that the likelihood of an erosional boundary occurring within the vertical stratigraphy of the dune is high, based on the basic assumption that barrier and indeed dune activity resumes soon after the washover event.

Complementary to the GPR investigation of the Killalea sequence is two small transects of the Batemans Bay deposit. One transect indicates the prograding nature of the beach ridge sequence that underlies the shell-rich deposit studied in Chapter 8. Unfortunately efforts to identify the extent of the shell-rich deposit were complicated by the proximity of the deposit to the surface and the presence of a road, subsurface pipes and overhead electrical wires.

#### **9.1 Brief review of the ground penetrating radar technique with examples**

The ground penetrating radar (GPR) technique allows the operator to image, locate and identify changes in electrical and magnetic properties in the ground through the use of electromagnetic wave propagation and scattering (Leatherman, 1987). The technique is particularly applicable to sandy sediments and is, therefore, a desirable tool to interpret and reconstruct dune systems including those of coastal barriers or beachridge sequences (Leatherman, 1987; Jol and Smith, 1991; Bristow, 1995; Jol *et al.*, 1996, 2003; Van Heteren *et al.*, 1996, 1998 Bristow *et al.*, 2000; Neal and Roberts, 2000; Neal, 2004). Using the propagation and subsequent reflection of pulsed high frequency electromagnetic energy (Figure 9.1), the GPR method can provide high resolution (down to cm), near continuous profiles of many coarser-grained deposits to depths of up to 60 m (Jol *et al.*, 2003). Electromagnetic energy is reflected off discontinuity surfaces and return to a receiver (Figure 9.2). The first two waves received are an airwave and a

ground wave, which is followed by a reflected wave and commonly a lateral wave (Neal, 2004)

Examples of this technique that indicate its usefulness in dune settings include studies from coastal dunes in Wales (Bailey *et al.* 2001) northwestern United States (Jol and Smith 1991) and Denmark (Anthony and Moller 2002). For information on Ground Penetrating radar and its theory and processing the reader is referred to papers by Davis and Annan (1989); Beres and Haeni (1991); Jol and Smith (1991); Neal (2004) and the recent text of Bristow and Jol (2003).

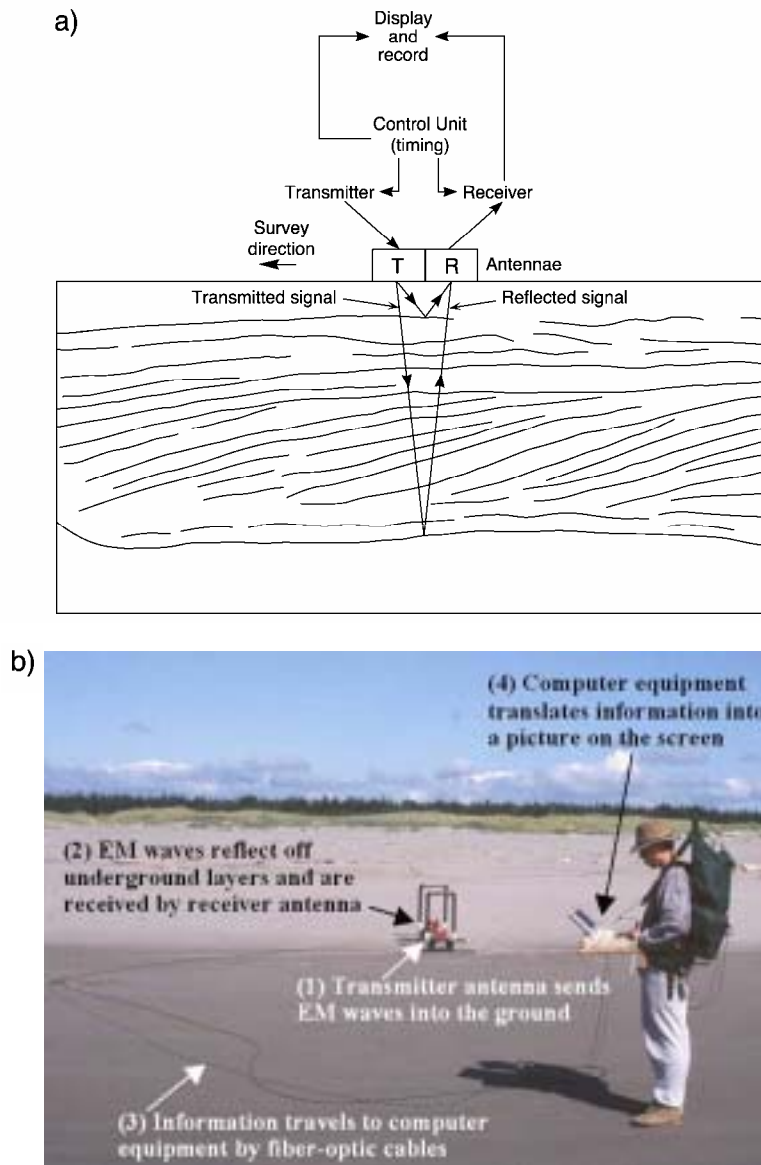


Figure 9.1 a) schematic diagram and photograph (b) of the principles of the ground penetrating radar technique and the equipment use (Bristow and Jol, 2003).

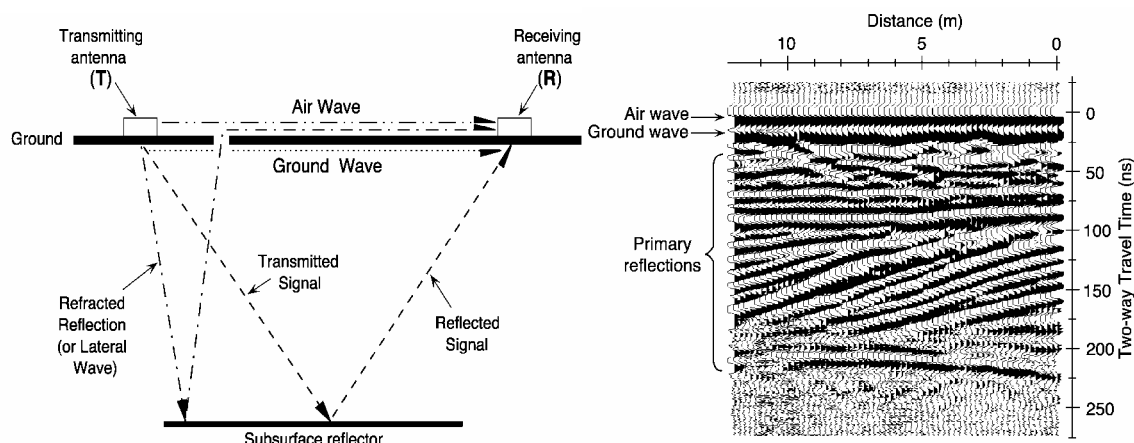


Figure 9.2 a) Schematic diagram of possible ray paths between transmitting and receiving antennae for the airwave, the ground wave, a lateral wave and a reflected wave (from Neal 2004; modified from Fisher et al., 1996). The lateral wave is anonymously reflected and can be problematic as it is not in time with the genuine return of the reflected signal of the profile. b) a radar profile showing the air and ground waves along with a series of primary reflections.

A particularly relevant recent example from Anthony and Moller (2002) used GPR on dunes from the North Sea coast of Denmark to define a series of radar-facies and contacts complemented by a coring program. In many cases they indicated that aeolian dune activity was often truncated by washover deposition resulting in sharp contacts between high-angle dipping aeolian beds and low-angle to laminated storm deposits.

## 9.2 Study sites

Ground penetrating radar transects were conducted at Killalea and Batemans Bay in order to investigate subsurface contacts and stratigraphy. GPR work was conducted in September 2003 by Charles Bristow from Birbeck College, University of London. Selection of transect locations was dictated in part by time constraints as only three days were available for field work.

### 9.2.1 Batemans Bay

Two transects were conducted at Batemans Bay (Figure 9.3), the first (BBGPR-1) was conducted perpendicular to the hypothesised direction of beach ridge accretion. The second transect (BBGPR-2) was conducted shore normal to the beach ridges with the aim of investigating the irregular subsurface stratigraphy and to determine the extent of the shell-rich deposit identified in Chapter 8.

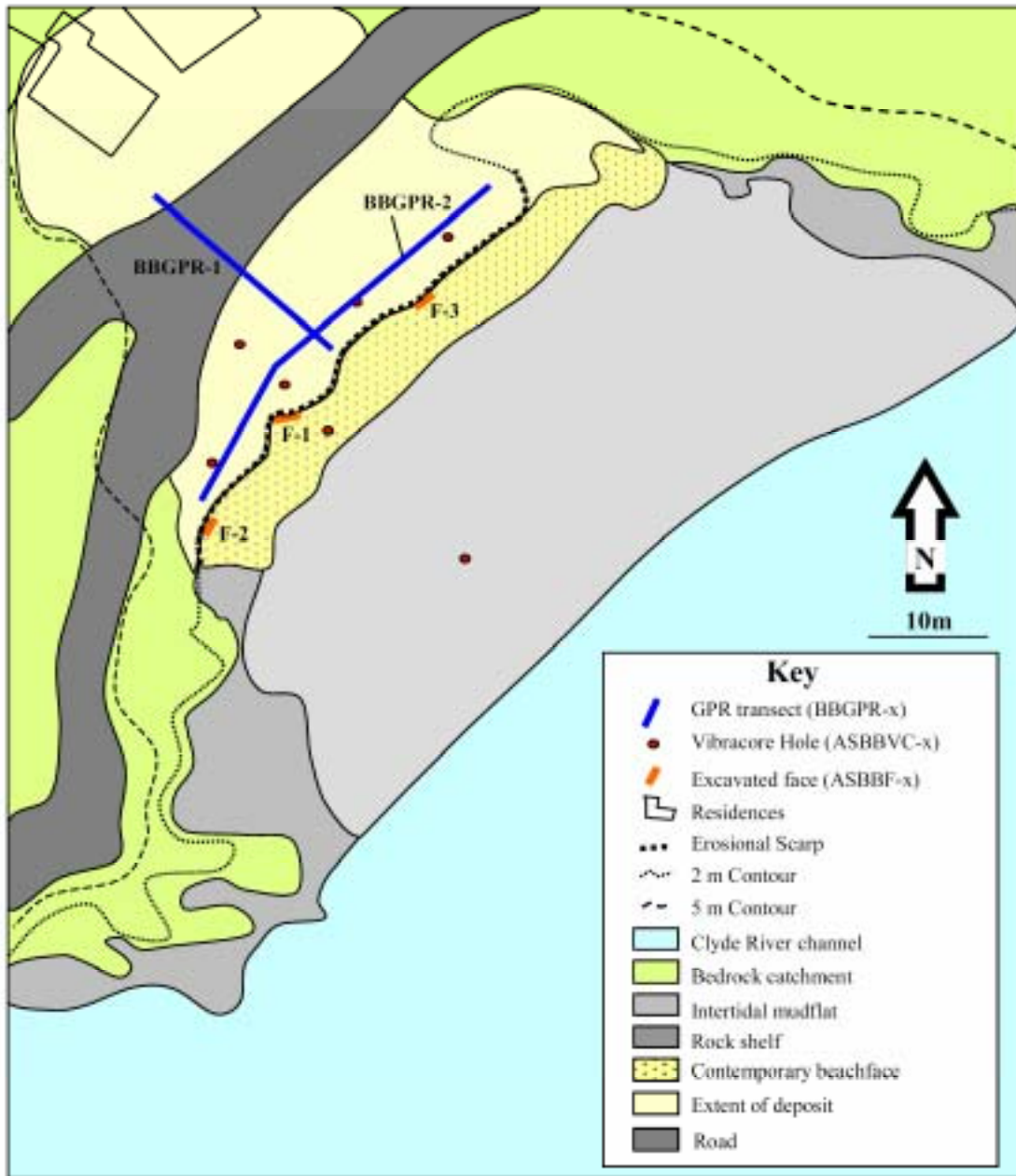


Figure 9.3 Morphological map of the Batemans Bay study site showing the location of ground penetrating radar (GPR) transects. BBGPR-1 was conducted to investigate the subsurface stratigraphy and to investigate the lateral extent of the coarse shell-rich deposit. BBGPR-2 was conducted in a shore parallel direction and failed to give any discernable reflection although a large subsurface pipe was identified.

### 9.2.2 Killalea Lagoon and dunes

At Killalea Lagoon three GPR transects were obtained (Figure 9.4), with the first (KGPR-1) collected from the landward extent of the sandsheet with the aim of identifying the extent of the deposit. Complementing this landward transect are two



transects (KGPR-2 and KGPR-3) collected perpendicular to shore through the dune sequence approximately 250 m seaward of the initial transect.

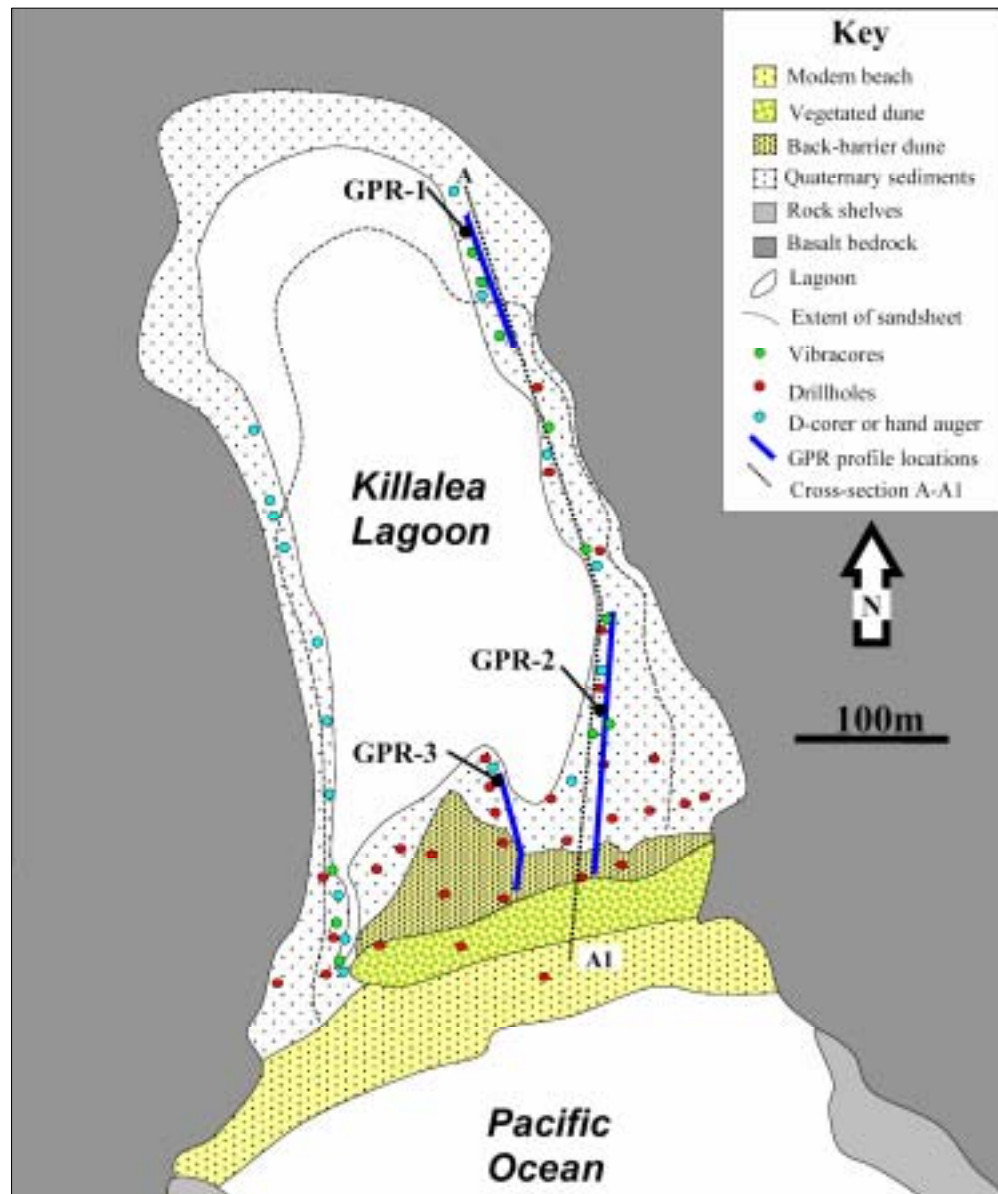


Figure 9.4 Morphological map of Killalea lagoon showing the location of ground penetrating radar (GPR) transects. KGPR-1 was conducted to investigate the lateral extent of the elevated sandsheet. KGPR-2 and KGPR-3 were conducted to investigate the contact between the sandsheet, barrier and lagoonal sequence.

### 9.3 Methodology

The GPR profiles were collected using a Pulse Ekko PE 100 with 1000 volt transmitter and 100 MHz antennae spaced 1 m apart in perpendicular broadside configuration with a step size of 0.5 m. The GPR data were processed using Pulse Ekko software and processing includes dewow, an age gain of 100 and topographic correction (Appendix

9.1). In addition, profile KGPR-2 has been migrated to collapse parabolic reflections from a wire fence at 60 m.

### 9.3.1 Velocity determination

The impedance of the subsurface material affects the velocity of the electromagnetic waves. As such less dense units such as lagoonal peats have lower velocities than those of weakly consolidated dune sequences. Velocities have been determined from common mid-point (CMP) surveys on the sand dunes and on the lagoon deposits. For example the velocity for the sand dunes at Killalea was determined to be  $0.15 \text{ m.ns}^{-1}$  with a corresponding velocity of  $0.06 \text{ m.ns}^{-1}$  for the peaty lagoon deposits.

## 9.4 Results

Based on the presentation format of Jol *et al.* (2003) GPR profiles and interpretation will be presented as follows; the horizontal scale of all profiles and schematic interpretations are presented as distance in metres, with two vertical scales for the GPR profile and one for the schematic. Two-way travel time (ns) appears as the first vertical scale (in italics) and secondly depth (m), based on the near-surface velocity of a radar pulse through the sediments closest to the profile. Air wave and ground wave arrivals (Figure 9.2) are present in all profiles as the two uppermost continuous reflections, respectively, and should not be considered part of the stratigraphic data.

### 9.4.1 Batemans Bay

Two transects were conducted at the Batemans Bay site. The first BBGPR-2, was conducted in shore parallel direction and although indicating a series irregularly shaped undulating reflectors provided little data on the structure of the subsurface. A second profile, BBGPR-1, was conducted perpendicular to the shore face (Figure 9.3) and returned a series of dipping reflectors (Figure 9.5). A major aim of this transect was to investigate the lateral extent of the elevated shell-rich identified in Chapter 8.

#### 9.4.1.1 Interpretation of BBGPR-1

The dipping reflectors (sigmoidal?) identified in Figure 9.5 are most likely indicative of a small prograded beach system. The genesis of the system remains problematic. It would require a significantly different orientation of the seaward embayment morphology to create a beach system in the small sheltered embayment (see discussion

in Section 8.9). As suggested in chapter 8 the beach complex is most likely the result of a combination of possible higher mid-Holocene sea level, and a more open offshore bathymetry as a result of differing seaward embayment morphology.

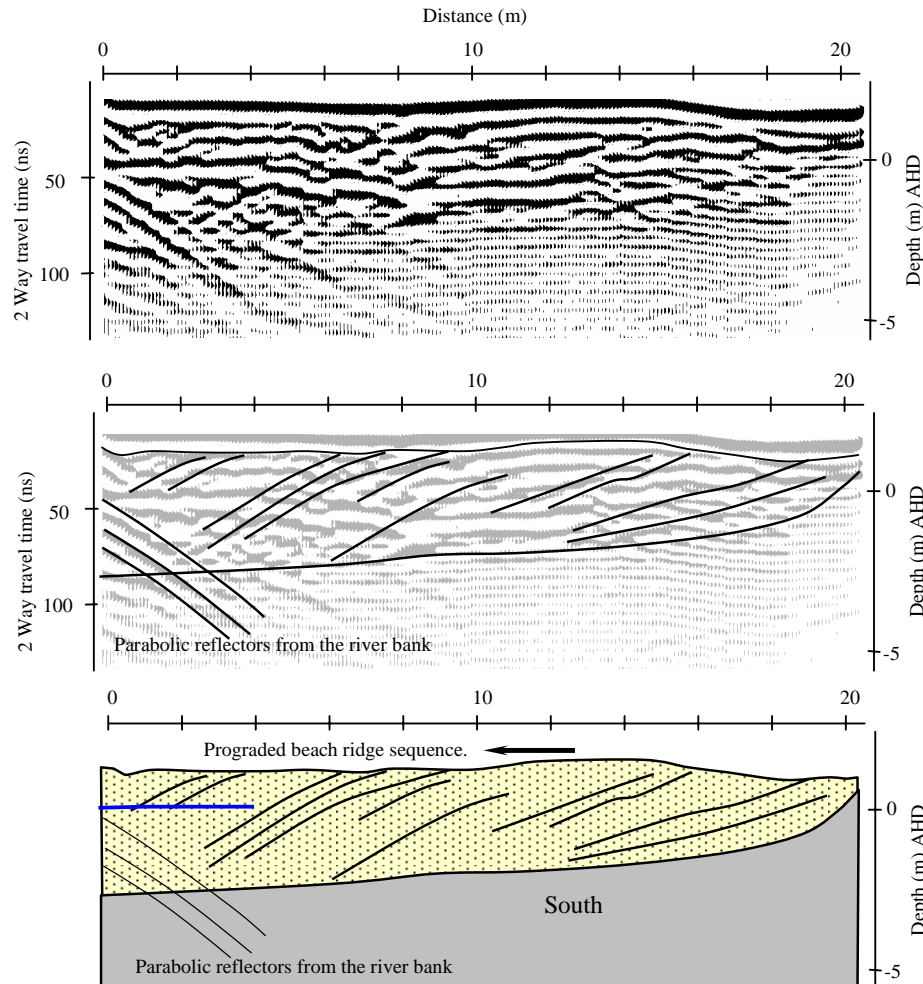


Figure 9.5 Ground Penetrating Radar transect (BBGPR1) showing a sequence of dipping beds infilling a shallow embayment at Batemans Bay. The genesis of the beach sequence is not well understood and the shell-rich deposit (blue line) investigated in Chapter 8 is not defined in the upper sequence.

#### 9.4.2 Killalea

Three GPR profiles were conducted for this study. The first (KGPR-1) was conducted at the landward extremity of the sand sheet in order to investigate the deposit with the aim of defining its extent and complementing the coring program, the second (KGPR-2) and third (KGPR-3) profiles aimed to investigate the contact between the lagoonal deposits, the washover sand and the Holocene dunes, with a working hypothesis that if the dunes were the source of the marine sand in the sand sheet could GPR identify any geomorphic signature for the modification of the system. The transects from Killalea are presented in Figure 9.6 and discussed below. The most landward transect (KGPR-1)

provided little information on the subsurface stratigraphy. KGPR-2 and KGPR-3 investigated the contact between the sandsheet, barrier system and lagoonal sequence.

#### **9.4.2.1 KGPR-1**

The GPR profile (Figure 9.6a) runs along the eastern edge of the lagoon to about 500 m inland. The location was selected to try and delimit the landward extend of the sandsheet which had been interfered from borehole data (Figure 7.7). The profile shows limited depth of penetration down to around 3 m with sub-parallel, sub-horizontal reflections above an irregular surface. The sub-horizontal reflections are interpreted to come from fine-grained, bedded lagoonal sediments overlying and infilling an eroded bedrock topography. This profile (Figure 9.6a) provides little information on the sandsheet but did assist in defining the depth to bedrock and indicated the dissected nature of the underlying bedrock basin in which the Quaternary sediment is deposited. Borehole data show that the sandsheet lies very close to the surface and is only in the order of 40-80 cm thick throughout the southern part of the transect before tapering off rapidly to its landward extremity about half way along the transect. The sandsheet is overlain in most places by less than 10 cm of organic-rich lagoonal sediment and could not be resolved because it has been obscured by the direct airwave and ground wave signal intrinsic to the methodology.

#### **9.4.2.2 KGPR-2**

The site of this profile was selected to investigate the seaward margin of the sandsheet and to target the interaction of the sandsheet, lagoonal sediments and dune system. The profile (Figure 9.6b) shows two different reflection patterns. The northern part of the profile contains sub-horizontal reflections, which pinch out towards the south, onlapping dipping reflections. The southern part of the profile has a low-angle reflection at the base overlain by tangential inclined reflections that downlap onto the low-angle reflection. The inclined reflections are truncated and overlain by a horizontal reflection. Above this there is a subhorizontal reflection and small discontinuous reflections within the gently undulating foredune topography. The lower low-angle reflection is interpreted to come from the top of an underlying Pleistocene barrier. The inclined tangential reflections which dip towards the north (inland) are interpreted as sets of cross-stratification from transgressive coastal dunes. The dunes are truncated by a second upper horizontal reflection interpreted to be an erosion surface formed during a

large-scale washover event. This erosion surface can be correlated with a similar reflection on profile KGPR-3 (Figure 9.6c). The erosion surfaces may be correlated with the sandsheet in the lagoon, however, the hyperbolae from the wire fence at 60 m partially obscure the critical stratigraphic contact.

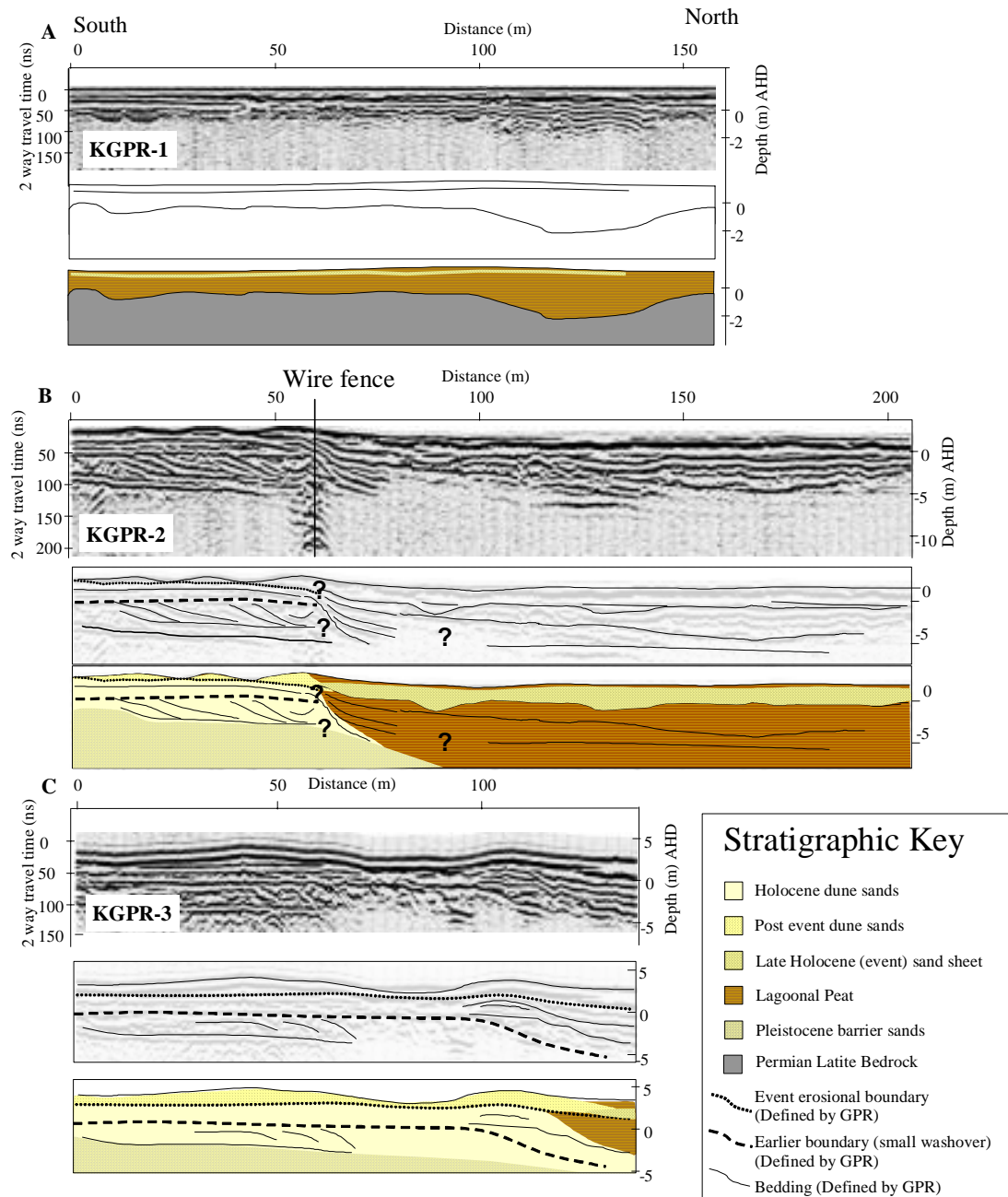


Figure 9.6 Ground Penetrating Radar transects a) KGPR-1 this transect had shallow penetration to bedrock and failed to identify with any clarity the sharp contact between the peat and sandsheet (Figure 7.9) observed in cores. Both KGPR-2 (b) and KGPR-3 (c) identified a truncating reflector indicative of erosion by washover that occurred above prograding Holocene dunes. The erosional reflector is then overlain by a series of irregular reflectors indicative of more aeolian dunes.

### 9.4.2.3 KGPR3

This profile complements that of KGPR-2 some 60 m to the east, away from the fence, and also shows the interrelationship of the lagoonal sediments and dune system. The GPR profile shows a low-angle inclined basal reflection overlain by tangential inclined reflections which are truncated. The low-angle inclined basal reflection is similar to the basal reflection in Figure 9.6b, and is interpreted as the top of the underlying Pleistocene barrier. The inclined reflections are interpreted as sets of cross-stratification from transgressive dunes and the erosion surface that truncates the dunes appears to dip beneath lagoonal deposits at around 100 m along the profile (Figure 9.6c). There is another shallow horizontal reflection in the upper part of the profile that represents a second erosional truncation that appears to correlate with the laterally extensive sandsheet in the upper fill of the lagoon sequence. The upper erosional surface appears to link with the seaward extent of the sandsheet as identified in both KGPR-1 and KGPR-2.

## 9.5 An erosional signature

Sedimentological data indicate that the source for the well-rounded predominantly quartz sand found in the sandsheet is the seaward barrier and corresponding offshore zone, as indicated by a mixed heavy mineral assemblage characteristic of barrier sediments with a component of inner shelf material characterised by immature platy minerals (Switzer *et al.*, in press). Grain size data and textural analysis show that a significant proportion of the sediments are well-rounded fine sand with pitted surfaces that may be of aeolian origin (Switzer *et al.*, 2004). It is hypothesized that the sediment was emplaced by large-scale washover in the late Holocene and that such an event would erode significant amounts of sand from the barrier. Subsequent post-washover geomorphic adjustments have resulted in the generation of new aeolian dunes and preserve an erosional sedimentary signature within the dunes. Sedimentological and geomorphic studies of dune systems from Europe (Jelgersma *et al.*, 1995) and the United States (Leatherman and Williams, 1977; Liu and Fearn, 1993; Sedgwick and Davis, 2002) suggest that it is often possible to identify both an erosional and depositional signature for a washover event. Anthony and Moller (2002) used GPR on dunes from the North Sea coast of Denmark to define a series of radar-facies and contacts complemented by a coring program. In many cases they indicated that aeolian

dune activity was often truncated by washover deposition resulting in sharp contacts between high-angle dipping aeolian beds and low-angle to laminated storm deposits.

GPR profiles KGPR2 and KGPR3 both indicate a period of transgressive dune building that is truncated by an early washover that does not have a corresponding extensive sandsheet and is onlapped by lagoonal sediments. This may be related to the depth of the lagoon at the time of washover. Overlying this sequence in the barrier is a succession of fine sands most likely to be the product of aeolian deposition that resulted in the formation of a series of small prograding dunes characterised by high angle bedding surfaces. These dunes were eroded and modified in the late Holocene. A flat-lying prominent reflector in both GPR profiles separates two sequences of high angle bedding and is inferred to represent an erosional contact generated by one large scale washover event that separates two periods of aeolian deposition. The contact is identified as a flat-lying reflector that truncates the angled reflectors of the bedding planes from the dunes and corresponds to the presence of a large sandsheet in the back barrier fill.

#### **9.6 Discussion of applicability of GPR technique to this type of study.**

The GPR technique is particularly applicable to unconsolidated sandy sequences and this renders it readily applicable to many coastal settings particularly on siliclastic coastlines.

The short transect undertaken at Batemans Bay identified the prograded nature of the beach sequence. As outlined in section 5.3.6 coring of this sequence was quite difficult due to the abundance of shelly material. A series of dipping reflectors were identified in transect BBGPR-1 suggesting a prograded sequence. The use of a more robust drilling technique such as a truck mounted auger rig would not have shown this structure.

The identification of the planar reflector at Killalea (KGPR2 and KGPR3), referred to here as the erosional signature, answered a fundamental question related to large-scale washover of dunes by highlighting the preservation of the erosional boundary in the coastal dune sequence. Although not tested on a modern event, it is hypothesised that such a signature may also be found in other coastal sequences affected by large-scale washover. Furthermore it is likely that such large-scale erosional features exist in

ancient sequences and this technique although in its infancy (Neal, 2004) may be applicable to the study and interpretation of such older rock sequences.

### **9.7 Synthesis.**

Ground penetrating radar is a non-invasive geophysical technique that detects electrical discontinuities in the shallow subsurface, usually less than 50 m. It does this through the generation of discrete pulses of high frequency (MHz) electromagnetic energy that are transmitted, propagated and reflected in the subsurface before being received and processed to give a representative image of differential reflection caused by changes in the subsurface. The GPR technique used in this study is particularly useful in sandy sediments and is thus ideally suited to the analysis of sandy coastal sequences.

The initial investigation of the Batemans Bay sequence encountered several problems with vibracoring the sequence. Ground penetrating radar provided confirmation of the suspected prograded nature of the embayment fill, although the genesis of the sequence remains poorly understood. The investigation of the lateral extent of the shell-rich deposit (Figure 8.14) was not possible using the GPR equipment used in this study as it was undefined due to the thin nature of the deposit and its proximity to the surface.

The aim of the Killalea GPR investigation was to investigate the landward margin of the washover deposit and contacts between the dune and lagoonal sequences. The sandsheet was poorly defined at its landward margin in transect KGPR1 although this transect assist in defining the depth to bedrock.

Two flat lying erosional boundaries were identified as truncating reflectors in transects KGPR2 and KGPR3. The lower boundary identified in KGPR3 is not associated with any back barrier washover sedimentation and is thought to be the result of washover during transgressive dune development as the boundary appear to dip below the onlapping lagoonal deposits.

A second erosional boundary lies higher in the stratigraphy and is found in both KGPR2 and KGPR3 transects where a series of dipping reflectors interpreted as dune beds, are truncated by a prominent horizontal reflector. This reflector corresponds



stratigraphically to the seaward end of the washover sandsheet and is interpreted as an erosional boundary that corresponds to that depositional event.

### **9.8 Conclusions**

- A short GPR transect that was conducted perpendicular to the shore identified the prograded nature of a small pocket beach system located in a pocket embayment at Batemans Bay.
- Ground penetrating radar transects of the Killalea barrier system identified a stratigraphically consistent erosional contact between a sequence of truncated pre-event dunes and several small overlying post-event dunes.
- This study outlines a relatively simple non-invasive method for the identification of erosional signatures formed a result of prehistoric large-scale over-wash by storm surge, exceptionally large waves or tsunamis.

## Chapter 10

### Chronology

#### Introduction

The chronology of the deposits at Killalea and Batemans Bay was investigated using four different dating techniques. Shell samples collected from cores and excavated faces at Batemans Bay were dated using conventional radiocarbon ( $^{14}\text{C}$ ) techniques complemented by amino acid racemisation (AAR). Peat and root samples collected from cores taken at Killalea lagoon were dated using AMS radiocarbon (AMS  $^{14}\text{C}$ ) and all of these chemical techniques were complemented by Optically Stimulated Luminescence (OSL) dating, which dates the deposition of the sediments using quartz grains.

The aim of the dating scheme was to date the emplacement of the shell-rich facies at Batemans Bay and the washover sand sheet at Killalea. Frustratingly, the dating results from each embayment were problematic. The limitations of the dating program are discussed in this chapter along with problems encountered in these deposits. The main problem encountered in both deposits is the unknown but obvious influence that groundwater movement through these very porous units has on Quaternary dating techniques.

#### 10.1 Quaternary dating techniques

Many dating techniques are available to the Quaternary geologist, each with its own flaws, intricacies and limitations. Some dating techniques such as lichenometry require nothing more than a ruler and a keen eye, whilst others cost well over \$1000 a sample and take up numerous labour hours and laboratory time. The aim is almost always the same; to characterise the chronology. To do this one must choose and use the techniques most appropriate to the situation or geological system under investigation.

#### 10.2 Techniques used in this study

The dating program of any Quaternary sedimentology geology project is based on sediment composition and the availability of suitable material for applicable techniques. In this project shells and peat were taken for  $^{14}\text{C}$  and AMS  $^{14}\text{C}$  with some shells to be used for AAR analysis. Three shells were dated with both AAR and  $^{14}\text{C}$  with the aim of

directly calibrating the methods. Sandy sediments were also taken for OSL dating from Killalea and the older beach sequence at Batemans Bay.

### 10.3 Radiocarbon analysis of peat and shelly fauna

For more than fifty years conventional  $^{14}\text{C}$  dating has been used to date Quaternary deposits and remains the most utilised dating tool in geological applications ranging from ~0.3 ka to ~50 ka (Arnold, 1995). The technique is based on the principle that living organisms continually take up carbon from the environment, including the  $^{14}\text{C}$  isotope. Upon death of the organism the carbon exchange stops and the  $^{14}\text{C}$  radioactivity decays at a rate determined by its half-life of 5730 yrs. Hence, by measuring the residual  $^{14}\text{C}$  concentration in organic samples, and provided they have not been contaminated by younger material (e.g. via bacterial action, soil organic acids) or by older material (e.g. geologic calcium carbonate), it is possible to calculate the time elapsed since the material was originally formed. A more comprehensive review of this method, including its limitations and corrections for variations of  $^{14}\text{C}$  in different systems (e.g. *reservoir effects*), can be found in Vita-Finzi (1973), Arnold (1995) and Head (1999).

All radiocarbon samples taken for this study were sent to University of Waikato Radiocarbon Laboratory (Wk), New Zealand. At Killalea the modern dates were used in conjunction with the dates obtained by B.G. Jones and I. Eliot that were dated at the University of Sydney (SUA).

#### 10.3.1 Conventional radiocarbon

In order to measure radiocarbon ages it is necessary to find the amount of radiocarbon in a sample. This measurement can be made either by measuring the radioactivity of the sample (the conventional beta-counting method) or by directly counting the radiocarbon atoms using a method called Accelerator Mass Spectrometry (AMS).

Most conventional radiocarbon measurements are conducted by measuring the  $^{14}\text{C}$  activity of benzene (prepared from the sample) through the measurement of its beta-decay. The benzene is produced as follows: carbon dioxide, obtained by burning the sample, reacts with metallic lithium to form lithium carbide. The lithium carbide is hydrolysed to acetylene which is subsequently converted to benzene by catalytic

trimerisation (Head, 1999). Scintillation counting results are statistically analysed and reported as conventional radiocarbon ages corrected with  $^{13}\text{C}$  values.

### 10.3.2 AMS radiocarbon

In contrast to ‘conventional’ radiocarbon dating, which quantifies the radioactive decay of  $^{14}\text{C}$ , technology developed during the 1970’s allowed age determination by utilising direct carbon isotope analysis of  $^{14}\text{C}$  and  $^{12}\text{C}$  by mass separation. One of the major advantages of AMS  $^{14}\text{C}$  dating is that it allows dating of a smaller quantity of sample.

### 10.4 Amino Acid Racemisation (AAR)

Amino acid racemisation dating is a chemical dating technique that measures the relative abundance of the isomeric forms of amino acids preserved in a wide range of organic materials (Murray-Wallace 1993). Amino acids exist in two geometric forms, ‘L’ (Levo-rotatory) and ‘D’ (Dextro-rotatory). In living organisms the L-form is dominant but when the tissue dies the process of racemisation begins, converting the L-form to the D-form until equilibrium is reached (i.e. D/L ratio = 1 for enantiomeric amino acids). The rate at which this occurs depends on the organism and is sensitive to temperature. If the rate of racemisation is known and the temperature can be determined, the time elapsed since the death of the organism can be assessed. Amino acid dating was conducted at the University of Wollongong (UWGA) and applied to seven shell samples taken from throughout the older beach sequence and shell-rich unit at Batemans Bay.

Results reported in this study are based on the fast racemising aspartic acid (ASP). The rapid rate of racemisation of this acid potentially permits greater age resolution of Holocene time than for any other amino acids, and accordingly was selected for analysis. D/L ratios, including analytical uncertainty, were calculated and numeric ages were determined using the calibration techniques of Sloss *et al.* (in press).

### 10.5 Optically Stimulated Luminescence (OSL)

Optical dating (Huntley *et al.*, 1985; Aitken, 1998) is used to determine the time elapsed since sediment was last exposed to sunlight. The ability to do this lies in the capacity of naturally occurring minerals, such as quartz and feldspar, to record the amount of exposure to ionising radiation emitted from radioactive elements in the surrounding

sediment (primarily potassium, thorium and uranium). These records come in the form of trapped electrons. These electrons, which have been detached (ionised) from their parent nuclei in the crystal lattice diffuse into the vicinity of a defect in the lattice that is attractive to electrons, thereby becoming trapped (Aitken, 1998). The more prolonged the exposure to ionising radiation, the greater the number of trapped electrons. These electron stores are emptied when the sediment is exposed to sunlight and they gradually repopulate after burial beneath additional sediment. On excavation, if the mineral is stimulated optically, there is an associated emission of light defined as optically stimulated luminescence (OSL). The intensity of this signal is directly related to the number of trapped electrons. By comparing this 'natural' signal with those obtained from laboratory dosed aliquots of the same sample, an estimate of the radiation dose which produced the natural OSL signal (defined as the equivalent dose,  $D_e$ ) can be obtained. Measurements of uranium, thorium and potassium concentrations in the surrounding sediment, yield an estimate of the dose rate (mGy/year) to the sample. The age of the sample (i.e. the duration of burial) is then calculated using the following equation:

$$\text{Age} = \text{Equivalent Dose} / \text{Dose Rate}$$

### 10.5.1 Sample collection and preparation

The samples for optical dating collected from the Batemans Bay were sampled using an extraction method that involved pushing a light-proof 35mm PVC sample tube into the sediment, packing the ends with newspaper before extracting the tube and capping both ends. Samples for OSL collected from Killalea were collected with a 75mm aluminium vibracore pipe.

Sample preparation was carried out under subdued red (>590 nm) illumination in the OSL laboratory at the University of Wollongong. Sediment was removed from the tube and material was removed from both ends of the sample to exclude any grains that could have been exposed to sunlight during sample collection. The outer 5-10 mm of samples was scraped off to remove possible mixed sediments from the edge of the tube. Fine sand (90-125µm) quartz grains were extracted for analyses. These grains were obtained by treating the sample with hydrochloric acid, hydrogen peroxide and sodium hydroxide to remove carbonate and organic materials. They were then etched in 45% hydrofluoric acid for 45 minutes to remove the outer alpha-irradiated layer from the

quartz grains and to completely remove any feldspars. This was followed by a treatment with hydrochloric acid to remove acid-soluble fluorides.

### 10.5.2 Dose rate estimation

Concentrations were then corrected into dose rates using the conversion factors listed by Aitken (1998) and the beta-attenuation factors of Mejdahl (1979). An internal dose rate in mGy/year was derived from in-situ and high resolution gamma spectrometry, and the cosmic-ray dose rate (0.075 mGy/year) was calculated following Prescott and Hutton (1994). The cosmic-ray and external beta and gamma dose rates were adjusted for the sample time-averaged moisture content, which was estimated for each sample by determining the mass of water divided by mass of dry sediment, x 100.

### 10.5.3 Equivalent dose estimation

An automated RISO TL/OSL reader fitted with blue (470 nm) light-emitting diodes as the stimulation source (420-550 nm) and three U-340 detection filters (290-370 nm) was used for OSL measurements. The reader is also equipped with a 40 mCi  $^{90}\text{Sr}/^{90}\text{Y}$  beta source delivering  $0.105 \text{ Gy s}^{-1}$  for irradiation. All OSL measurements were performed for 60 sec at  $90^{\circ}\text{C}$ . The OSL signal used for equivalent dose estimation is the background-corrected 0-4.8 s OSL signal. The equivalent dose for the sample was estimated using the single aliquot regenerative-dose protocol (see Galbraith et al., 1999; Murray and Wintle, 2000).

## 10.6 Dating results

Dating results are presented in tables and discussed in the following sections. Details and results for radiocarbon (Wk), AAR and OSL samples taken during this study are presented in Appendix 6. Many of the results were problematic and these problems are discussed in Section 10.7. In the broadest sense the dating of both the Killalea sandsheet and the shell-rich unit at Batemans Bay confines the deposition of these units to the last 1000 years.

### 10.6.1 Killalea

Radiocarbon dating from Killalea Lagoon identified a Quaternary succession of last interglacial sediments that are onlapped by a Holocene barrier system and associated

lagoon. Detailed dating of the upper fill confined the depositional age of the large sandsheet deposit.

Dating of peat and soil samples collected by B.G. Jones and I. Eliot in 1978 and 1980 identified a thick succession of presumably last-interglacial sediments that yielded a series of very old radiocarbon dates (24-35ka) that would be very close to background levels (Table 10.1). The small radiocarbon signal recorded is possibly the result of post depositional contamination by modern carbon moving through the sequence. It is extremely unlikely that these dates represent the depositional age of the sequence as sea-level during this time is estimated to be between –30 and –70 m (Section 2.5; Figure 2.7a). Specimen SUA844 was taken from the soil profile identified by B.G. Jones and I. Eliot and dates as approximately 14.5ka. This horizon possibly records the boundary between the underlying Pleistocene system and the modern Holocene barrier system

Sample (Depth AHD)	Specimen Number	Technique	Material dated	Unit	Sample notes	Age (yrs)
5K - 10	SUA844	<sup>14</sup> C	Peat	Soil profile	None available	14640 ± 170
5K - 18	SUA845	<sup>14</sup> C	Peat	LIG	None available	34200 ± 1000
17K - 10	SUA847	<sup>14</sup> C	Peat	LIG	None available	24500 ± 360
32K - 9	SUA848	<sup>14</sup> C	Peat	LIG	None available	24300 ± 340
32K - 14	SUA849	<sup>14</sup> C	Peat	LIG	None available	32000 ± 1000
10K - 9	SUA850	<sup>14</sup> C	Peat	LIG	None available	33900 ± 1100
21K - 10	SUA85	<sup>14</sup> C	Charcoal	LIG	None available	33100 ± 1000
28K - 12	SUA852	<sup>14</sup> C	Charcoal	LIG	None available	27500 ± 1500
15K - 13	SUA1196	<sup>14</sup> C	Organic clay	LIG	None available	35600 ± 1700
15K - 16	SUA1197	<sup>14</sup> C	Grey clay	LIG	None available	33700 (min)
22K - 9	SUA1199	<sup>14</sup> C	Organic clay	LIG	None available	32860 (min)

*Table 10.1 Late Pleistocene dates from the lower lagoon sequence and soil profile at Killalea Lagoon. It is likely that these deposits are much older than indicated by the dating as relative sea level at this time (24-35 ka) was more than 30 m lower than present. One probable source of this error is the contamination of the sequence by younger radiocarbon. These dates were obtained in 1979 and 1980 and it is likely that modern techniques could clarify the age of the lower sequence. It is likely that this sequence is of last interglacial age ~125-130 ka. Sample SUA844 may date the soil profile that underlies the Holocene sequence.*

Dating from this study along with samples by Jones and Eliot, (SUA - samples) indicate a sequence of organic-rich clays and peats spanning the last 10ka overlies a mottled soil profile (Table 10.2). Several AMS radiocarbon dates (Wk 13344, 13345, 13346) were taken from just below the sandsheet. One conventional radiocarbon sample taken by

Jones and Elliot (SUA1198) dates at  $180 \pm 80$  yrs and represents the thin peat sequence that overlies the sandsheet.

Sample (Depth AHD)	Specimen Number	Technique	Material dated	Unit	Sample notes	Age (yrs)
5K - 3	SUA843a+b	$^{14}\text{C}$	Peat	Lower Peat	None available	$3380 \pm 80$
7K - 4	SUA846	$^{14}\text{C}$	Peat	Lower Peat	None available	$4970 \pm 90$
KS27 - 1	SUA1190	$^{14}\text{C}$	Peat	Lower Peat	None available	$470 \pm 90$
8K - 1	SUA1191	$^{14}\text{C}$	Clay Peat	Lower Peat	None available	$2665 \pm 75$
8K - 8	SUA1192	$^{14}\text{C}$	Organic clay	Trans	None available	$9090 \pm 150$
13K - 2	SUA1193	$^{14}\text{C}$	Organic clay	Lower Peat	None available	$1220 \pm 90$
13K - 8	SUA1194	$^{14}\text{C}$	Organic clay	Trans	None available	$11700 \pm 160$
15K - 3	SUA1195	$^{14}\text{C}$	Clay Peat	Lower Peat	None available	$1610 \pm 90$
22K - 3	SUA1198	$^{14}\text{C}$	Sandy Peat	Upper Peat	None available	$180 \pm 80$
30K - 3	SUA1200	$^{14}\text{C}$	Organic clay	Trans	None available	$8185 \pm 135$
19K - 2	SUA1201	$^{14}\text{C}$	Organic clay	Lower Peat	None available	$2350 \pm 90$
32K - 3	SUA1202	$^{14}\text{C}$	Peat	Lower Peat	None available	$2745 \pm 85$
KVC5-0.90 m	W13343	AMS $^{14}\text{C}$	Drowned root	Lower Peat	Groundwater	$108 \pm 6$
KVC8- -1.2m	W13346	AMS $^{14}\text{C}$	Peat	Lower Peat	Groundwater	$4632 \pm 49$
KVC5-0.30 m	W13344	AMS $^{14}\text{C}$	Peat	Lower peat	Groundwater	$245 \pm 42$
KVC8-0.20 m	W13345	AMS $^{14}\text{C}$	Peat	Lower peat	Groundwater	$423 \pm 41$
KVC3-1.2 m	ASKOSL-1	OSL	Quartz sand	Sandsheet	Caesium <sup>137</sup>	$560 \pm 190$
KVC5-1.0 m	ASKOSL-2	OSL	Quartz sand	Sandsheet	(Minimum age model) Caesium <sup>137</sup>	$720 \pm 270$

*Table 10.2 Holocene dates from the Killalea Lagoon sequence. Samples with specimen codes SUA were taken by Jones and Eliot in 1978 and 1980. Samples coded ASKVC were taken for this study. Sample Wk 13343 contained modern (bomb) carbon due to groundwater movement through the sandsheet. It is also uncertain what affect this had on samples W13344, W13345 and the radiation dose for the OSL samples (see discussion below). Despite the uncertainties it is apparent from both the AMS radiocarbon and the OSL that the sandsheet deposit is was deposited approximately 500 yrs BP.*

### 10.6.1.1 Dating the deposition of the sandsheet

For this study the principle aim of the dating program was to define the time of deposition of the marine sandsheet identified in the upper fill. To this end three AMS radiocarbon samples Wk13344, Wk13345, Wk13346 were taken from the underlying peat and two OSL dates obtained using the quartz sand of the sand sheet. The root system of a large reedy plant (Figure 10.1) was found protruding from the peat sequence into the sandsheet (Sample W13344). The root, identified in core ASKVC5 was thought to be the best chance of dating the deposit as it appeared that the reed had been snapped off during deposition of the sand sheet. Unfortunately the root appears to



be contaminated with modern (bomb) carbon (see below) and the age of the root appears anomalously young at  $108 \pm 6$  yrs.



Figure 10.1 Photograph of the large root sample (Wk13344) that was dated using AMS radiocarbon. The sample returned an age of  $\sim 108$  yrs and was contaminated with modern 'bomb' carbon suggesting that the deposit was younger than 1960. It is likely that the modern age is the result of modern carbon in groundwater migrating through the porous sandsheet deposit.

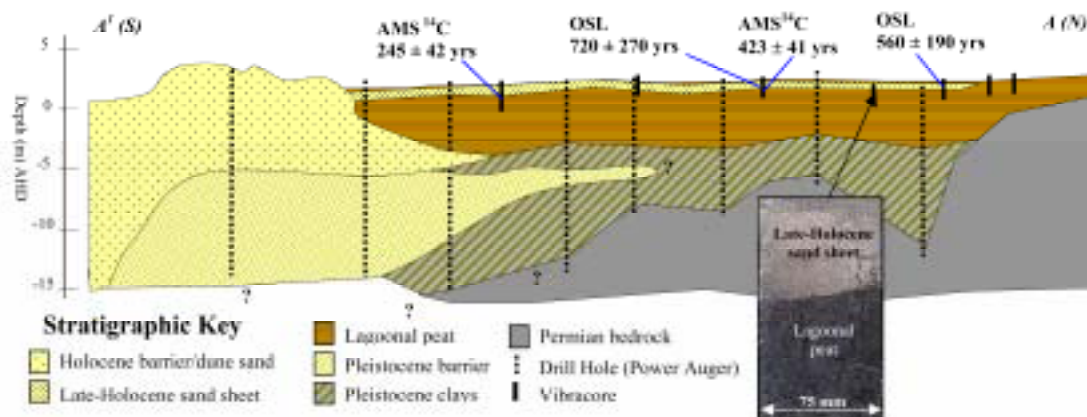


Figure 10.2 Schematic stratigraphy and dates from Killalea lagoon. The dating program of AMS radiocarbon and OSL dating confines the deposition of the sandsheet to around  $\sim 500$  yrs ago. The event is attributed to a tsunami event some around 1500AD.

All dates collected from the confining peat and the sandsheet suggest that the sandsheet is less than 1000 years old with a mean age of approximately 500 yrs BP. The sandsheet event is therefore attributed to large-scale washover event around 1500 AD that is attributed to a late-Holocene tsunami as discussed in Chapter 7.

### 10.6.2 Batemans Bay

All dating of the beach sequence at Batemans Bay indicates a mid- to late-Holocene age for the prograded beach sequence with a younger coarse shell-rich unit overlying the sequence. The younger shell-rich unit returned mixed dating results possibly indicative of reworked material incorporated during deposition. All dates from Batemans Bay are provided in Table 10.3. The  $^{14}\text{C}$ , AAR and OSL dates from Batemans Bay all support the hypothesis that the sequence is the result of a prograded beach system and suggests that much of this material was deposited between 5000-2500 years.

#### 10.6.2.1 Dating the deposition of the shell-rich unit

Samples from the coarse shelly unit yield both young and old dates that may indicate the mixed nature of the sediments. It is important to note that the articulated *Anadara trapezia* shell dated using conventional radiocarbon Wk9439 and AAR (UWGA702) both gave an age of ~1000 yrs BP. Two single *Anadara trapezia* valves dated using AAR (UWGA700 and UWGA701) gave ages in excess of 2000 yrs BP and are thought to be indicative of reworked shells. The articulated shell gives an interim date for the deposit at around 1000 yrs but considerable uncertainty exists as to the affects of groundwater movement on the radiocarbon ages and temperature and groundwater on the AAR dating.

Sample (Depth AHD)	Specimen Number	Technique	Material dated	Facies/Unit	Sample notes	Age (yrs)
ASBBF2 (0.7 m)	UWGA702	AAR	Anadara (art.)	Shell-rich facies	Articulated shell	1060±50
ASBBF2- 2.52 m	Wk9439	$^{14}\text{C}$	Anadara (art.)	Shell-rich facies	Articulated shell	1284 ± 58
ASBBF2 (2.23 m)	UWGA700	AAR	Anadara	Shell-rich facies	Single valve	2060±100
ASBBF2 (2.25 m)	UWGA701	AAR	Anadara	Shell-rich facies	Single valve	2670±120
ASBBVC7 (-0.45 m)	UWGA704	AAR	Anadara	Tidal flat facies	Single valve	2330±110
ASBBVC3 (1.2 m)	UWGA703	AAR	Anadara	Beach facies	Single valve	2540±120
ASBBF1 (0.8m)	UWGA698	AAR	Anadara	Beach facies	Single valve	3610±170
ASBBF1 (1.2m)	UWGA699	AAR	Anadara	Beach facies	Single valve	7840±350
ASBBF2- OSL-1	ASB1	OSL	Quartz sand	Beach facies	Central age model	2840±840
ASBBF2-OSL-2	ASB2	OSL	Quartz sand	Beach facies	Central age model	2390±210
ASBBF1- 2.2 m	Wk9440	$^{14}\text{C}$	Anadara	Beach facies	Single valve	2506 ± 67
ASBBVC3-1.8 m	Wk9441	$^{14}\text{C}$	Anadara	Beach facies	Single valve	2852 ± 72

Table 10.3 Dating results from the Batemans Bay sequence. The majority of dates come from the prograded beach sequence (beach facies) and date around mid-Holocene. The two dates obtained from an articulated *Anadara* shell indicate that the shell-rich unit is approximately 1000 yrs old. This is the only date that constrains the depositional age of the unit.

### 10.8 Limitations of the dating program

All dating programs and techniques have limitations and it is beyond the scope of this study to discuss the intricacies and pitfalls of each technique. The aim of this dating program was to broadly define the evolutionary chronology of each embayment and focus on the time of deposition for the sandsheet at Killalea Lagoon and the elevated shell-rich unit at Batemans Bay.

The first limitation involves the dating of *Anadara trapezia* shells from Batemans Bay by amino acid racemisation. This technique was used to determine the relative ages of molluscan fossils from Batemans Bay with most samples returning chromatographs with well-defined peaks for a wide variety of amino acids. Occasionally peaks were not as well defined possibly due to poor sample preservation, and low concentrations of indigenous amino acid.

The extent of racemisation in the fossil molluscs is related to several variables including diagenetic temperature history (Wehmiller, 1982), moisture content (Rutter *et al.*, 1985) and sediment radiation flux (Rutter and Blackwell, 1995). It is assumed that these variables would exhibit significant fluctuations through geological time at Batemans Bay as groundwater movement and variability in radiation flux inherently affect the deposit. It was also noted during in situ gamma spectrometry that the deposit has relatively high  $^{235}\text{U}$  levels.

The second limitation of the dating program lies in the radiocarbon techniques. Both conventional and AMS radiocarbon dating have inherent errors and limitations. The first limitation that affects most dating programs is the decay rate is logarithmic resulting in significant upper and lower limits. Young samples may not have decayed enough to give a signal whilst the practical upper limit is around 50,000 yr BP. After 50000 yrs BP so little  $^{14}\text{C}$  remains after almost 9 half-lives that it may be hard to detect and obtain an accurate reading, regardless of the size of the sample.

Other limitations relate to the ratio of  $^{14}\text{C}$  to  $^{12}\text{C}$  in the atmosphere, systematic errors and reservoir effects (Williams *et al.* 1998). Although it was originally thought that the atmospheric ratio was relatively constant, cross-dating using other techniques like dendrochronology have shown that the ratio of  $^{14}\text{C}$  to  $^{12}\text{C}$  has varied significantly during

the history of the Earth. Despite its limitations radiocarbon techniques are still the most common dating technique for Holocene deposits. Two anomalies point to considerable uncertainty in the radiocarbon dating of the Killalea sandsheet and these are discussed below (Section 10. 9)

The dating of the Batemans Bay deposit is problematic. Although it is apparent that the prograded beach system is mid-Holocene and the shell-rich unit is considerably younger, several limitations to the program suggest that the dating of this system should be considered provisional pending further investigation.

Major uncertainties exist in the affects of groundwater movement through the system and the secondary transport of modern organic material. High-levels of  $^{238}\text{U}$  measured in-situ gamma spectrometry do not match the high radiation counts (K. Westaway pers comm., 2004). High-resolution gamma spectrometry of at least two samples will be needed to clarify this issue and obtain a full decay chain.

The third problem affecting the program at Bateman Bay is the diagenetic temperature requirements of the AAR program as AAR assumes minimal temperature fluctuations that may not be justified in a system that is that close to the surface.

### **10.9 Dating porous sand sheets**

The dating program applied to the sandsheet at Killalea Lagoon provides a valuable insight into the dating of porous sandsheets. Both AMS radiocarbon and OSL were affected by groundwater preferentially moving through the porous sandsheet. The presence of both  $^{137}\text{Cs}$  in the high-resolution gamma spectrometry results taken from ASKVC5 some 75 cm below the surface, and bomb carbon in the radiocarbon results of WK13343 (68 cm below the surface) indicate that modern (post 1960) material is travelling to depths in excess of 1 m.

As a result of this process all AMS radiocarbon samples taken from just below the sandsheet returned ages contaminated by modern carbon. In particular the dating of the root sample (Wk13343) provides a key example as this sample was found to contain bomb radiocarbon indicating that it was less than 50 years old and conflicting with the reported age of approximately 108 yrs. It is apparent from the other dating results that

the deposit is considerably older (~500 yrs BP) and that considerable amounts of modern carbon including bomb carbon, are mobile in the sandsheet and have been incorporated into the deposit.

Analysis of calibrated curves for samples from Wk13344 and Wk13345 indicate that both these AMS radiocarbon samples taken from just below the surface contain peaks of modern carbon which are interpreted as being periods of high groundwater flow that introduces large amounts of mobile carbon into the underlying stratigraphy (Appendix 6).

The inference that groundwater flow through the sandsheet is giving anomalously young radiocarbon ages is supported by the high-resolution gamma spectrometry results taken for the OSL palaeodose determination. The sediment sample taken from the lower part of the sandsheet returned high levels of  $^{137}\text{Cs}$  another radionuclide associated with nuclear activity and indicative of very young (less than 60 yrs) ages.

Many washover deposits are identified by their contrast with the confining facies and in the case of storm and tsunami deposits this often consists of a lense of marine sand confined by low energy fine-grained sediments. The results from Killalea Lagoon indicate that the dating of such deposits should be conducted with consideration of the potential for contamination by modern material transported by preferential groundwater movement through the more porous sandsheets. Although well defined in the Killalea Lagoon deposit, it is uncertain what affect groundwater contamination has had on the Batemans Bay deposit.

#### **10.10 Chronological summary**

The evolution of the Killalea embayment is presented in Figure 10.3a. The presence of a well developed soil profile that overlies a sequence of older fine-grained lagoonal sediments suggests that the lower part of the Killalea Lagoon sequence was deposited as a barrier system presumably during the late-Pleistocene. Radiocarbon dating conducted in 1978-1980 by Sydney University (SUA) on samples collected by B.G. Jones and I. Eliot suggested that the shallow lower sequence ranged from 24-35 ka. Sea-level is not recorded at current levels during this time and most Quaternary sea level curves, such as that of Shackelton (1987), show that sea level during this time fluctuated between –30

and –70 m when compared to that of the present. It is likely that these dates are either too close to background to be adequately interpreted or they are much older samples contaminated by younger material. Only one date was obtained from the soil profile and it dates at approximately 14 ka. The soil profile separates the underlying Pleistocene system from the overlying Holocene sequence.

A Holocene barrier/dune system onlaps an older presumably Pleistocene system and encloses a coastal lagoon. A series of radiocarbon dates from the upper lagoonal sequence date the infilling of the shallow lagoon from approximately 8 ka. Deposition of the lagoonal sequence is punctuated by the late-Holocene deposition of the extensive sandsheet attributed to a tsunami and discussed in Chapter 7.

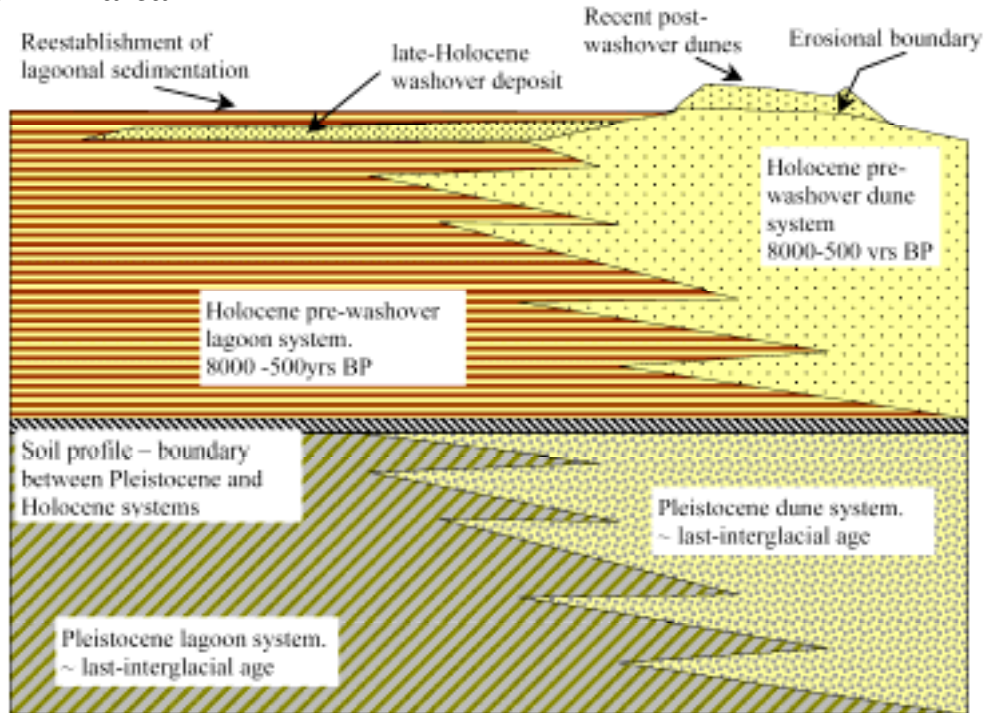
One of the major foci of this study was to date the deposition of this sandsheet. As noted above AMS radiocarbon and OSL dating of samples taken from the sandsheet and upper parts of the underlying peat places the age of the sand sheet at around 1500 AD. In places the sand is overlain by accumulations of organic-rich silt that contain charophytes suggesting re-establishment of freshwater lagoon conditions. This overlying sequence was dated by B.G. Jones and I. Eliot (SUA1198) and yielded a stratigraphically consistent date of  $180 \pm 80$  yrs.

The depositional history of the Batemans Bay sequence is summarized in Figure 10.3b. The interpretation of the lower sequence is limited by the shallow nature of the drilling program. It is assumed the prograded beach sequence is the basal unit and immediately overlies bedrock. This inference is supported by the ground penetrating radar results presented in Chapter 9.

Dating of the beach sequence indicates that the majority of the shelly fauna is of mid-Holocene age and that beach growth occurred from approximately 7000 yrs BP and ceased approximately 2400 yrs BP. This period coincides with the relative sea-level highstand identified by Baker *et al.* (2000a,b) and was most likely the result of a combination of higher sea level and a more open embayment. It is important to note that many of these dates come from single valves of *Anadara trapezia* and it is likely that many of them are reworked into the beach sequence. They should, therefore, be treated as indicative of a maximum age for the sequence. Despite these general limitations it is

apparent that the beach deposit is early- to mid-Holocene in age and underlies a considerably coarser shell-rich unit that is significantly younger.

### a Killalea



### b Batemans Bay

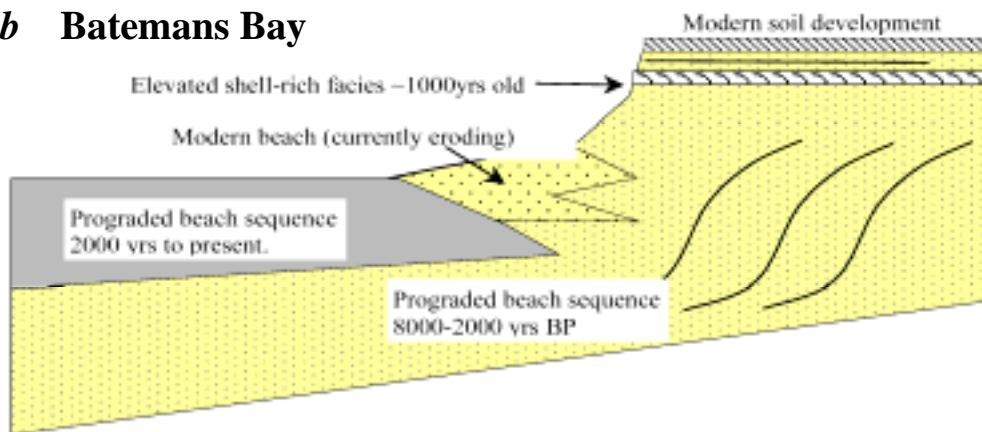


Figure 10.3 a) Summary figure of the chronology of the Killalea Lagoon sequence. A Pleistocene barrier lagoon system is overlain by a soil profile that separates the Pleistocene system from the younger Holocene barrier lagoon system. The deposition of a large extensive sand sheet is recorded in the upper fill and dates at approximately 500 yrs BP. The sandsheet is overlain by a small accumulation of peaty clays that indicate a return to lagoonal conditions. b) Summary diagram of the chronology of the Batemans Bay sequence showing prograded beach system that is overlapped by a mudflat sequence and modern beach. Overlying the prograded beach is a shell-rich facies that is inferred to be considerably younger. The dating of an articulated shell by both  $^{14}\text{C}$  and AAR suggest that the deposit is approximately 1000 yrs old.

One key date was taken on an articulated *Anadara trapezia* shell from the shell-rich unit at Batemans Bay. This shell is hypothesised to have been transported and deposited by a very large late-Holocene overwash event attributed to a tsunami (Chapter 8). Both dates Wk9439 and UWGA702 indicate that the deposit is around 1000 yrs old. These dates are stratigraphically consistent and are considered as indicative of the young age of the event.

### 10.11 Synthesis

Both the Killalea Lagoon sandsheet and the shell-rich unit at Batemans Bay are attributed to late-Holocene washover events and exhibit considerable contrast with their confining Holocene facies. Dating of the deposits is limited by uncertainties about groundwater, radiation levels, temperature change and water content. The use of multiple dating techniques did, however allow correlation between the techniques.

Deposition of the Killalea Lagoon sandsheet is confined by AMS radiocarbon and OSL dating to 400-700 yrs BP and is most likely attributed to a tsunami around 1500 AD (see discussion in Chapter 11). The dating of the washover deposit was complicated by the unknown influence of groundwater moving through the porous sandsheet. The presence of modern ‘bomb’ carbon and  $^{137}\text{Cs}$  in the system indicate that the system contains material that is younger than 1960.

The chronology of the Batemans Bay deposit is not as well-defined as the Killalea sequence and should be considered within the limitations of the program. Although most of the dating was conducted on single valves of transported and reworked *Anadara* shells it is apparent that the prograded beach ridge is of early to mid-Holocene age. This inference is supported by the two OSL dates obtained from the excavated faces at the front of the sequence that date at approximately 2000-3000 yrs old.

The upper shell-rich unit is more problematic due to its proximity to the surface and potential contamination from groundwater and the overlying soil. Two dates obtained ( $^{14}\text{C}$  and AAR) from an articulated shell suggest the deposit is approximately 1000 yrs old. The dating of this sequence confirms the relatively young age of the deposit but further refinement of the dating program will be required to confine the depositional age of the deposit. The application of different techniques, such as single grained OSL and



the careful examination of new samples to remove possible contamination may further confine the emplacement of both deposits.

### **10.12 Conclusions**

- The lower parts of Killalea sequence consists of a Pleistocene barrier/lagoon sequence that is overlain by a well-developed soil profile. Dating of the lower lagoon sequence by Jones and Eliot obtained a series of dates between 24-35 ka. It is unlikely that these dates reflect the true age of the deposit, and the age is more likely to be last interglacial.
- Overlying the Pleistocene sequence is a Holocene sequence of lagoonal clays and peats that date from 8000-500 yrs BP. The system was inundated by large washover event resulting in the deposition of an extensive sandsheet that is confined by AMS radiocarbon and OSL dating to approximately 500 yrs BP (1500 AD).
- The Batemans Bay sequence is more problematic. Although the mid-Holocene age of the prograded beach is well defined it is apparent that further dating is need to adequately bracket the depositional chronology of the shell-rich unit. Two dates from articulated shells indicate that the deposit is probably ~1000 yrs old.
- Although accurately dating both events has proven difficult it can be concluded that the deposition of both the Killalea Lagoon sandsheet and the shell-rich unit at Batemans Bay are late-Holocene in age with the Killalea sandsheet confined to the period 400-700 yrs BP and the shell-rich unit confined to the last 1000 yrs.

## Chapter 11

### Evidence for large-scale washover from the southeast Australian coast

#### Introduction

The following chapter re-iterates and discusses many of the key findings of this research. The study sites are located on the embayed high-energy southeast Australian coast (Roy, 1984). The coastline experiences a dominance of oceanic swell from the southeast and is thus classified as a wave-dominated coast (Heap *et al.*, 2004). The coast is in equilibrium with high-energy events and storm events rarely breach the well-developed barrier systems along the coast. Most storm events, including those that generate waves in excess of 10 m are erosional on this coastline and although documented as creating large-scale erosion problems are rarely noted to breach barrier systems (Thom, 1974). The deposits presented in this study are anomalous. They are coarse high-energy deposits found in sheltered elevated positions or in back-barrier environments characterised by low energy sediment deposition. They are the result of large-scale washover deposition that can only be attributed to storms or tsunamis.

#### 11.1 Holocene sea levels and high-energy events

The deposits studied at Abrahams Bosom Beach, Batemans Bay and Killalea Lagoon are not purely the product of higher Holocene sea level. The deposits all result from overwash deposition. Each deposit is characteristically different from those attributed to relative sea level change. The sandsheets investigated at Killalea Lagoon and Bateman Bay were formed by high energy events from the east to southeast and no similar deposits exist in a northeast orientation (Sloss *et al.* in press, Nichol and Murray-Wallace 1994). A sea level highstand in the order of  $\sim +2$  m AHD during the mid Holocene (Flood and Frankel, 1989; Young *et al.*, 1993; Baker and Haworth, 1997) has been noted for this coast and although general agreement exists within the literature on the transgressive record, the suggestion a maximum level of +1-2 m sometime between 6-3 ka has generated much more debate. It is noted however that a relative fall to present level since 3 ka is also apparent in most studies (Belperio *et al.*, 2002).

Sediment on most open beaches is dominated by quartz sand that is constantly reworked by variable wave energy related to storm and fair-weather conditions. It is also noted that in most systems sediments are in a state of quasi-equilibrium where high-energy

events (storms) on open beaches are erosional and erode material from the beach to the nearshore zone where it is stored until fair-weather conditions dominate and beach accretion is restored (Figure 7.2). In addition to this on a regional scale sediment is moved along the coast by a south to north littoral drift generated by gyres from the east coast current (Short, 1993).

One notable exception is presented in Chapter 6 of this study. The small barrier/beach system at Abrahams Bosom Beach is not in equilibrium with high-energy waves as it lies in an extremely sheltered embayment. Subsequently, very large storms that generate swell from the northeast to east can overtop the small barrier and carry sediment into the small back-barrier lagoon. The two events presented in Chapter 6 provided a unique opportunity to study modern storm deposition on this coast thus providing a modern storm analog for the comparison of the deposits identified at Batemans Bay, Killalea and other sites along the southeast coast.

### **11.1 Sedimentary differences between storm and tsunami deposits**

Sandsheets found in low energy back-barrier environments are often indicative of washover deposition by storm surge, large waves or tsunami. Differentiating between these deposits in geological sequences can only be accomplished by developing well-defined facies models using mineralogy and sedimentological features from deposits of known origins.

One of the key aspects of this study is the review and discussion of the inherent difficulties in the global study of washover deposits. To this end many global examples of washover sand deposits attributed to storm and tsunami were reviewed in Chapter 3. This chapter concluded with a review of many tsunami signatures identified in the literature, pointing out that many of these attributes, such as the presence of marine microfauna or marine sand can often be interpreted as purely indicative of marine inundation. Recent research into modern tsunami and storm events has provided several key identifiable features (Table 3.6) for tsunami deposits that may allow the investigation of older sequences to be less complicated.

In particular storm and tsunami deposits may be differentiated by comparing and contrasting: the contact with the underlying sediments; the range of identifiable source

sediments; the degree to which the sediments are sorted; the presence and thickness of graded beds; and evidence for directional flow changes.

Storm events are usually non-erosional and contrast with tsunami deposits that often contain rip-up clasts of the underlying stratigraphy (Kortekaas, 2002; Gelfenbaum and Jaffe, 2003). Direct contrasts also exist in sediment source, with storm deposits eroding mainly beach face and dune material where tsunami erode material from a much larger range of environments (Nanayama, 2000; Switzer *et al.*, 2004, in press). Other diagnostic criteria of sediment sorting characteristics and the presence and nature of graded beds, are inherently related to the source area of sediments (Table 3.6). Differential sorting and graded beds require a range of grains sizes; it is apparent that in some cases a restricted grain size range can make it difficult to use these criteria with any interpretive confidence. Finally the presence of sedimentary features that indicate uni- or bi-directional current flow has been cited as definitive of storm or tsunami, with storms characterised by uni-directional flow (Nanayama, 2000).

This review and discussion was then followed by a review of evidence for tsunami from the southeast Australian coast (Chapter 4). One major aim of this research is to clarify key aspects of this debate by investigating elevated boulder deposits that have been attributed to tsunami. Boulder deposits found on rocky coasts can provide striking evidence of overwash events (Chapters 3 and 4). However, without detailed knowledge of fabric analysis and well-developed facies models for high-energy events on these coasts, such deposits give equivocal results and often remain undifferentiable in many cases. It is also impossible to tell if a boulder's movement is the result of single or multiple steps (events).

The sedimentology of two storm deposits was presented in Chapter 6. The southeast Australian coast lacks published sedimentary evidence for tsunami inundation and the storm deposits provide the first insight into the sedimentary characteristics of modern washover deposits from this coast. The storm deposits provide a key modern analog to which the sedimentary characteristics of palaeo-washover deposits at Killalea and Batemans Bay can be compared.

The southeast Australian coast lacks historical evidence for large tsunami and no modern tsunami deposits exist along this coast. In the absence of a modern tsunami deposit the deposits investigated in this study are compared to global examples and the criteria defined in Chapter 3 along with comparison to the modern storm deposits studied in Chapter 6.

## 11.2 Tsunami research from the southeast Australian coast

Substantial geomorphic evidence for large-scale overwash by late Holocene tsunami has been presented from the New South Wales south coast by Bryant *et al.* (1996), Young *et al.* (1997), Bryant (2001) and Bryant and Nott (2001). Young *et al.* (1997) suggested that up to six events can be identified beginning approximately 7,500 years ago and ending as recently as 600 years ago. Summarising much of this geomorphic research, Bryant *et al.* (1996) and Bryant and Nott (2001) presented four broad signatures of these tsunami: erosional bedrock sculpturing, imbricated boulders, constructional features such as mounds of sand and cobbles in sheltered embayments, and uncemented clastic deposits including extensive chaotic sandsheets. Much of this research has been controversial and features such as bedrock sculpturing and cobble mounds require further analysis with direct comparison to tsunami-generated examples.

A re-appraisal of several large accumulations of boulders found on coastal rock platforms and ramps in the Jervis Bay region of southeastern Australia was provided in Chapter 4. These deposits are elevated above sea-level and in many places consist of imbricated boulders weighing up to 20 tonnes. The Greenfields Beach site is a small shallow dipping rock ramp with elevated boulders some 7 m above contemporary sea-level that occurs within the shelter of Jervis Bay and contrasts directly with boulders on top of Little Beecroft Peninsula that exist up to 30 m above sea-level. Boulders at both sites were measured for dimension, orientation and lithology. Notes were also taken on clast size, imbrication, dip direction, jointing, cross-bedding, and bioturbation.

Some boulders at both sites exhibit obvious signs of imbrication as a response to flow in a landward direction whilst other larger clasts appear characteristic of fallen blocks with no hydraulic reworking. Both of these sites were studied by Young *et al.* (1996) and Bryant *et al.* (1992; 1996) who attributed the boulder deposition to tsunami. Although

striking these deposits present significant analytical problems some of which have been discussed controversially (Felton and Crook, 2003).

These deposits provide compelling evidence for large-scale movement by oceanic events. It is however almost impossible to attribute a single depositional mechanism to these deposits. The analysis is complicated by two insurmountable limitations. Firstly a general lack of facies models for rocky shorelines has been identified by Felton (2002) and Felton and Crook (2003). Secondly it is impossible to attribute these deposits to a unique event. One cannot definitively state that the boulders are purely the result of tsunami washover. It is likely that storm and tsunami may have both played a role in the development of the high-level boulder beds and the degree to which each of these events contributed and the number of steps in the movement are not definable.

#### **11.2.1 Storm deposits from Abrahams Bosom Beach: a modern storm analog**

Two storm events in March and July 2001 generated large swell from the northeast that breached a small barrier complex at Abrahams Bosom Beach on the southeast coast of Australia (Chapter 6). Both events are associated with large swells from the east-northeast generated by intense low-pressure systems in the southwest Pacific and were events were capable of breaching the barrier and depositing a fan-shaped tongue of marine sediment into the back-barrier estuary.

The internal stratigraphy of the sandsheets consist of a series of fining up sequences that are generally less than 20 mm thick. In vertical profile the washover deposits consist of a succession of layered sands to which the layered appearance can possibly be attributed to variations in heavy minerals and shell hash. The base of each layer is usually characterized by darker coloured quartz sand with relatively abundant heavy minerals, although at no times do the heavy minerals exceed 3%. The base grades to a quartz sand with little heavy mineral content that grades farther upwards to a quartz sand with shell hash that is often absent possibly a result of erosion by the succeeding wave pulse.

#### **11.3 Unusual deposits from Killalea Lagoon and Batemans Bay**

In this study the sedimentary characteristics of a large prehistoric overwash sandsheet and elevated shell-rich deposit, which are both hypothesised to be tsunamigenic are

compared with the modern storm deposits from two large storms at Abrahams Bosom Beach.

Both the sandsheet at Killalea Lagoon and the shell-rich deposit at Batemans Bay indicate that very large overwash events have occurred in the geological past, thus confirming earlier observation in the Dunmore embayment (Switzer *et al.*, in press) and allowing an extension of knowledge concerning risk management coastal hazards for this coast.

### 11.3.1 Washover at Killalea Lagoon

The Killalea deposit exists as an elevated laterally extensive marine quartz sandsheet in a freshwater lagoonal environment that exhibits an obvious contrast with the low-energy organic rich lagoonal deposits that exist above and below the sequence. The deposit exists up to 700 m inland and rises to a height of 1.6 m (AHD). A conservative volume for the deposit is more than 21000 m<sup>3</sup>. On volume alone the deposit contrasts directly with the much smaller storm washover deposits presented in chapter 6 that are less than 10% of this volume.

The Killalea sandsheet deposit contains a dominance of clean fine- to medium-grained quartz sand with minor heavy minerals. Rip-up clasts of the underlying lagoonal stratigraphy are incorporated into the lower parts of the deposit along with evidence for the removal of dune vegetation including *Spinifex* sp. Two facies are identified in the sandsheet deposit - the first a clean unimodal sand and the second a bimodal slightly muddy sand that is hypothesised to contain material from the inner shelf as suggested by the presence of a unique heavy mineral assemblage. Little evidence of grading is found in the deposit and this is hypothesised to be the result of good sorting in the sand-dominated lithologies of the source area in combination with the complex hydrodynamics of the overwash event.

The Killalea deposit is attributed to a large-scale washover from the southeast that is capable of breaching the barrier and carrying very large amounts of sandy sediment into the back-barrier lagoon. When compared to the modern storm deposit striking differences in extent, composition and grading exist. The deposit lacks many characteristics of modern storm deposits and is most likely attributed to a late-Holocene

tsunami. Dating of the deposit by AMS radiocarbon and OSL presented in Chapter 10 confines the date of deposition to between 180-700 yrs and the event is most likely attributed to a tsunami around 1500AD.

### **11.3.1 The elevated shell-rich unit at Batemans Bay.**

An unusual coarse shell-rich marine sand unit is found in the upper fill of a small pocket embayment at Batemans Bay. The sequence exists up to 2.5 m above present mean high tide level and is located approximately 2 km to the west of the current influence of ocean waves. The upper part of the sequence is characterised by a series of organic-rich shelly sand layers that contain shell and exist to a height of +2.5 m AHD.

Coring and ground penetrating radar identified a prograded beach sequence composed of mixed bimodal fine- to medium-grained quartz sand that has prominent but variable shell hash and dating of the sequence by radiocarbon and amino acid racemisation indicates the prograded beach sequence is of mid Holocene age. Analysis of contemporary grab samples suggests that the material in the elevated coarse unit is similar to material derived from the present marine channel, tidal delta and surrounding rock shelves. Ground penetrating radar transects across the sequence have highlighted a continuous erosional contact at the level of the coarse debris layer.

The presence of large volumes of marine sand, along with articulated bivalves and a dominantly marine macrofauna, suggest a large-scale mass movement of sediment by an oceanic event attributed to a late Holocene tsunami.

### **11.4 An erosional signature from the coastal dune at Killalea Lagoon**

Ground penetrating radar was used to investigate the landward margin of the washover deposit and contacts between the dune and lagoonal sequences at Killalea Lagoon. Although the sandsheet was poorly defined at its landward margin the dune transects did deliver interesting results. Two flat lying erosional boundaries were identified as truncating reflectors in GPR transects (Figure 9.6). A lower boundary identified in KGPR3 is thought to be the result of washover during dune development, as the reflectors appear to dip below the onlapping lagoonal deposits.



A second erosional boundary lies higher in the stratigraphy and is found in both dune to lagoon transects. In both transects the series of dipping reflectors interpreted as dune beds are truncated by a prominent horizontal reflector. This reflector corresponds stratigraphically to the seaward end of the washover sandsheet and is interpreted as an erosional boundary that corresponds to that depositional event. This study provides the first geological erosional signature for large-scale dune washover by prehistoric tsunami.

### **11.5 Bolide impacts and the 1500AD east coast tsunami – Fact or fiction?**

In his controversial monograph, Bryant (2001) attributed many of the tsunami features he identified on the southeast Australian coast to a ‘mega tsunami’ caused by a bolide impact in the southwest Pacific Ocean. In support of this hypothesis, Bryant pointed to Maori and Aboriginal legends of fire in the sky including a controversial interpretation of a Maori legend about the "fires of Tamatea" (Bryant, 2001). In response, Goff *et al.* (2004) suggested that the interpretation is based on misunderstood Maori place names, and identification of a meteor impact crater at Tapanui, which was in fact debris from a landslide.

Recently work by Abbott *et al.* (2003) claimed to have identified the crater to which the 1500AD tsunami is attributed. The Mahuika crater is located on the New Zealand continental shelf at 48.3 S, 166.4 E and is said to have dimensions approximately 20 km wide and more than 150 m deep. Abbott *et al.* (2003) cited several lines of evidence that suggest this impact is responsible for the 1500 AD event. The first is the site of the crater relative to the southeast Australian coast, where the authors suggest that the impact would have created a tsunami wave that struck from approximately southeast at about 45° to the coast. The second line of evidence is from images of the submarine topography and the presence of impact ejecta in all of the submarine dredge samples near the crater.

The only constraint on the date of the impact is the shallow nature of sediments deposited over the crater. The thin blanket of sediments suggests that the deposit is young (~500 yrs BP). Further evidence for the event is the distribution of tektites, which are found on the side of the crater opposite to the direction of bolide arrival. Many bottom samples from around the crater were found to contain impact ejecta. Tektite-

bearing samples were only located southeast of the crater, in the opposite direction from the southeast Australian coast, where the impact fireball was allegedly observed by aborigines (Bryant, 2001) suggesting that the bolide travelled across the Australian mainland before impacting south of New Zealand. Bryant (2001) also suggested that this event was capable of driving the Maori people of New Zealand away from the coast.

Particular criticism for this hypothesis has come from Goff *et al.* (2002, 2004) who suggest that considerable seismic activity, including several large tsunami around this time, would be the driving force for any mass movement of people away from the coast. Goff *et al.* (2004) suggested that significant evidence for tsunami inundation does exist on both the New Zealand and southeast Australian coastlines. The authors, however disagreed on the source of such events with Goff *et al.* (2004) suggesting that the event is more likely to be the product of seismic activity on the southwest or south coast of New Zealand's South Island.

Although the chronology of the newly discovered impact crater remains unresolved it may provide a valuable insight onto tsunamigenic activity along the southeast Australian coast. It is very interesting to note that dating of the Killalea lagoon sandsheet confines its deposition to approximately 1500AD and that the sandsheet is attributed to a tsunami on sedimentological grounds. A bolide impact would easily be capable of generating a tsunami large enough to deposit the sandsheet at Killalea. It is also important to note that the work of Switzer *et al.* (in press) noted that a young age (<1000 yrs BP) is likely for the upper sandsheet identified in the Dunmore embayment found to the west of the Killalea site.

#### **11.6 Possible sources of tsunami that strike the southeast Australian coast.**

This study identifies two deposits that provide considerable sedimentological evidence for late Holocene overwash into coastal embayments along this coast and supports the initial work by Switzer *et al.* (in press) there is considerable sedimentological evidence for tsunami deposits on the southeast Australian coast.. Both events are attributed to tsunami as both deposits were compared to a modern storm deposit where significant contrasts are highlighted.

Tsunami are generated by many different geological processes, including earthquakes, submarine sediment slides and bolide impacts (Dawson, 1999). Throughout the Quaternary the southeast Australian coast can be considered as a tectonically stable, sediment deficient margin (Roy, 1994). It is unlikely therefore that any tsunami along this coastline is the result of submarine earthquakes on the continental shelf off the southeast Australian coast. Although evidence exists for significant submarine landslide activity on the continental slope (Jenkins and Keene, 1992) it is also unlikely that sediment slumps on the thinly sedimented continental margin would cause significant risk of tsunami as although undated, the slides appear to be significantly older than the Quaternary (C. Jenkins, pers comm., 2002).

The deposits are attributed to a tsunami washover from an event that generated waves from the southeast. One tsunami source suggested by Bryant *et al.* (1996) is the Macquarie Ridge southwest of New Zealand, where twelve large earthquakes were observed between 1920 and 1984 (Jones and McCue, 1988). Many tsunami are attributed to sediment slides and although sediment slides on the Australian continental slope are not considered high risk the possibility of sediment slides on the sediment laden tectonically active coastline of the south island of New Zealand does deserve particular mention.

The large and active Alpine Fault in New Zealand extends off the southwest corner of the south island. A large rupture with vertical displacement on the submarine extension of this fault could easily generate a tsunami large enough to deposit many of the sedimentary features observed in this study.

### **11.7 Study synthesis: searching for sedimentary evidence of tsunami inundation**

When studying washover deposits it is important to understand the equilibrium state of a coastline. The southeast Australian coast is a high-energy coast dominated by ocean swell from the southeast. Storm events are usually erosional on the southeast Australian coast and it is unlikely that storms will result in overwash events on high-energy systems such as Killalea that face southeast.

Embayments such as Abrahams Bosom Beach that face northeast are sheltered from much of this wave energy and form environments where high-energy waves are in

disequilibrium with the geomorphic set-up of the embayment. Such sites can be considered sites of maximum potential for overwash and preservation of storm waves. Two such disequilibrium events occurred in 2001 and provided a key modern analog for the study of storm washover deposits on this coast.

An extensive review of tsunami and storm research from the last 15 years has highlighted numerous contradictions in the search for signatures of tsunami inundation (Table 3.5). Many signatures cited in the literature as indicative of storm or tsunami deposition are more accurately described as signatures of marine inundation. For example the presence of marine microfauna, or increase in elements like sodium, chlorine and magnesium are indicative only of marine inundation and cannot be attributed to storm or tsunami. Table 3.6 identified five main sedimentological criteria that differentiate storm deposits from tsunami deposits. When compared to storm deposits, tsunami deposits are noted to have the following general characteristics: they are more chaotic and poorly sorted due to sediments being derived from a wider variety of sources, they have an erosional basal contact, show thicker graded sequences and exhibit evidence of bi-directional flow where individual landward flow and back flow facies can be identified. Storm deposits often exhibit thin laminae and foreset bedding, most likely a product of multiple small pulses of landward directed energy that contrast with thicker graded-beds identified within tsunami deposits (Gelfenbaum and Jaffe, 2003; Tuttle *et al.*, 2004).

Substantial geomorphic evidence for large-scale overwash by late Holocene tsunami has been presented from the New South Wales south coast by Bryant *et al.* (1992; 1996), Young *et al.* (1996; 1997), Bryant (2001) and Bryant and Nott (2001) over the last decade. Summarising much of this geomorphic research, Bryant *et al.* (1996) and Bryant and Nott (2001) presented four broad signatures of these tsunami: erosional bed-rock sculpturing, imbricated boulders, constructional features such as mounds of sand and cobbles in sheltered embayments, and uncemented clastic deposits including extensive chaotic sandsheets. In particular the study of boulder assemblages on the coast has caused considerable debate. In Chapter 4 two key boulder sites were reappraised to test the hypothesis of tsunami deposition forwarded by Young *et al.*, (1996). It was concluded that although the boulder deposits provide compelling evidence for large-scale overwash events, one cannot definitively state that the boulders

are purely the result of tsunami washover. It is likely that both storm and tsunami may play a role in the development of the high-level boulder beds and the degree to which these events and the number of events (steps) in the movement are not definable.

Of key importance to the scientific merit of this project was the use of a well-developed modern analog for storm deposition that allows direct comparison to the deposits at Killalea and Batemans Bay. Investigation of the 2001 storm washover deposits from Abrahams Bosom Beach identified a series of fundamental characteristics for storm deposits on this coast. Both storm deposits at Abrahams Bosom Beach were both found to contain a dominance of fine- to medium-grained sand and exhibit thin graded beds with microfacies representative of repeated pulses of wave energy during washover.

A thin laterally extensive sandy deposit exists in the upper embayment fill of Killalea Lagoon, a predominantly freshwater swamp. Coring of the deposit suggests the Killalea deposit is significantly larger than the storm deposits at Abrahams Bosom Beach as it extends continuously up to 700 m inland and tapers landward rising to ~1.6m AHD. The deposit sharply overlies the peaty lagoonal sequence and consists of fine- to medium-grained sand with some organic material dominated by fragments and rootlets of *Spinifex* grasses.

Although somewhat problematic, dates derived from peat taken from just below the sharp contact of the sand sheet all provide a calibrated peak that suggests the sandy deposit occurred around 1500AD. The silty organic nature of the overlying sediments suggests that the event was short lived and lagoonal sedimentation resumed soon after sandsheet deposition. The Killalea Lagoon sandsheet is found behind a high-energy beach/barrier system that is rarely inundated by storm waves. The sandsheet is ten times greater in volume than the July (larger of the two) storm deposit at Abraham Bosom Beach.

An unusual coarse shell-rich marine sand unit is found in the upper fill of a small pocket embayment at Batemans Bay in southeastern New South Wales. The sequence exists up to 3 m above present mean high tide level and is located approximately 2 km to the west of the influence of ocean waves. The upper part of the sequence is characterised by a series of organic-rich shelly sand layers that contain articulated shells and extend to a

height of +3.5 m AHD. Coring identified a prograded beach sequence composed of mixed bimodal fine- to medium-grained quartz sand that has prominent but variable shell hash. Dating of the sequence by radiocarbon and amino acid racemisation indicates the prograded beach sequence is of mid Holocene age. Analysis of contemporary grab samples suggests that the material in the elevated coarse unit is similar to material derived from the present marine channel, tidal delta and surrounding rock shelves. Ground penetrating radar transects across the sequence have highlighted a continuous erosional contact at the level of the coarse debris layer. The presence of large volumes of marine sand, along with articulated bivalves and dominant marine macrofauna, suggest a large-scale mass movement of sediment from an oceanic event. I suggest that this deposit is the result of a late Holocene tsunami or exceptionally large storm. Such a storm would have to be several orders of magnitude greater than any recorded storm for this coast.

Complementing the sedimentary study at Killalea and Batemans Bay was a ground penetrating radar study. Interestingly 2 transects of the Killalea Barrier system show an erosional contact between a series of truncated pre-event dunes and several small overlying post-event dunes which outlines a relatively simple non-invasive method for the identification of an erosional signature for prehistoric large-scale washover by storm surge, exceptionally large waves or tsunami.

Dating of both the Killalea and Batemans Bay deposits was problematic. It is apparent that the Killalea deposit is around 500 yrs old whereas the Batemans bay deposit may be about 1000yrs old. The Killalea date corresponds to one of the dating peaks attributed to tsunami that was summarised in Bryant, (2001) and Bryant and Nott (2001). The study also concludes that considerable caution must be taken to dates that may be affected by groundwater movement through the porous washover sandsheets.

Geological evidence for large-scale oceanic inundation exists in several places along the south coast of New South Wales and should be considered in reference to coastal management and hazard mitigation programs. This study highlights sites at Killalea Lagoon and Batemans Bay, and compliments the earlier study of the Dunmore embayment (Switzer *et al.* in press). As stated in Chapter 5 many sites along this coast were identified as containing sandsheet deposits in their upper fill. This thesis and the

initial study at Dunmore will provide a valuable reference for the future study of these sites. It is hoped that expansion of this research program to sites such as Crooked River, Werri Lagoon, Cullendulla Inlet and sites to the south of Batemans Bay will result in a detailed history of large-scale washover from this coast.

Such research is important and this study indicates two very important concepts for the management of this coastline. Firstly the storm deposits show that ambient north facing embayments are not in equilibrium with the general southeasterly-dominated coastal wave set-up. As a result it is noted here that large swells from the northeast are more likely to breach small barrier systems. It follows therefore that coastal towns or properties at the southern end of embayments are at risk of coastal flooding from such events. It is also likely that such events are more likely to be recorded in the geological record of estuaries as washover sandsheets as such events are in disequilibrium with the ambient nature of many north facing embayments.

The imbricate boulder deposits at Jervis Bay and the washover sandsheet deposits at Killalea Lagoon and Batemans Bay all suggests that the coastline is susceptible to large washover events over geological timescales. Such events must be considered in term of coastal management and development. It must be noted that although no tsunamis have occurred in recorded history this coastline should not be considered as risk free.

## **11.8 Conclusions**

- Sedimentary evidence for large-scale washover deposition along the Australian southeast coast is found as sandsheets in estuaries and anomalous boulder accumulations on rocky ramps and headlands.
- Large imbricated allochthonous boulders found elevated up to 33 m above present sea-level indicate high energy deposition on sheltered rock ramps and coastal headlands attest to very high wave energies in the past. The most striking boulder deposits are found in the ambient location of a large bay and have been transported more than 30m horizontally along a boulder ramp and elevated to a height of more than 5m above present sea-level. Although this evidence is

striking, it is impossible to identify if the boulders were moved in one movement or have been moved by several events over time.

- The most compelling evidence for tsunami events is found in the upper fill of several embayments along the coast. Laterally extensive marine sandsheets are identified in back-barrier lagoons and elevated shell-rich sands are found on the margin of a large drowned river valley. These deposits exist up to 3 km landward of the influence of modern coastal processes.
- The back-barrier sandsheet at Killalea Lagoon presents an obvious contrast with the finer confining sediments of the coastal lagoon and barrier estuary. The sandsheet is composed of mixed marine sediment dominated by dune sand but also containing platy heavy mineral assemblages indicative of nearshore to inner shelf sediments. This marine sediment is mixed with clasts of coastal vegetation and rip-up clasts of soil and lagoonal muds and clays.
- The marginal river valley material at Bateman Bay occurs as a coarse shell-facies containing large, often articulated, bivalve shells and oysters, along with cobbles of mixed lithology in a matrix of marine sand. This suggests deposition of predominantly seaward tidal channel material above a prograded beach succession.
- The advantage of the sandy deposits over boulders lies in the analysis of their internal sedimentology and the presence of datable peat and shelly sands that provide dateable material to confine the age of the sand sheets and coarse shell deposit respectively. The internal sedimentology of the deposit yields little structure and sediments consist of a series of massive, laminated or graded beds that often incorporate organic debris and occur as laterally extensive sandsheets extending up to 600m from the coast.
- These deposits contrast with storm washover deposits from Abraham Bosom Beach which consist of thin graded beds of nearshore, beach face and dune sediment only. Individual beds are a few centimeters thick and can be traced



throughout the deposit. The storm deposits are the result of numerous wave-generated landward pulses of sediment movement whereas the larger more chaotic sandsheet deposit at Killalea is the result of several very large pulses whereas the larger more capable of eroding and transporting shelf, nearshore, dune and terrestrial sediments landward, followed by partial reworking of the material by back flow. These latter characteristics are indicative of the chaotic transportation and deposition of such deposits by short-lived high-energy events attributed to tsunami.

- Optically Stimulated Luminescence (OSL) dating of quartz sediments from the sandsheets supplemented dating of the confining deposits by conventional radiocarbon on shell material and the underlying peat. Dating from the Killalea Lagoon site suggest that the depositional event here is attributed to a large-scale inundation event around 1500AD whereas the coarse shelly facies at Batemans Bay is probably about 1000 yrs old.
- Possible tsunami sources include sediment slides off the continental slope of Australia or New Zealand, seismic events in New Zealand and the Macquarie Ridge, and bolide impacts in the Tasman Sea or southwest Pacific.

### **11.9 Recommendations for further work**

The detailed characterisation of other extensive sandsheets on this coast may provide further evidence of late Holocene overwash activity attributed to tsunami. This evidence could add to a considerable bank of geomorphic evidence for tsunami reported for this coast.

This study has set out to look for sedimentological evidence for large-scale overwash. Upon review of global research a list of diagnostic sedimentological criteria for differentiating between storm and tsunami has been assembled and should be applied to the study of other coastal embayments on high energy coasts.

Studies such as this allow quantification of large washover events that extend the record of potentially damaging events to geological timescales, a concept that is important for coastal risk assessment studies.

This study is one of very few that has focused on the differences between tsunami and storm deposits. More research in this area is needed and the recent Indian Ocean tsunami will provide a great modern analog for such work (see epilogue)

The study has highlighted the presence of large-scale washover on the southeast Australian coast and attributed these deposits to one or two late-Holocene tsunami. Significant research should continue into the risk of tsunami striking the southeast Australian coast. Such research will need to investigate the risks associated with the tectonically active, sediment-laden, continental shelf of the South Island of New Zealand.

## **Epilogue**

On December 26, 2004 during the final stages of this study a devastating tsunami occurred in the Indian Ocean. The event destroyed villages, taking thousands of lives and changing the world and the way we view tsunami forever. An earthquake of more than 8.7 on the Richter scale occurred in the Indian Ocean northwest of Sumatra, Indonesia. The vertical displacement along the fault line has been estimated as up to 30 m (average reports of around 10 m). The movement displaced trillions of tonnes of water and caused a very large tsunami. Within hours the tsunami had destroyed the northern parts of Sumatra along with many of the bustling villages and coastal resorts of Thailand, Sri Lanka, India and the Maldives. The death toll as I finish this review has reached more than 220,000 people and will never be finalised. Aid of more than \$US 6 billion has been pledged from around the world and although this may save many lives and assist in the rebuilding some things can never be rebuilt. One thing is certain; this event will shape the face of tsunami research for many years to come.

This brief review presents a short analysis of the event. Much of the material has been obtained from internet sites that vary in reliability. The most important information came from two news articles in Nature. Many of the concepts are speculative and will require further investigation. Nevertheless this event will be fundamentally important to many aspects of tsunami research and cannot go without mention.

### **E .1 Earthquake and tsunami**

An earthquake occurred off the northwest coast of Sumatra 00.59 GMT, destroying buildings in many parts of northern Sumatra. The first signs of the earthquake were picked up at the Cocos Island station in the Indian Ocean, indicating an earthquake in excess of 8.0 on the Richter scale (Marris, 2005). The earthquake caused a tsunami that struck Banda Aceh, in northern Sumatra, with devastating force some 30 minutes after the earthquake. Many people had just started cleaning up after the damage of the quake. The tsunami strikes the coast with an estimated speed of 40-60 km hour (USGS website) devastating large parts of northern Sumatra (Figure E1).

*Epilogue. Indian Ocean Tsunami*



Figure E1 Image of Meulaboh in northern Sumatra. The wholesale devastation is obvious. Less obvious is the sandsheet deposit that is combined with the debris (Marris, 2005, image Alankara).

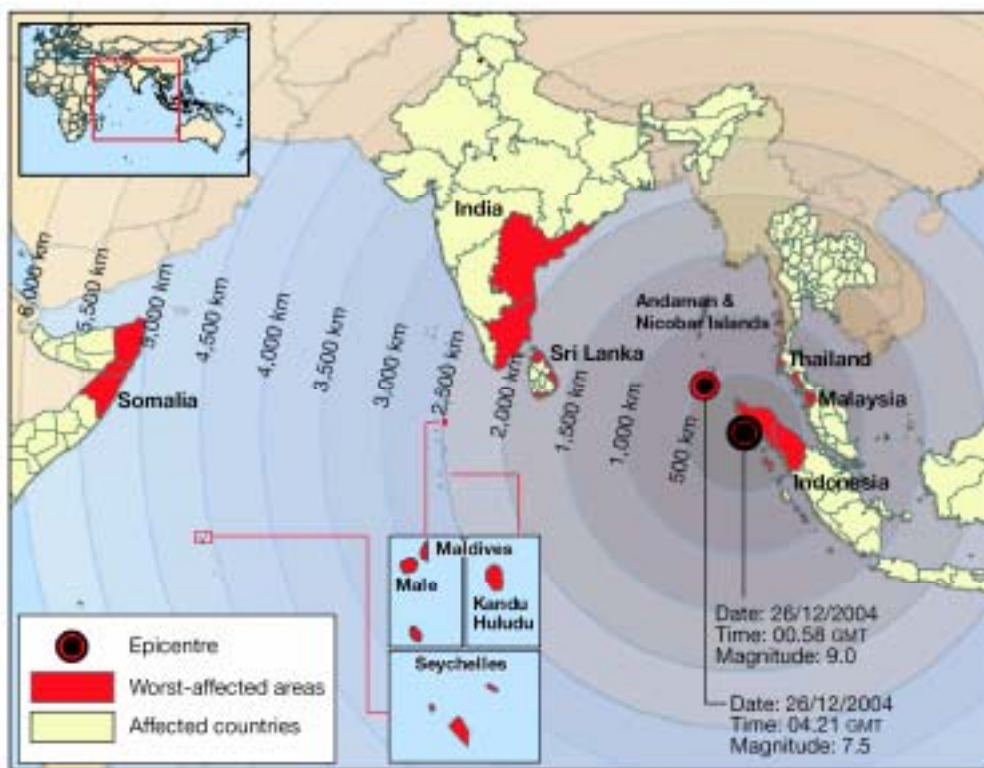
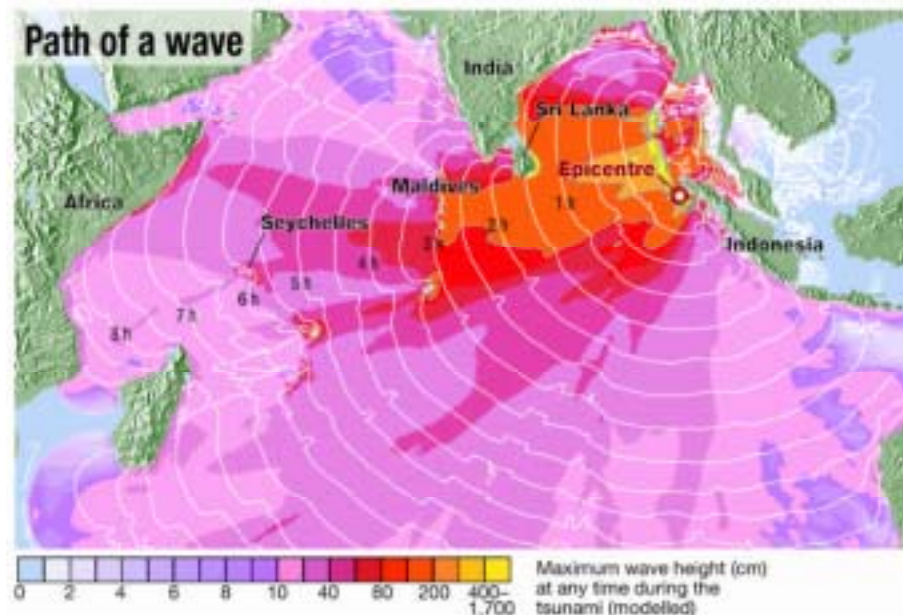


Figure E2 Map showing sites of earthquakes and path of tsunami and worst affected areas (Marris, 2005; image from Reliefweb).

## **E.2. Tsunami distribution**

Figure E1 shows a map of the timeline and wave heights of the tsunami. Note the complex refraction patterns particularly around the Maldives and Seychelles Islands. Considerable complexity also exists around the shallow waters of the Andaman Sea off Thailand (to the north and northeast of the epicenter).



*Figure E3 Modelled wave heights and travel times of the tsunami on the 26 December 2004. Note the complex affects of bathymetry on a broad scale. Note also the significantly higher wave heights along the coast of northeastern Africa (Schiermeier, 2005).*

## **E.3 Differences in bathymetry, run-up and wave approach**

In many areas the affects of the offshore bathymetry remain unknown. One observation clearly obvious from news footage was the difference in the tsunami characteristics at the shoreface. In the shallow bathymetry offshore of Thailand the wave slowed to less than 50 km/hr and broke very much like an ocean swell wave. Video footage from Thailand shows the wave breaking offshore and striking the coast as a wall of whitewater. This contrasts with the wave style recorded by eyewitnesses in the Maldives off India where reports generally describe a surge without breaking waves. It is also apparent that the wave velocity in the Maldives was significantly greater than that recorded in Thailand. This is most likely directly related to the lack of ramp-like bathymetry in the coral atoll environment of the Maldives. This concept is similar to that presented in Figure 3.2 where the difference in storm surge behaviour between the

steeper coast of eastern Australia and the ramp like coast of southeastern USA was noted. The dramatic differences in tsunami behaviour between coastlines highlight the complexity of dealing with modelling complex bathymetric systems as different wave characteristics are dependent on, and a function of the affects of, the lead-up bathymetry.

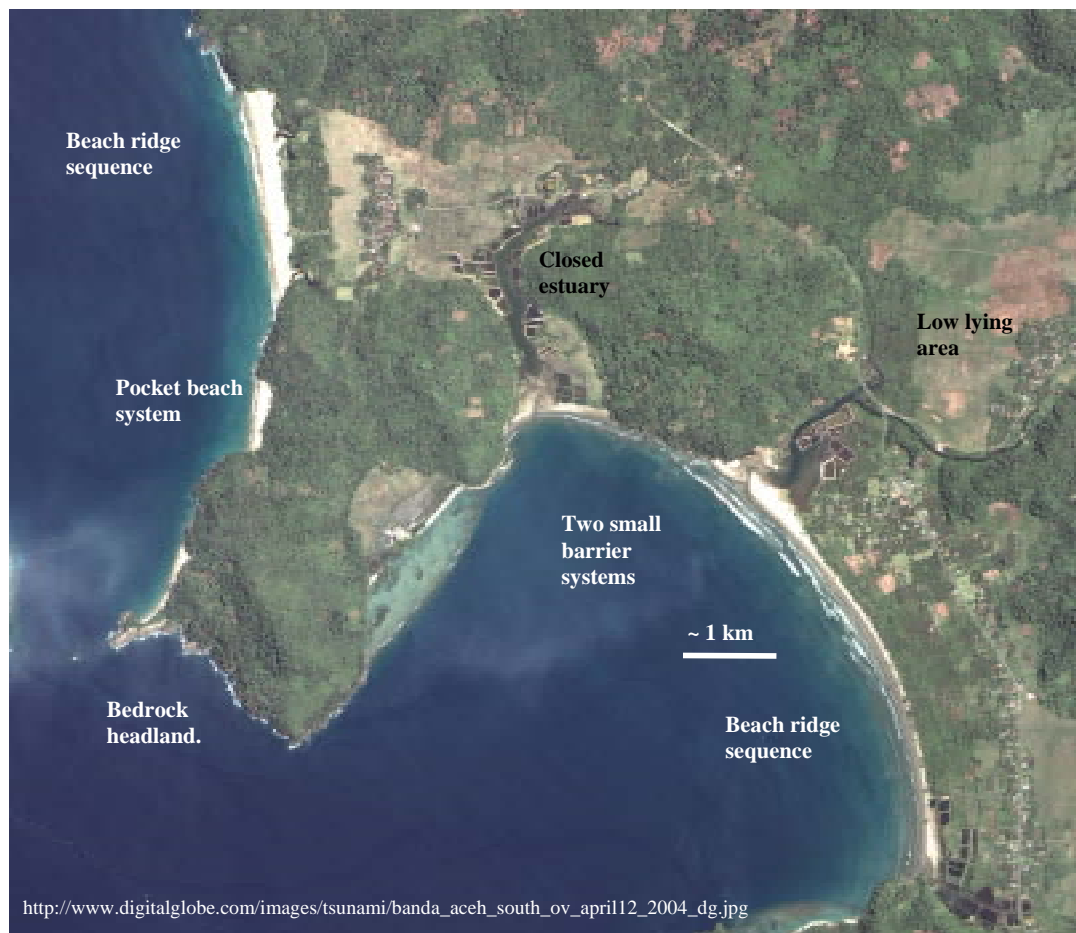
#### **E.4 Aerial photography and satellite images**

Perhaps the most provocative images in the media have come from satellite images of the most devastated areas, particularly around Banda Aceh, in northern Sumatra. The majority of the images are of built up areas and show little more than the extent of run-up. Two key satellite images come from a relatively underdeveloped section of the coastline where wave heights are thought to have exceeded 12 m (NOAA) and they show the affects of the tsunami on several different coastal environments (Figures E4 and E5).

Figure E4 shows a satellite image taken in April 4, 2002, before the tsunami from the northwest. A series of bedrock headlands (former islands), beach ridges and small barrier systems exist along the coast and confine a series of (mostly closed) estuaries. The geomorphic affects of the tsunami are clearly visible in Figure E5 in a satellite image captured on the January 2, 2005.

Several key aspects of tsunami sedimentation and erosion are identified in the post tsunami image. Firstly, the amount of geomorphic change is most dramatic in the estuary systems and much less on rocky coasts or in pocket embayments. Run-ups in the low lying valleys appear to be in excess of 5 km. It is also clearly obvious that one of the landforms that receive a dramatic amount of change is the estuary mouth.

Both of the prominent estuaries contain very little sediment in the mouth of the system, and showing obvious signs of large-scale erosion (Figure E6). Large amounts of sediment appear to lie inland of the road system as a continuous sandsheet that extends at least 5 km up the estuary. It is also apparent that the unlike the estuary mouth, the beach and barrier system although considerably eroded retains its basic geomorphic form.



*Figure E4 Satellite image of the west coast of the northern part of Sumatra, Indonesia just south of Banda Aceh taken on April 4, 2002. The high energy coastline has a series of bedrock outcrops, estuaries and pocket beaches that would provide a valuable location to study the impact of a large tsunami on different coastal features.*

### **E.5 Sedimentation studies**

Many research groups have collected sediments from the tsunami deposit (Figure E7) including the USGS and several Japanese, European and local research groups. The deposits from this event will provide unique opportunity to investigate the sedimentary characteristics of a modern tsunami deposit. Investigation of areas such as that presented above provides an opportunity to study the impact of tsunami on a variety of coastal environments. One immediate observation is that the greatest amount of geomorphic change comes from the mouths of estuaries and this requires further investigation. Significant erosion is also observed on beach ridges and pocket embayments but these features appear to retain their geomorphic expression. The sandsheet deposit appears to be relatively thin as the expression of the agriculture fields can be observed in many locations.





*Figure E5 Post tsunami satellite image of the west coast of the northern part of Sumatra, Indonesia just south of Banda Aceh taken on January 2, 2005. Large amounts of erosion are clearly visible particularly at the mouths of estuaries. The deposition of an extensive sandsheet is also clearly visible from the image.*

Figure E6 shows a close up of one of the estuaries in the larger image. The obvious geomorphic change in the estuary mouth is clearly visible along with the extensive sediment sheet that drapes the agricultural fields. It is also apparent that the sediments of the estuary are now subject to continued reworking by wave energy. This site is directly comparable to many estuaries on the high-energy southeast Australian coast and may provide a modern analog for these tsunami studies. It is also comparable to estuaries on other high-energy coasts such as those of Portugal and Chile and should be compared to the palaeotsunami deposits identified on those coasts.





*Figure E6 Satellite image of an estuary from the west coast of the northern part of Sumatra, Indonesia just south of Banda Aceh (Figure E4 and E5) taken on January 2, 2005. Large amounts of erosion are clearly visible at the mouth of the estuary. An extensive sandsheet drapes the agricultural fields to the east of the estuary. Sites like this are directly comparable to the southeast Australian coast.*



*Figure E7 USGS geologist Bruce Jaffe takes a photograph of tsunami deposited sediments in Sri Lanka. These deposits will provide valuable insight into the depositional characteristics of tsunami. The deposit in the photograph appears to consist of massive medium-grained sand.*

### **E.6 Future work**

In parts of Indonesia this event definitely qualifies as a “mega tsunami”. This area will provide a valuable site to test many theories on the impacts of very large-tsunami on coastlines.

The variety of coasts devastated by the event should also allow for regional studies of both high and low energy coasts. For example work in the Maldives should improve the understanding of large tsunami affects on coral atolls and provide a opportunity to test the work of Bourrouilh-Le Jan and Talandier, 1995.

Other features that should be investigated include bedrock erosion and sculpturing, boulder (mega-clast) movement and the transport of sediments from offshore. This study concluded that tsunami deposits are very dependent on the sediment characteristics of the source area. It is pertinent that all tsunami signatures are investigated in these systems in order to develop globally applicable methods for studying tsunami deposits.

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