SEDIMENTOLOGY OF TWO WAVE-DOMINATED, INCISED VALLEY ESTUARIES: NEW SOUTH WALES SOUTH COAST

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ABSTRACT

The southern sector of the New South Wales (N.S.W.) coast, delimited by the extent of the Lachlan Fold Belt and southern portion of the Sydney Basin structural provinces, provides an opportunity to examine estuarine depositional complexes in a number of bedrock controlled valley settings. Sedimentation in these estuaries has progressed since the mid-Holocene under a process regime characterised by a high wave energy shoreface, a micro tidal regime, relatively low fluvial inputs and a relative sea-level stillstand.

A tripartite zonation of estuarine facies is shown to be a consistent feature of estuaries in the study area. The three facies zones are termed: barrier/inlet (Zone A); estuarine lagoon (Zone B), and; tidal fluvial (Zone C). Each zone comprises an assemblage of morphostratigraphic units with distinct sedimentological character interpreted to be intimately linked to the sediment source and the dominant processes operating within the zone.

Zone A sediments, sourced from marine and nearshore environments, are mature quartz dominant sands. Bedforms vary from three-dimensional dunes with negligible bioturbation near the estuary mouth, to two-dimensional moderately bioturbated dunes in the medial portion of Zone A, to intensely bioturbated incipient dunes at the landward part of Zone A. These variations are attributed to the landward decrease in tidal range and flow velocity. Zone B sediments are of terrestrial origin and are typically silty to sandy muds deposited in a low energy lagoon. The lagoon floor lacks dune bedforms and sedimentary structures include laminae, wavy beds and abundant burrow traces. Zone C sediments are also sourced from the estuary catchment, but are much coarser. Marked variations in textural properties are observed in both the surface and subsurface; they incorporate muds, silty sands and sandy gravels often with a high amount of organic detritus. Grain size variations and graded beds are interpreted to reflect temporal and spatial fluctuations in the fluvial flow regime. Despite being influenced by tides, Zone C deposits do not display a strong tidal signature.

The sedimentological traits of each zone are found to be common to the two estuaries examined in detail, Wapengo Lagoon and Narrawallee Inlet, the former being partially filled and the latter completely filled. The Narrawallee sequence is

interpreted to represent successive Late Quaternary episodes of sea-level highstand estuarine sedimentation and intervening glacial lowstand fluvial scouring. Amino acid racemization dating suggests a Last Interglacial age for the older Narrawallee deposits. Despite the complexity introduced by multiple filling and scouring in Narrawallee, facies zonation and character is maintained.

The preservation of Last Interglacial deposits in Narrawallee and possibly in Wapengo attests to the high potential for their inclusion in the geologic record. Ancient examples of incised valley estuarine deposits are presented in support of this observation. Further, incised valley deposits have considerable economic value because they incorporate hydrocarbon source rocks juxtaposed to high quality reservoirs with good lateral seals and top seals.

An understanding of the organisation and character of estuarine facies also has applications to environmental management. In this regard, geomorphic, hydrologic and biologic responses to human induced sea-level rise are considered. Those areas of estuaries considered to be most sensitive to disturbance are also identified.

Finally, the tripartite facies zonation in south coast estuaries is summarised as an idealised vertical transgressive sequence for wave-dominated estuaries that have evolved under a protracted period of relative sea-level stillstand.

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DECLARATION OF ORIGINALITY

Except where otherwise stated, the results and concepts presented in this thesis are due solely to the author.

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CHAPTER 1: INTRODUCTION

1.1 DEFINITION AND CLASSIFICATION OF MODERN ESTUARIES

1.1.1 Definitions

Estuaries mark the transition from terrestrial to marine environments and they are characterised by a high degree of spatial and temporal variance in their sedimentological, hydrological, chemical and biological properties (Bird, 1967b; Wolfe and Kjerfve, 1986). Sediment reaches estuaries as bed load, suspended load and dissolved load from the hinterland via rivers, and from the shoreface via tidal inlets. In situ sediment production by estuarine biota also occurs (Bird, 1967b; Caspers, 1967; Bricker and Troup, 1975). The flux of sediment from outside an estuary is not uniform because fluvial and tidal processes vary both within an estuary and over time (Steers, 1967; Dyer, 1973; Bowden, 1980). Similarly, rates of biological production vary according to fluctuating salinity, temperature and turbidity conditions (Rochford, 1951, 1959; Caspers, 1967; Bowden, 1980).

The complex nature of interrelationships between depositional patterns and processes in estuaries is well recognised, and there are numerous published definitions of what constitutes an estuary, yet few definitions capture the complete character of estuaries. This shortcoming may be attributed, in part, to each definition being a reflection of the interests of the particular researcher(s). For example, early definitions attempted to establish the seaward and landward boundaries of estuaries and construct models of their hydrographic character by concentrating upon properties such as salinity, density, circulation patterns and mixing processes (e.g. Rochford, 1951, 1959; Pritchard, 1955, 1967; Fairbridge, 1968). The frequently cited estuary definition of Pritchard (1967) illustrates the initial emphasis on hydrographic properties. Thus,

> *an estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage (Pritchard, 1967: p.3).*

From the sedimentologists viewpoint, however, the Pritchard definition is incomplete because it does not adequately recognise the sedimentary regime of estuaries, nor does it specify the exact nature of the interaction between tidal and fluvial processes. Dissatisfied with a definition based solely on water chemistry and general mixing processes, the geologist Rhodes Fairbridge was prompted to define an estuary as,

> *...an inlet of the sea reaching far into a river valley as far as the upper limit of tidal rise, usually being divisible into three sectors: (a) a marine or lower estuary, in free connection with the open sea; (b) a middle estuary, subject to strong salt and freshwater mixing; and (c) an upper or fluvial estuary, characterised by fresh water but subject to daily tidal action. (Fairbridge, 1980: p.1)*

The Fairbridge definition could be seen as an improvement upon the Pritchard definition, inasmuch that it recognised the existence of three zones, between which tidal and fluvial processes differ, but it did not adequately identify the geomorphic properties of the estuarine deposits within those zones.

The same three salinity zones were recognised by Bird (1967a) in several southeast Australian estuaries. Moreover, Bird extended his observations to include the gross character of sedimentary facies in each zone. The three zones in southeast Australian estuaries include: a tideless, low salinity (0-10 $^{o}/_{oo}$) zone located in the vicinity of river mouths; a central zone that has a small tidal range and low to moderate salinity (5-30 $^{o}/_{oo}$); and, a saline (30-35 $^{o}/_{oo}$) tidal zone at the seaward end of the estuary (Bird, 1967a). The details of the characteristics of deposits within each zone are presented in section 1.2.

The lack of a completely satisfactory geomorphic/geologic definition of estuaries was recognised by Dalrymple and Zaitlin (1989) who proposed the term 'estuarine complex' to represent,

> *...the marine-influenced, lower reach of a river valley, from the headward limit of marine influence (usually the tidal limit), to the major facies break at it's seaward end which separates the valley sediments from normal marine deposits. (Dalrymple and Zaitlin, 1989: p.10).*

The estuarine complex is defined graphically in Figure 1.1. The important aspect of the estuarine complex concept is that it recognises that the seaward and landward boundaries of an estuary defined in terms of water salinity and those defined in terms of facies distribution do not necessarily coincide. For example, in a drowned river valley estuary (see section 1.1.2) the seaward salinity boundary ($30^{o}/_{oo}$) of the estuary can be located either seaward or landward of the outer edge of the sediment body in the estuary mouth, depending on freshwater discharge. Likewise, reversing tidal currents and water level fluctuations influence depositional conditions for a significant distance upstream of the landward limit of saline waters, defined by Pritchard (1967) as $0.01^{o}/_{oo}$ (Fig. 1.1) (Zaitlin, 1987). The estuary complex definition is, therefore, adopted in this study.

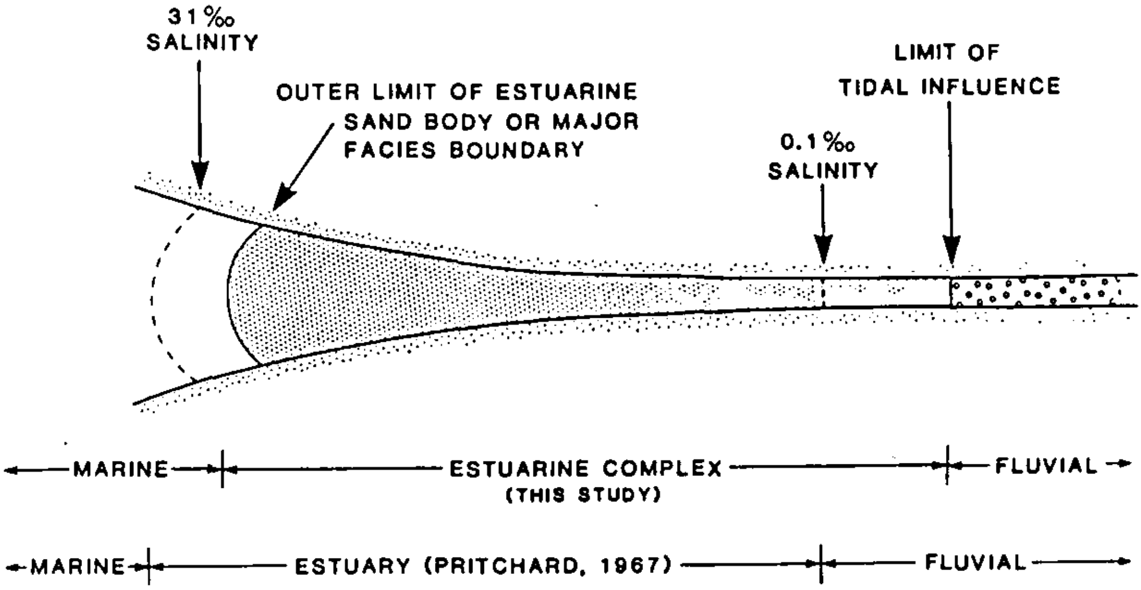


Figure 1.1: Sketch showing the definition of an estuary as defined by Pritchard (1967) and the estuarine complex of Dalrymple and Zaitlin (1989).

1.1.2 Classification

The classic volume, *Estuaries* edited by Lauff (1967), includes several papers that approach the task of estuary classification from geological (Pritchard, 1967), hydrological (Pritchard, 1967; Steers, 1967) and biological (Caspers, 1967) perspectives. Estuary classification schemes now abound in the literature, with a separate scheme for almost every coast along which estuaries have formed. Recent examples include those devised for estuaries along the coasts of New South Wales (N.S.W.) (Roy, 1984a), southwest Western Australia (Hesp, 1984), New Zealand (Hume and Herdendorf, 1986); and, eastern China (Li and Ping, in press). Many of these schemes are variations upon themes introduced by the earlier classifications proposed from observations of estuaries worldwide. A summary of three such classification schemes follows.

One classification, suggested by Pritchard (1967), recognised the general physiographic characteristics of four types of estuaries.

(a) Drowned river valleys. Coastal river valleys incised into a relatively broad, low gradient continental margin and subsequently flooded by the postglacial rise in relative sea-level have resulted in drowned river valley estuaries (Pritchard, 1967). Estuaries along the United States Atlantic coast are good examples of this type of estuary (see Leatherman, 1987). Roy (1984a) classifies the larger estuaries of N.S.W. (e.g. Hawkesbury River) as examples of this type. Estuarine sediments occupy a V-shaped valley that usually extend 30-40 metres below present sea-level and include fluvial and marine deposits that are predominantly intertidal and subtidal, though some systems possess a bay barrier near the estuary mouth.

(b) Fjord estuaries. Glacial scouring of coastal valleys has produced U-shaped estuary valleys that are 300-400m deep. The seaward end of the estuary is typically occupied by a drowned terminal moraine deposit that acts as a coarse grained barrier (Pritchard, 1967). Examples of fjord estuaries exist along the coast of Norway (Pritchard, 1967), western Canada (McCann and Kostaschuk, 1987) and the South Island of New Zealand (Hume and Herdendorf, 1986).

(c) Bar-built estuaries. Barrier-lagoon systems form where a chain of barrier islands or a single barrier/spit anchored at one or both ends to a headland accumulate to above sea-level. Estuaries of this type may exhibit a similar morphology to drowned river valley estuaries to the extent that the inner (landward) portion of the estuary is also a flooded river valley (Pritchard, 1967).

Tidal exchange in bar-built estuaries is significantly less than in drowned valley estuaries because the inlets connecting the lagoon to the ocean act to restrict tidal flows. Examples of bar-built estuaries may be found along many of the temperate coasts of the world, including the eastern sea-board of the United States, southeastern Australia, central China, South Africa and southern Ireland (see chapter three).

(d) Estuaries produced by tectonic processes. The final class of estuary defined by Pritchard (1967) was intended to include estuaries that do not fall into any of the other three types. It includes embayments that exist as a result of faulting or subsidence. San Francisco Bay is cited by Pritchard (1967) as an example. The coastal valleys of the emergent Pacific northwest coast of the United States are also examples of estuaries with a tectonic influence (Peterson, et al., 1983; Clifton et al., 1989).

The second major estuary classification scheme was derived from observations of density gradients that form when saline and fresh waters meet in an estuary (Pritchard, 1955, 1967; Berthois, 1978). Pritchard (1967) suggested a classification scheme based upon the role of tidal, wind and fluvial processes in forcing estuarine circulation. Thus, tide-dominated estuaries are characterised by strong turbulence and mixing of saline with fresh waters to produce a partially stratified estuary (Wright and Sonu, 1975). In wind-dominated estuaries, mixing and circulation is driven by wind generated waves, whereas in river-dominated systems the inflow of fresh water dilutes the wedge of saline water that protrudes into the estuary mouth. The observations of Pritchard were formalised into a three-fold classification by Berthois (1978) and Bowden (1980) as follows:

(a) Salt-wedge estuaries, distinguished by approximately equal tidal and river discharge, resulting in a stratified water body in which denser saline waters form a distinct wedge below the river waters and the only mixing is that related to vertical advection (Bowden, 1980). Density stratification in tidal inlets was observed to cause vertical segregation of strongest flood and ebb currents (Wright and Sonu, 1975). The stronger flood currents occur near the bed and ebb currents are concentrated in the upper layers. Because the majority of sediment transport is in the form of bedload, the net sediment flux in stratified inlets is in a flood (landward) direction.

(b) Partially mixed estuaries, in which tidal discharge is an order of magnitude greater than fluvial discharge and there is a significant degree of mixing and diffusion resulting in break up of stratified flow and the creation of a vertical salinity gradient; and,

(c) Well-mixed estuaries, characterised by an indistinct vertical salinity gradient resulting from a tidal discharge that is two orders of magnitude larger than river discharge (Pritchard, 1955; Berthois, 1978; Bowden, 1980).

It is possible to classify estuaries further in terms of absolute tidal range (Davies, 1964; Hayes, 1975, 1979). Three tidal regimes are recognised: microtidal (0-2m); mesotidal (2-4m); and, macrotidal (>4m) (Davies, 1964). These categories were initially intended to apply to tidal conditions along the open coast but they have also been applied to barrier-lagoon systems by Hayes (1975, 1979), and is the third of the estuary classification schemes. It is possibly the most significant scheme for the geomorphologist because each tidal regime is associated with a distinct estuarine morphological character (Hayes, 1975, 1979). The morphological contrasts are most evident at the seaward (outer) portion of an estuary because the majority of tidal and wave energy is expended in that zone.

Along microtidal coasts, outer estuarine deposits are primarily the product of wave action. That is, on a coast that has a small tidal range and a highly energetic wave climate, the seaward portion of estuaries consists of: a wave built barrier/spit complex that often stretches across the whole embayment and is oriented normal to the prevailing wave approach; infrequent tidal inlets (usually one only) that are generally stable; extensive flood-tidal delta and storm washover deposits; and, a small to negligible ebb-tidal delta (Hayes, 1979). Excellent examples of estuaries with these characteristics occur along the coast of southeast Australia, where the spring tidal range is 1.6m and the modal wave height between 2.0 and 2.5m (Wright et al., 1980).

Mesotidal coasts display characteristics that are consistent with increased tidal energy (mean range= 2-4m) and decreased wave energy (modal wave height= 0.6-1.5m) relative to microtidal coasts. The seaward zone of estuaries consists of: stunted "drumstick" shore parallel barriers; numerous migrating tidal inlets; minor to moderate flood-tidal delta and washover deposits; and, large ebb-tidal deltas. The barrier-lagoon coast of central to southern U.S.A. is a good example of mesotidal estuaries of this type (Hayes, 1979).

Macrotidal shorelines represent the extreme end of the spectrum and are characterised by almost complete dominance by tidal processes with little morphologial evidence of wave action. The seaward portion of macrotidal estuaries is not occupied by a barrier island complex. Instead, sand bars and subtidal sand ridges, oriented approximately parallel with the funnel shaped estuary shore, are the morphological expression of tide dominance (Hayes, 1979; Dalrymple and Zaitlin, 1989). Macrotidal estuarine deposits of this type have been documented from the Ord River, Western Australia (Wright et al., 1973, 1975), the South Alligator River, Northern Territory (Woodroffe et al., 1985a, 1985b) and the Bay of Fundy, Nova Scotia (Knight, 1980; Dalrymple et al. 1990).

It is evident from the above discussion that efforts to understand and distil the complexity of estuarine environments have resulted in a variety of definitions and attendant classification schemes for estuaries, each one based upon the parameters that were of major concern to the individual researcher(s). While any definition and classification may appear limited in terms of applications to other areas of estuarine research, the information contained within each definition is essential for a complete understanding of estuarine character. In particular, an appreciation of hydrodynamic processes (salinity, circulation, mixing, tides, waves) is critical because, as shown in the following section, those same processes have a very important influence on estuarine depositional patterns (Hayes, 1979).

1.2 TRIPARTITE FACIES ZONATION IN ESTUARIES AND THE CONCEPT OF ESTUARY END-MEMBERS

A characteristic that appears to be common to all estuaries is the existence of three distinct facies zones. In terms of estuarine hydrology, the tripartite zonation pattern has long been recognised (Rochford, 1951, 1959; Dionne, 1963). However, the presence of a complementary zonation of sediment types was not clearly identified until Bird (1967a) examined the microtidal estuaries along the wave-dominated coast of southeastern Australia.

According to Bird (1967a), each zone occupies a specific area within an estuary, displays a distinct geomorphic character and is influenced by a particular depositional process. The zones were described by Bird (1967a) as: (a) a saline tidal zone near the estuary mouth in which marine sands are deposited; (b) a central zone with a small tidal range and moderate salinity that is characterised by fine-grained sediment delivered by rivers and produced in situ (i.e. organic detritus); and (c) a tideless low salinity zone located near the river mouth in which fluvial sands and silts accumulate. There did not appear to be any significant mixing of marine and fluvial sediment in the estuaries examined by Bird (1967a,b). Therefore, the seaward zone was dominated by marine sediment and the tideless zone by fluvial sediment. Carbonaceous sediment was also identified, but it is produced primarily in situ by estuarine organisms and was assessed to be of relatively minor importance (Bird, 1967a,b). In addition, it was noted that the area of each zone varied between estuaries as a function of the shape and dimensions of the estuary, river discharge, and volume of tidal exchange.

One intention of this study is to document the organisation of facies in individual estuarine systems along the N.S.W. south coast. To that end, it is necessary to define a set of geomorphic features common to all systems. The morphostratigraphic unit of Frye and Willman (1962) is, therefore, adopted as the basic mapping unit. A morphostratigraphic unit is defined as,

> *a body of rock that is identified primarily from the surface it displays: it may or may not be distinctive lithologically from contiguous units; it may or may not transgress time throughout its extent. (Frye and Willman, 1962:p.112).*

For this study, a suite of 13 morphostratigraphic units were defined from aerial photographs of south coast estuaries. Definitions of these units are presented in Table 1.1.

FACIES ZONE AND DOMINANT LITHOLOGY	MORPHOSTRATIGRAPHIC UNIT
ZONE A Quartzose sands	*Barrier Spit: "A barrier island or barrier beach that is connected at one end to the mainland" and here represents the most seaward portion of palaeovalley fill. *Back-barrier Flat: "A relatively flat area, often occupied by pools of water, separating the exposed or seaward edge of a barrier from the lagoon behind it" This unit may derive from either storm washover or be a relict flood-tidal delta. *Flood-tidal Delta: "A delta formed at the mouth of a tidal inlet on the...lagoon side of a barrier island or baymouth bar by...tidal currents that sweep sand in the inlet" *Tidal Channel: "A major channel followed by the tidal currents, extending...landward...into a tidal marsh or tidal flat", or flood-tidal delta. *Beach-ridge Plain: "A low, essentially continuous mound of beach or beach-and-dune material...on the backshore of a beach beyond the present limit of storm waves or the reach of ordinary tides, and occurring singly or as one of a series of approximately parallel deposits...roughly parallel to the shoreline."
ZONE B Muds and sandy muds	*Barrier Basin: "A basin produced by the formation of a...[bay-mouth] barrier." *Supratidal Shoreline: "Pertaining to the shore area marginal to the littoral zone, just above high tide level" Taken here to include deposits occurring adjacent to and above the barrier basin shoreline and resulting from wind-driven wave reworking of basin sediments. *Intertidal Shoreline: "Pertaining to the...depth zone between high water and low water", and here refers to deposits adjacent to and below the barrier basin shoreline. Also the product of wave reworking.
ZONE C Silty sands and gravels	*Supratidal Fluvial Delta : "The low, nearly flat alluvial tract of land at or near the mouth of a river..." here taken to include the extension of land beyond the general trend of the basin shoreline. *Intertidal Fluvial Delta: The subaqueous extension of the supratidal portion of a fluvial delta, often present as a subaqueous levee. *Fluvial Channel: "The bed where a natural body of surface water flows...", and here includes medial channel bar deposits. *Point Bar: "low, arcuate ridge of sand and gravel developed on the inside of a growing meander" and attached to the convex side of a fluvial channel. Commonly unvegetated. *Floodplain: "The surface or strip of relatively smooth land adjacent to a river channel...", and here includes levee ridges and overbank depression deposits. The floodplain boundary is defined by the abrupt break in slope at the contact with bedrock. This boundary also defines the pre-transgression palaeovalley.

Table 1.1: Definitions of estuarine morphostratigraphic units (source: Bates and Jackson, 1980).

Morphostratigraphic units from within the same zone are distinguished by their respective surface morphology, location and lithologic characteristics, including sediment texture, sedimentary structures and gross mineralogy. The tripartite character of N.S.W. estuaries is apparent when the morphostratigraphic units are grouped according to general environments of deposition and lithofacies as follows:

> Zone A extends landward from the estuary mouth and comprises those units associated with barrier and tidal inlet sedimentary processes and features a well sorted sandy lithofacies. Morphostratigraphic units include barrier spit, backbarrier flat, flood-tidal delta, tidal channel and beach-ridge plain.
>
> Zone B, defines the central portion of the estuary and consists of units related to low energy lagoonal depositional conditions with a mud to silty mud lithofacies. Morphostratigraphic units include barrier basin, supratidal and intertidal shoreline.
>
> Zone C, positioned at the landward end of a system, represents an assemblage of units resulting from tidally-influenced fluvial processes characterised by a moderately to poorly sorted silty muds, silty sand and gravel lithofacies. Morphostratigraphic units include supratidal and intertidal fluvial delta, fluvial channel, point bar and floodplain.

The tripartite zonation appears to be applicable to a range of estuary types and, in recent years, has been specifically recognised in both modern and ancient deposits. Modern examples include: Gippsland Lakes in Victoria (Bird, 1967a, 1978); Mallacoota Inlet, Victoria (Reinson, 1973, 1977); all N.S.W. estuaries (Roy et al., 1980; Roy, 1984a); the microtidal James estuary in Virginia (Nichols et al., 1989); the inner portion of the macrotidal Bay of Fundy (Dalrymple and Zaitlin, 1985); and, the macrotidal Gironde estuary in western France (Allen, 1989). Ancient examples include: the Lloydminster member of the lower Cretaceous Senlac heavy oil pool, Saskatchewan (Zaitlin and Shultz, 1984, 1990); the late Cretaceous Horseshoe Canyon Formation, Alberta, (Rahmani, 1988); and, the Crystal field of the lower Cretaceous Viking Formation, Alberta (Reinson et al., 1988). That the tripartite zonation has been recognised in such a variety of modern and ancient deposits suggests that the pattern is independent of the local process conditions and geological settings.

The spatial distribution and geometry of facies in coastal environments is often explained in terms of the association between coastal morphology and relative dominance of waves, tides or rivers (Davies, 1964, 1980; Galloway, 1975; Hayes, 1975, 1979; Heward, 1981; Davis and Hayes, 1984). The concept of relative dominance of a depositional process has recently been extended to explain differences in the morphology of estuarine complexes (Dalrymple and Zaitlin, 1989). A summary model describing the facies organisation and geometry in estuaries along wave-dominated and tide-dominated coasts is offered by Dalrymple and Zaitlin (1989). The model identifies a spectrum of estuary types with the end-members of the spectrum defined as wave-dominated and tide-dominated estuaries (Fig. 1.2). It is important to stress that dominance of one process does not imply complete exclusion of the other. River-dominated coasts display a deltaic depositional morphology and therefore are considered not to be part of the estuary spectrum (Galloway, 1975). Both estuary end-members exhibit a tripartite facies organisation, yet important differences exist in the morphological and architectural character of the facies zones between wave-dominated and tide-dominated systems.

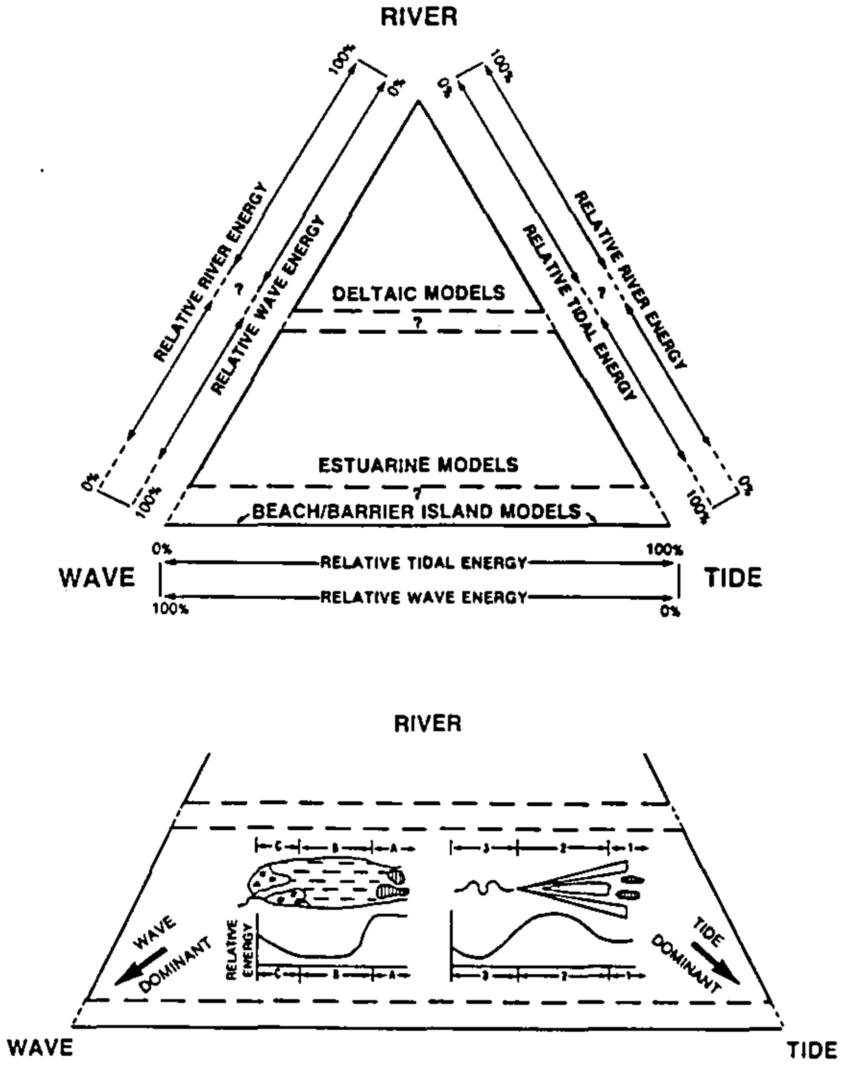
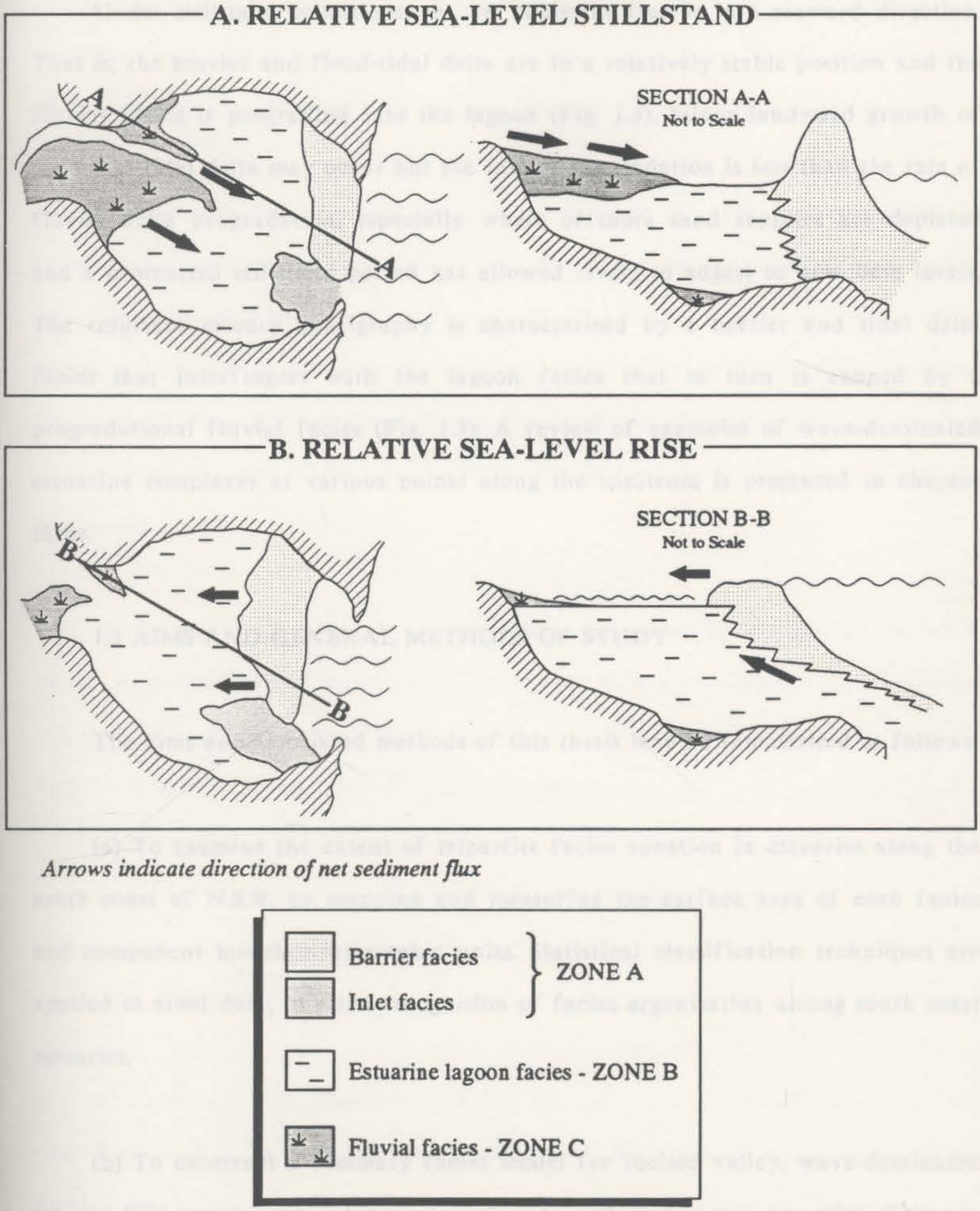


Figure 1.2: Conceptual diagram showing (a) the relationship between relative process energy and coastal depositional environments and, (b) the generalised facies morphology in wave-dominated and tide-dominated estuaries, and longitudinal variations in total relative energy (reproduced from Dalrymple and Zaitlin, 1989).

Tide-dominated estuaries are characterised by a funnel shaped plan-form with an outer zone (Zone 1) of elongate tidal sand bars, a central zone (Zone 2) of braided upper flow regime sand flats that reflect the increase in tidal current energy that occurs within the zone, and an inner zone (Zone 3) of fluvial deposits that are associated with a channel that changes from a straight to meandering to straight morphology in an upstream direction (Fig. 1.2) (Dalrymple and Zaitlin, 1989). The morphology of tide-dominated estuaries is interpreted by Dalrymple and Zaitlin (1989) to result from the interaction of landward weakening tidal currents and seaward weakening fluvial currents. Examples of estuaries displaying these traits include the Ord River (Wright et al., 1973, 1975), the South Alligator River (Woodroffe et al., 1985a, 1985b), the inner portion of the Bay of Fundy (Knight, 1980; Dalrymple et al. 1990), and the Gironde estuary (Allen, 1989).

The status of relative sea-level along a coast is also an important control upon estuarine depositional morphologies. It is proposed here that sea-level adds an additional dimension to the spectrum of estuary types. The end-members are defined as rapid transgressive and long term stillstand coasts. Between these end-points the spectrum is occupied by coasts experiencing differing rates of sea-level rise. Regressive coasts are not included in the spectrum because when sea-level falls estuaries are stranded and the coast assumes the character of a river-dominated system.

Along wave-dominated coasts, a rising sea will result in a net sediment flux in a landward direction (Fig. 1.3). That is, the barrier-lagoon complex is continually adjusting by migrating landward. Consequently, the stratigraphy of an estuary along a transgressive coast will record the migration of the coarse barrier facies over the fine-grained lagoon facies. The rate of barrier migration and completeness of barrier reworking is dependent upon the rate of sea-level rise (Fig. 1.3).



Arrows indicate direction of net sediment flux

Figure 1.3: Sketch showing the generalised plan-form appearance and stratigraphy of facies zones A, B, C in wave-dominated estuaries under stillstand and transgressive sea-level conditions.

Under stillstand conditions, the net sediment flux is in a seaward direction. That is, the barrier and flood-tidal delta are in a relatively stable position and the fluvial facies is prograding into the lagoon (Fig. 1.3). Minor landward growth of the flood-tidal delta may occur but the rate of progradation is less than the rate of fluvial delta progradation, especially where offshore sand supplies are depleted and a protracted stillstand period has allowed rivers to adjust to new base levels. The resultant estuary stratigraphy is characterised by a barrier and tidal delta facies that interfingers with the lagoon facies that in turn is capped by a progradational fluvial facies (Fig. 1.3). A review of examples of wave-dominated estuarine complexes at various points along the spectrum is presented in chapter three.

1.3 AIMS AND GENERAL METHODS OF STUDY

The aims and associated methods of this thesis may be summarised as follows:

(a) To examine the extent of tripartite facies zonation in estuaries along the south coast of N.S.W. by mapping and measuring the surface area of each facies and component morphostratigraphic units. Statistical classification techniques are applied to areal data, to assist recognition of facies organisation among south coast estuaries.

(b) To construct a summary facies model for incised valley, wave-dominated estuary fills based upon sedimentological data collected in two estuaries, Wapengo Lagoon and Narrawallee Inlet (Fig. 1.4). Sedimentological data are analysed with a view toward assessing intra and inter zone variability as well as to establish relationships between depositional processes and sedimentological character. Both surface and subsurface data are considered, thereby enabling description of the present-day sediment units and those formed in the past. Detailed coring and drilling in the two sampling sites provide the bulk of the sedimentological data.

(c) To assess the long term preservation potential of each estuarine facies by considering likely responses to fluctuations in relative sea level, and comparing the characteristics of modern and relict deposits with those of ancient incised valley estuarine deposits. In addition, the economic value of estuarine deposits is assessed in terms of the potential for hydrocarbon reservoir and source rock formation. Comparisons between modern and ancient deposits are again made to facilitate the assessment.

(d) To assess the relevance of geomorphic/ sedimentologic estuarine studies to issues of environmental management. Particular emphasis is placed upon utilising facies models to assist in the prediction of responses/adjustments of estuarine systems to sea-level rise and human disturbance.

1.4 STUDY AREA AND FIELD SAMPLING SITES

1.4.1 Study area

The research area encompasses a 250 km section of the N.S.W. coast (Fig. 1.4) that is defined by the limits of the Lachlan Fold Belt and the southern tip of the Sydney Basin structural provinces. The south coast was selected because of the relative uniformity of the dimensions and geology of estuary valleys and their catchments. Coastal embayments are relatively small and narrow, and are fed by small rivers that drain catchments of high relief. This is in contrast to estuaries of the central and northern N.S.W. coast where the geologic and topographic setting provides for considerable variation in embayment size and configuration, catchment relief and river size (Chapman et al., 1982; Roy et al., 1980).

The Lachlan Fold Belt is dominated by Ordovician metasediments into which 55 coastal valleys have been incised. The 13 valleys of the southern Sydney Basin occur in Permian sandstones. All 68 valleys were flooded during the postglacial marine transgression (PMT) and are now occupied by varying amounts of estuarine deposits. In the context of the estuary classification for the N.S.W. coast put forward by Roy (1984a), the south coast systems include bay-mouth barriers and saline coastal lakes (see chapter three).

Depositional conditions are controlled by: a wave dominated shoreface; microtidal regime; relatively low fluvial input (Roy et al., 1980; Roy and Thom, 1981); and, sea-level stillstand since approximately 6500 yrs BP (Thom and Roy, 1983). In addition, the southeastern Australian coast occupies a passive continental margin and is, therefore, tectonically stable (Nakada and Lambeck, 1989). Collectively, these conditions provide a unique process setting for the study of estuarine sedimentation that is not adequately represented in the literature. Of particular importance is the relative stability of sea-level, since previous investigations of incised valley, wave-dominated estuaries have concentrated on actively transgressing shorelines, notably the Atlantic coast of North America (eg: Kraft, 1971; Armon, 1979; Kraft et al., 1979, 1987; Boyd et al., 1987; Carter et al., 1989b; Fletcher et al., 1990).

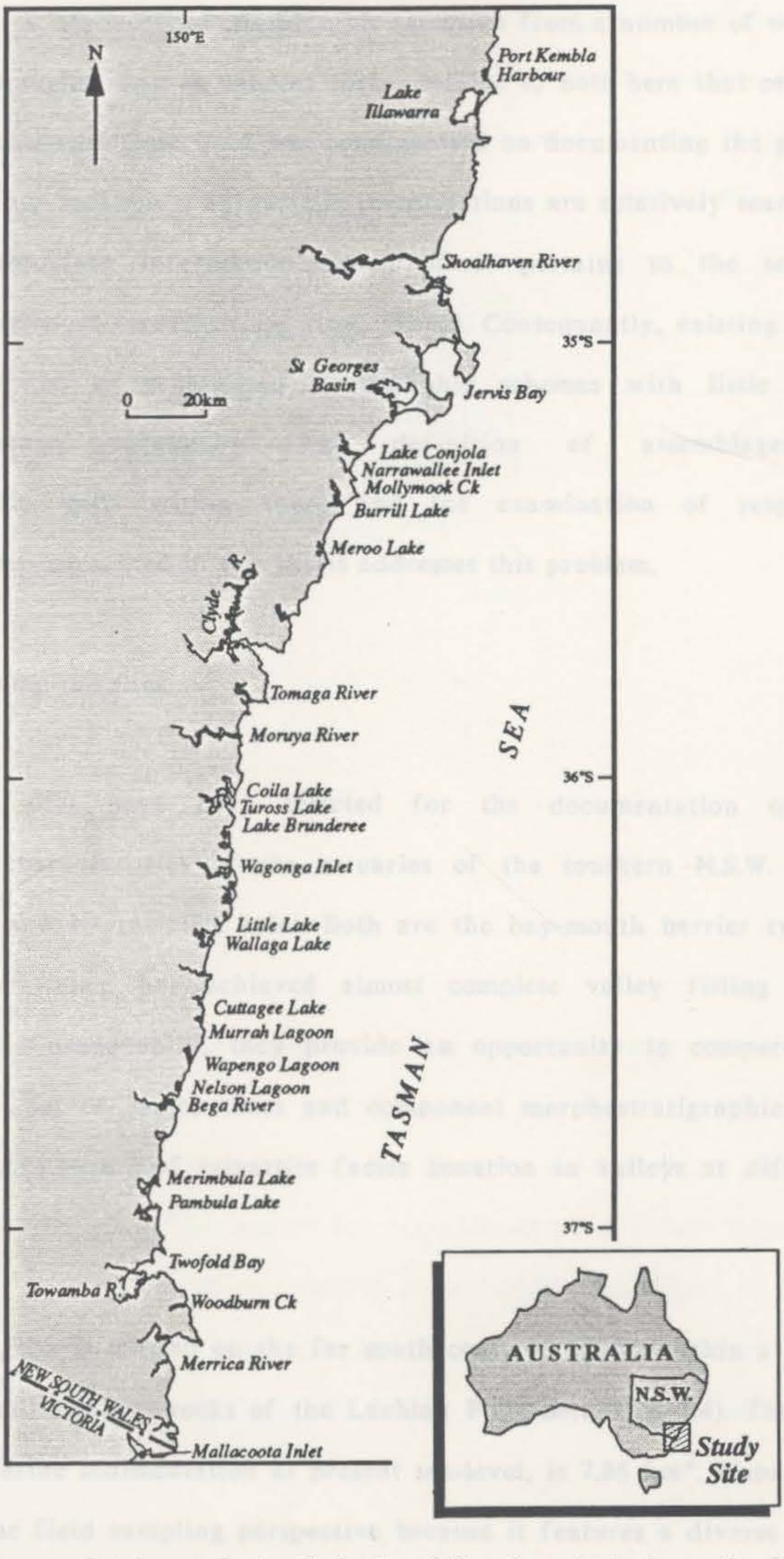


Figure 1.4: Location map of study area, showing the location of all south coast estuaries mentioned in the thesis.

The study area has received considerable attention from a number of workers and their work is summarised in chapter three. Suffice to note here that previous geomorphic and sedimentologic work has concentrated on documenting the general properties of surface sediments. Subsurface investigations are relatively scarce. Of the available subsurface information, much of it pertains to the seaward (barrier/inlet) portion of estuaries (e.g. Roy, 1984b). Consequently, existing facies models are restricted to generalised stratigraphic schemes with little detail regarding intrazone variability. The definition of assemblages of morphostratigraphic units within zones and the examination of respective sedimentologic traits presented in this thesis addresses this problem.

1.4.2 Field sampling sites

Two study sites have been selected for the documentation of the sedimentological characteristics of the estuaries of the southern N.S.W. coast, Wapengo Lagoon and Narrawallee Inlet. Both are the bay-mouth barrier type of estuary, yet Narrawallee has achieved almost complete valley filling while Wapengo has not. Consequently, they provide an opportunity to compare and contrast the character of facies zones and component morphostratigraphic units and to test for consistency of tripartite facies zonation in valleys at different stages of infill.

Wapengo Lagoon is located on the far south coast of N.S.W. within a valley incised into metasedimentary rocks of the Lachlan Fold Belt (Fig. 1.4). The area available for estuarine sedimentation at present sea-level, is 7.86 km^2. Wapengo is appealing from the field sampling perspective because it features a diverse array of morphostratigraphic units that are readily observable at the surface. The estuary is permanently open to the sea and is tidal to within three kilometres of the head of the floodplain. Only Zones A and C have well defined tidal channels, which terminate at the edge of the Zone B. The intermediate zone (B) is a broad flat bottom basin, but is able to convey tidal waters between Zones A and C (Fig. 1.5).

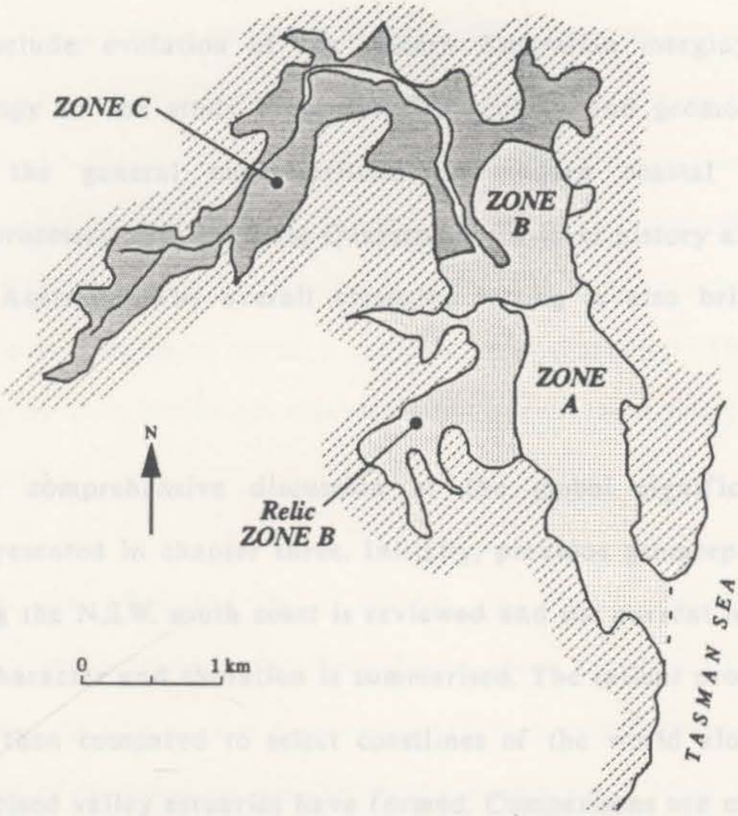


Figure 1.5: Generalised map of Wapengo Lagoon showing facies zones A, B, C.

Narrawallee Inlet occupies a valley cut into Permian sandstone and siltstone of the Sydney Basin (Fig. 1.4). The estuary has experienced a significant degree of valley filling, thereby providing an opportunity to investigate the nature of facies organisation in a complete valley sequence. The inlet is permanently open to the tidal exchange with Croobyar and Currowar Creeks tidal almost to the landward limit of the floodplain.

1.5 STRUCTURE OF THE THESIS

Following this introduction, chapter two presents additional background information related to the physical setting of the N.S.W. south coast. Factors considered include: evolution of the eastern Australian margin; structural and regional geology of the study area; detailed geology and geomorphology of the study sites; the general characteristics of modern coastal and hinterland depositional processes; and, the Late Quaternary sea-level history along the coast of southeastern Australia. The overall estuarine setting is also briefly assessed in global terms.

A more comprehensive discussion of the global significance of N.S.W. estuaries is presented in chapter three. Initially, previous geomorphic and geologic research along the N.S.W. south coast is reviewed and the current level of estuarine and barrier character and evolution is summarised. The salient properties of N.S.W. estuaries are then compared to select coastlines of the world along which wave-dominated incised valley estuaries have formed. Comparisons are made with regard to general depositional process conditions (waves, tides, fluvial discharge), relative sea-level history and resultant morphostratigraphic character of barrier-lagoon complexes. It is subsequently argued that the N.S.W. coast represents a unique type of estuarine setting that is not adequately represented in the literature.

Chapter four outlines the methods employed for this thesis. First, the strategy devised for estuary mapping and generation of morphometric data is explained. Second, the statisitical procedures used to objectively analyse morphometric data and classify individual estuaries are described. Third, field sampling methods are briefly described and sample locations are given. Finally, laboratory analytical methods are described.

Chapter five is the first of four results chapters. The subject of the chapter is the outcome of the statistical analysis of estuarine morphometric data. Specifically, this involves development of an objective regional classification scheme for south coast estuaries. Furthermore, the significance of the classification is assessed in terms of the contribution it makes toward an improved understanding of modes and rates of estuary filling. In relation to the question of estuary filling, a brief analysis of the properties of estuary catchments is presented. The focus is upon variables ranging from catchment size and slope gradients to relative erodibility of bedrock and soils.

Chapters six through eight present systematic descriptions of the sedimentological properties of the three facies zones (A, B, C) in the two main study sites, Wapengo Lagoon and Narrawallee Inlet. Supplementary data from other estuaries, collected by previous workers is also drawn upon. Prior to describing the sediments in each zone, the character of depositional processes operating within that zone are described. This allows the traits observed within the morphostratigraphic units of each zone to be placed in a process context.

The Late Quatenary evolution of Wapengo Lagoon and Narrawallee Inlet are described in the first section of chapter nine. As well as using chrono-stratigraphic information to construct an evolutionary history, the morphometric characteristics of estuaries are employed as an indicator of the relative stage of evolution achieved by estuaries.

The final substantive chapter addresses the questions related to the applicability of modern estuarine studies to the interpretation of ancient deposits and to assisting resolve environmental problems. In the first regard, the long-term preservation potential of each estuarine facies zone is assessed. The economic potential of each facies is also considered, with particular reference to hydrocarbon source rocks and reservoir rocks. In the second regard, the value of geomorphic models of the type put forward here is assessed in terms of usefulness as a management tool for predicting likely responses to phenomena such as sea-level rise and human disturbance.

Finally, chapter eleven offers a summary of the thesis findings. Sedimentological data are then drawn together in the form of a summary facies model for wave-dominated incised valley estuaries and concluding remarks regarding directions for future work are made.

CHAPTER 2: PHYSICAL SETTING OF STUDY AREA

2.1 INTRODUCTION

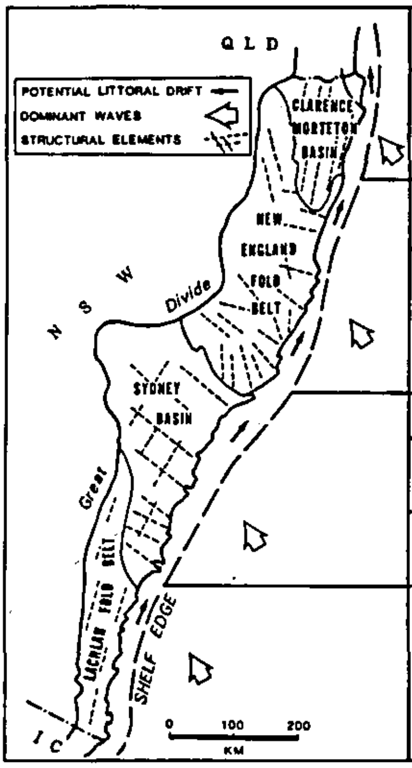
The objective of this chapter is to describe the physical character of the south coast of N.S.W. Aspects of the physical setting to be discussed include: (i) regional geology, incorporating structural and tectonic character as well as lithology; (ii) general geomorphological properties of the coastal fringe; (iii) the primary processes influencing estuarine evolution, including meteorologic climate, wave climate, tidal regime and the fluvial regime; and, (iv) the history of Quaternary sea-level change along the southeast Australian coast. By way of a chapter summary, the physical setting for N.S.W. estuaries is placed in a global context and the relative significance of the setting is briefly assessed.

2.2 REGIONAL GEOLOGY

2.2.1 Structural character, evolution and tectonic setting of the southeast Australian margin

The southeast coast of Australia intersects four major structural units that constitute the Tasman Geosyncline, including, from north to south: Clarence-Moreton Basin; New England Fold Belt; Sydney Basin; and Lachlan Fold Belt (Fig. 2.1). The association between these units is such that deposition in the two sedimentary basins postdated the formation of the fold belts (Packham, 1969). The Lachlan and New England Fold Belts derive from marine and non-marine depositional episodes. In the case of the Lachlan Fold Belt, deposition took place from the late Cambrian to early Carboniferous, and for the New England Fold

Belt deposition occurred between the Silurian and Permian (Packham, 1969). The Sydney and Clarence-Morton Basins are Permian to Jurassic in age and formed as fore deep and intra deep depositional sinks to the New England Fold Belt (McElroy et al., 1969; Packham, 1969; Chapman et al., 1982).



GEOLOGY	STRUCTURAL ELEMENTS	COAST RELIEF	RIVER SIZE	COASTAL EMBAYMENT TYPE
SOFT MESOZOIC SEDIMENT	PARALLEL TO COASTLINE ORIENTATION	LOW	VERY LARGE	LARGE AND BROARD
HARD PALAEOZOIC METAMORPHIC	TRANSVERSE TO COASTLINE ORIENTATION	MODERATE	VERY SMALL	SMALL AND NARROW
MODERATELY HARD PALAEOZOIC METAMORPHIC			MEDIUM	MODERATELY LARGE AND BROARD
SOFT TRIASSIC & PERMIAN		LOW	LARGE	LARGE NARROW INCISED VALLEYS PLUS LARGE TO SMALL ESTUARIES
JOINTED HARD HAWKESBURY SANDSTONE		MODERATE (PLATEAU)		
SOFT TRIASSIC & PERMIAN		LOW TO MODERATE	MEDIUM TO SMALL	
HARD PALAEOZOIC METAMORPHIC AND IGNEOUS	PARALLEL TO COASTLINE ORIENTATION	HIGH	SMALL	SMALL AND NARROW

Figure 2.1: Map showing the limits of the four structural units that consitute the N.S.W. coast eastward of the Great Dividing Range. The accompanying table summarises the geological, structural, topographic and embayment character of each unit. (reproduced from Roy and Thom, 1981).

Deposition was accompanied by a period of virtually continuous orogenic activity commencing at the end of the Ordovician and lasting until the Early Mesozoic (Packham, 1969). As a result, the deposits of the Lachlan and New

England Fold Belts are intensely deformed, whereas the younger sedimentary basin deposits are only moderately deformed (Bishop, 1988). All four structural units now occupy the eastern highland belt that extends the length of the eastern margin of the Australian continent. As shown in the discussion below, the mode and age of highlands uplift remains unclear.

After the major structural provinces had formed, rifting and sea floor spreading took place to establish the basic form of the continental margin and open up the Tasman Sea. Rifting was relatively rapid, beginning in the late Cretaceous (c.80 Ma ago) and ceasing by the the late Palaeocene (c.60 Ma ago) (Hayes and Ringis, 1973; Weissel and Hayes, 1977; Mutter and Jongsma, 1978; Shaw, 1978). The relative paucity of sediment along the N.S.W. continental margin and the narrow (<60 km), steep (>20^{o}) morphology of the margin is attributed by Shaw (1978) to the non-axial style of sea floor spreading in the north Tasman Sea. Reconstructions of the process of Tasman Sea widening identify numerous right lateral transform faults intersecting and offsetting the spreading ridge (Weissel and Hayes, 1977; Jongsma and Mutter, 1978; Mutter and Jongsma, 1978) . These faults prevented the formation of (and deposition within) rift valleys along the southeast Australian margin, as is normally associated with spreading sea floors (Jongsma and Mutter, 1978; Shaw, 1978). The Lord Howe Rise in the Tasman Sea contains all the prebreakup rift valley deposits (Jongsma and Mutter, 1978).

The age and style of uplift of the eastern highlands has long been a contentious issue, with debate dating back to early this century (e.g. Andrews, 1911; Craft, 1933; King, 1959; Browne, 1969; Hills, 1975; Wellman, 1979). A succinct review of the history of research related to the evolution of the eastern highlands is presented by Bishop (1988). Three models of highland evolution are described by Bishop (1988).

The first model, advocated by Lambeck and Stephenson (1986), involves slow and gradual erosion of a tectonically stable ancestral highland since Early Mesozoic times. The model requires that isostatic uplift occurred in conjunction with the erosion, thereby providing a mechanism for the existence of a highland belt sufficiently elevated to allow slow erosion rates to persist for a long period (Bishop, 1988). Further, isostatic uplift allows for the significant river incision that characterises the present highland topography.

The second evolutionary model, developed by Wellman (1979, 1987) argues from an analysis of ancient river beds preserved below basalt flows that uplift has been continuous since early Cretaceous times (90+/-30 Ma ago). The ancient fluvial deposits are preserved at elevations well above present river levels, which Wellman (1979) concludes is evidence for incision associated with dynamic uplift. Wellman (1979) invokes the continental breakup of Australia from New Zealand as an appropriate driving force for uplift. Certainly, the breakup period (80-60 Ma ago) and presumed preceding thermal doming coincides with Wellman's (1979) age estimate of uplift. However, the link between the opening of the Tasman Sea involving prerifting uplift and the evolution of the highlands has since been questioned (Bishop, 1988).

The third highland evolutionary model involves passive *subsidence* of the Mesozoic highlands, overprinted by periods of uplift during the Cainozoic (Jones and Veevers, 1982, 1983). The model employs highlands vulcanism and changes in rates of sediment supply to adjacent basins as indicators of a change from an active tectonic regime to a comparatively quiescent regime 95-90 Ma ago. Jones and Veevers (1982) suggest that since the beginning of the Cainozoic the highlands have subsided and sediment supply to flanking basins has been low. Subsidence has been interrupted by brief uplift periods during which basalt extruded onto the highland surface, the flanking basins subsided and sediment supply to the basins increased (Jones and Veevers, 1982). Bishop (1988) notes that the proponents of this model do not identify a driving mechanism for the short uplift periods and associated vulcanism. Several workers (e.g. Lister et al., 1986; Wellman, 1987) have attempted to link uplift and highlands vulcanism with Tasman Sea formation via such mechanisms as crustal heating and underplating, but the relationship is still far from clear (Bishop, 1988).

From this brief outline of eastern highland models it is clear that the issue of the mode of highland evolution remains unclear. A specific age has not been agreed upon, as shown by the two schools of thought, one arguing for an ancient (older than Late Mesozoic) uplift age (Lambeck and Stephenson, 1986; Jones and Veevers, 1982, 1983), the other for more recent (Late Mesozoic to Cainozoic) dynamic uplift (Wellman, 1979, 1987). Notwithstanding, it is apparent from the literature that most workers concur that the highlands are of great antiquity.

With regard to the tectonic setting of southeast Australia, Bishop (1988) makes the point that the eastern highlands appear to be unrelated to the present plate margin. The southeast margin of the continent is now distally situated relative to the boundary between the Indo-Australia plate and the West Pacific plate, which intersects the east coast of New Zealand (Berryman, 1987) (Fig. 2.2). Consequently, the highlands are remote from the plate tectonic processes that operate at convergence zones. Furthermore, intra-plate movement between the oceanic and continental crusts of the Indo-Australian plate is thought to be negligible (Nakada and Lambeck, 1989).

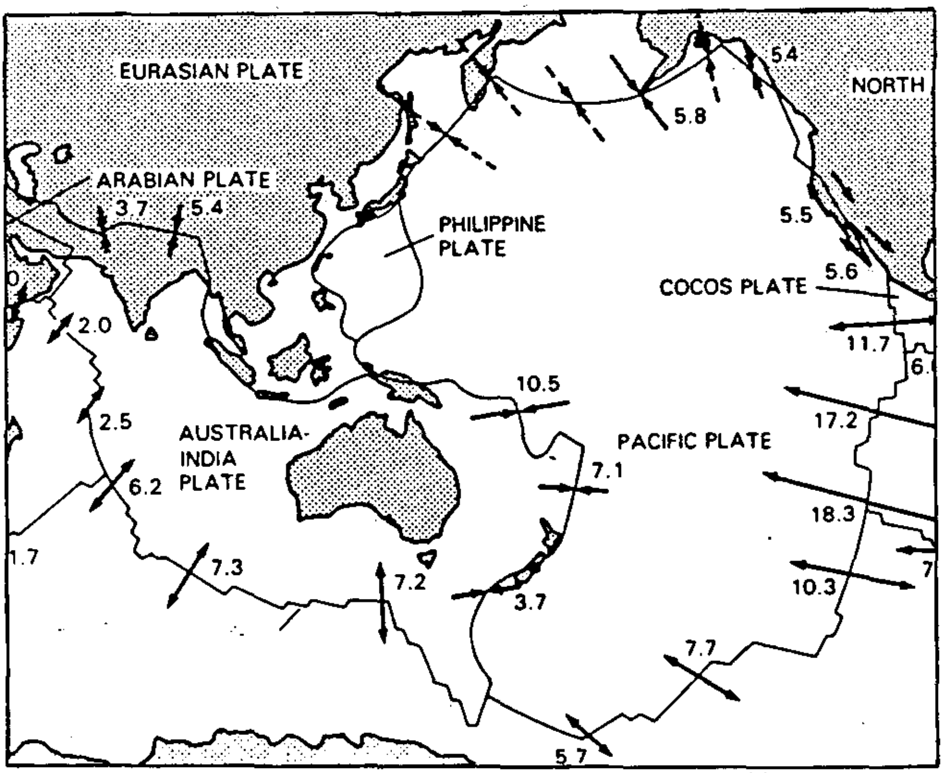


Figure 2.2: Map showing the location of the eastern Australian coast relative to the boundary between the Indo-Australian plate and Pacific plate. Numbers indicate the relative velocity of plate movement (cm/yr) and arrows show direction of movement. (reproduced from Berryman, 1987).

In terms of the present study, the salient point to be drawn from the highland landscape models is that the present topography and drainage systems of the coast and hinterland are very old, tectonically stable and most certainly were well established before the Quaternary period.

2.2.2 Lithologic characteristics of the Lachlan Fold Belt and southern Sydney Basin

The study area on the N.S.W. south coast lies within the Lachlan Fold Belt and the southern portion of the Sydney Basin. The boundary between the two structural units occurs near Durras Lake (Fig. 2.3). With regard to the stratigraphic relationship between the two units, the Permian Sydney Basin rocks lie disconformably over the Ordovician Lachlan Fold Belt rocks and the basement strata are often exposed in creek beds within coastal catchments (Rose, 1976; Hickey, 1978). Lithologically, the two structural provinces are diverse.

The coastal zone of the Lachlan Fold Belt is made up primarily of Ordovician metasedimentary (quartz rich greywacke, slate and cherts) and Devonian intrusive (granite) rocks (Packham, 1969). Coastal outcrops of Ordovician beds are confined to the section of coast north of the Bega River. South of the Bega River, Devonian rocks are the most common outcrop (Fig. 2.3). Metamorphism was caused by a series of orogenic episodes, notably the Benambran (early to middle Silurian), Bowning (early Devonian), and the Tabberabberan (mid-Devonian) (Cas, 1983). Consequently, the Lachlan Fold Belt is the most structurally complex and intensely folded of the four N.S.W. provinces (Packham, 1969).

One of the two field sites chosen for this study, Wapengo Lagoon, is situated within an area dominated by outcrop of Ordovician metasediments (see inset, Fig. 2.3). Over 60% of the lagoon catchment area, including the lower reaches, drains slopes formed from metasediments. The main lithologic components of the metasediments are phyllite, slate, schist and greywackes with minor amounts of quartz rich siltstones and sandstones (Packham, 1969; Sundararamayya, 1983). The upper reaches of the Wapengo catchment, representing approximately 30% of the drainage area, incorporates the eastern limit of the Devonian Bega Granite Batholith. The Batholith has a variable grain size due to the presence of quartz rich coarse grained pegmatite, fine grained aplite, biotite granite, granodiorite, diorite-gabbro and horneblende-gabbro (Vallance, 1969). The remaining c.10% of the catchment is occupied by a small outcrop of mid-Devonian Eden Rhyolite. The outcrop is located near the northern shore of the lagoon, where it disconformably overlies Ordovician metasediments. The rhyolite is porphyritic with quartz and minor feldspar and is interbedded with tuff, volcanic breccias and felsites (Packham, 1969; Sundararamayya, 1983). The Bega Granite and Eden Rhyolite are tentatively correlated by Packham (1969) with intrusive activity and vulcanism during the Tabberabberan orogeny. Vulcanism and orogenic activity would have induced regional metamorphism of the Ordovician sedimentary country rock.

The southern portion of the Sydney Basin extends north from Durras Lake and comprises a series of six sedimentary formations that are collectively termed the Shoalhaven Group. The formations are: Nowra Sandstone; Wandrawandian Sandstone; Berry Formation; Conjola Formation; Yadboro Conglomerate; and, Pigeon House Siltstone. The rocks in these formations are all Permian and of marine origin and include quartz sandstones, siltstones and conglomerates (McElroy, et al., 1969).

The catchment and palaeovalley of the second field site selected for this study, Narrawallee Inlet, lies within the bounds of the Conjola Formation of the Shoalhaven Group (see inset, Fig. 2.3). The Conjola Formation occupies 39% of the

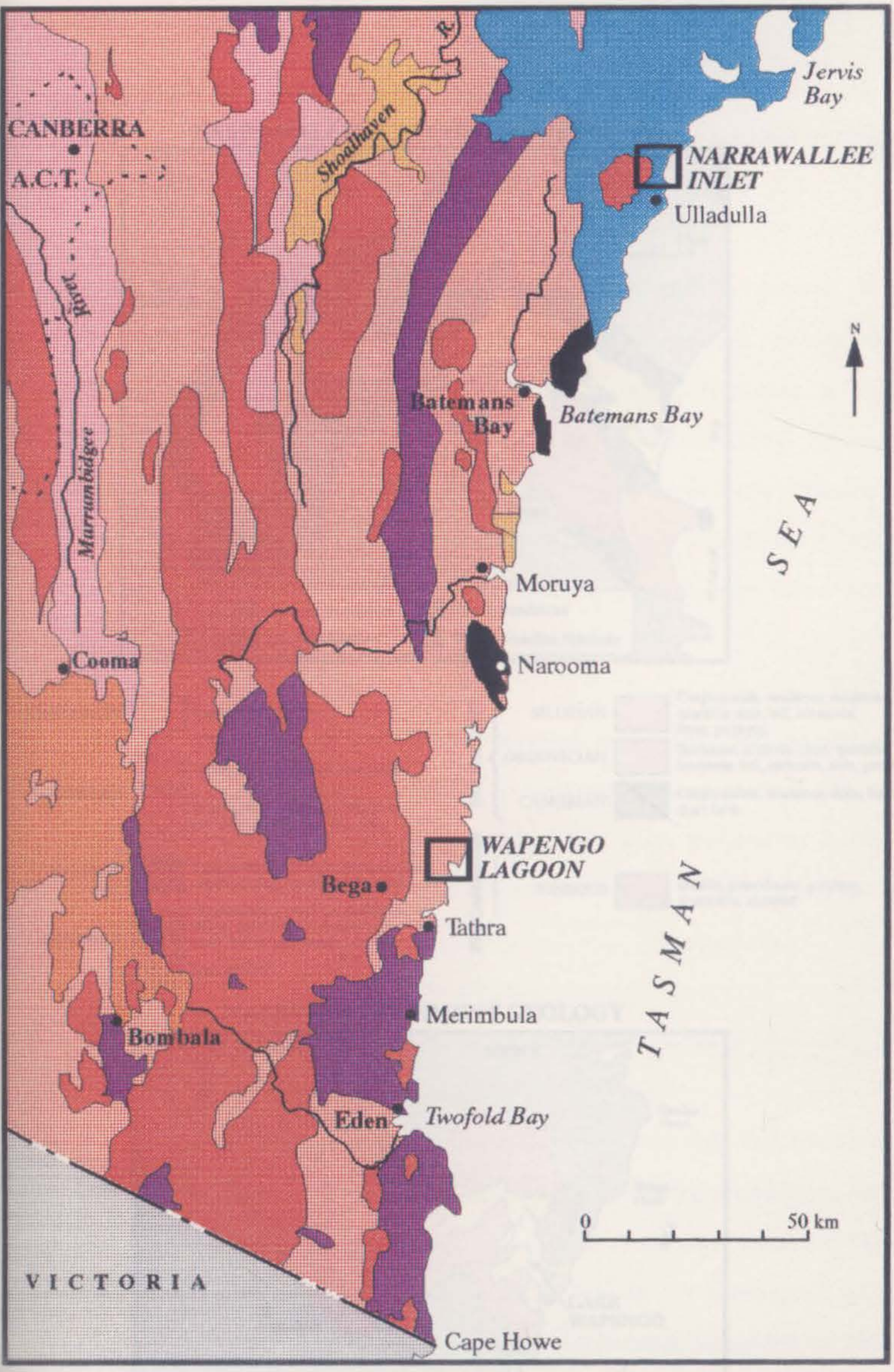
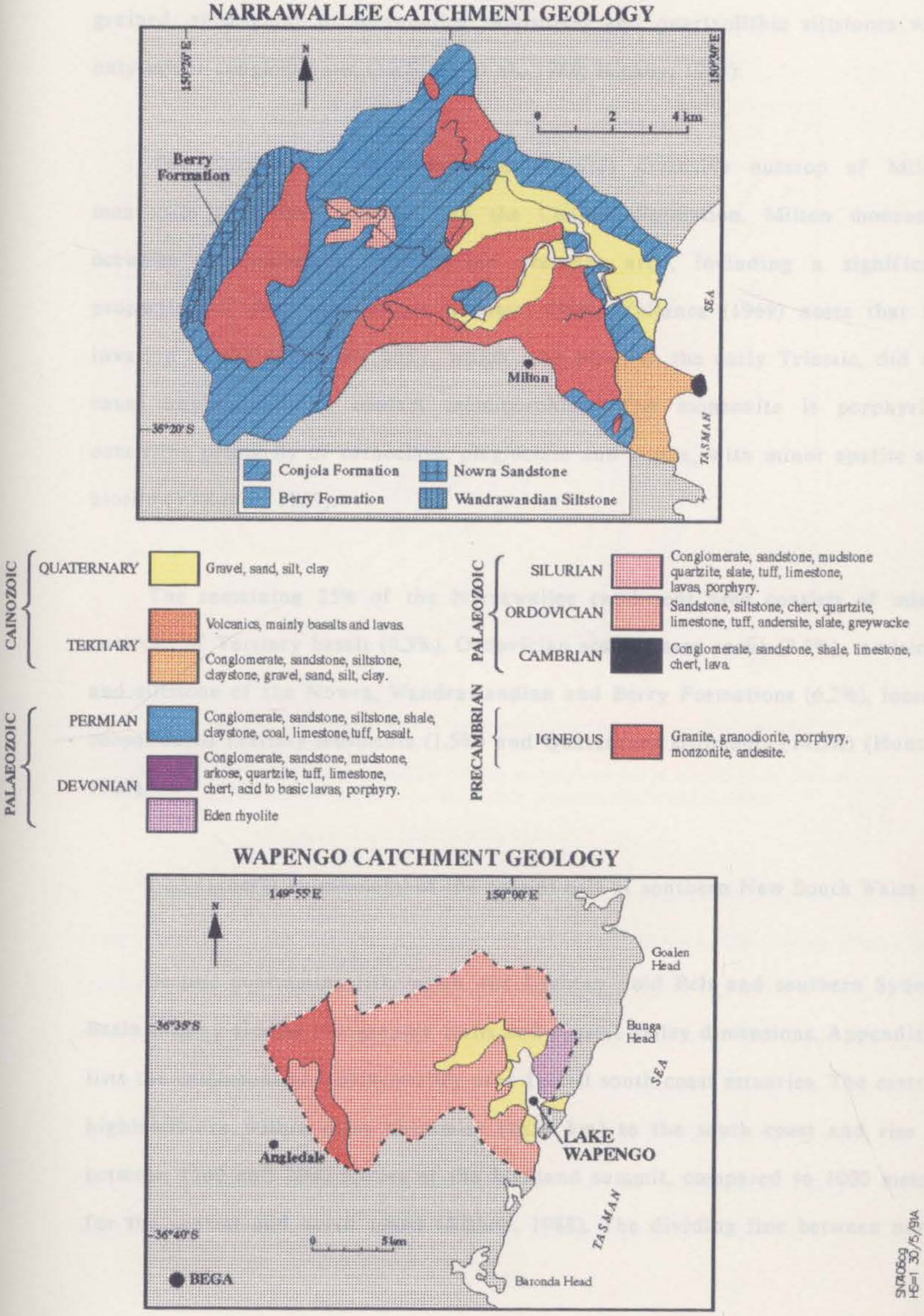


Figure 2.3: Generalised geology of the N.S.W. south coast with insets (next page) showing geology of the catchments of Wapengo and Narrawallee estuaries. (sources: 1:250,000 Geological Sheets; Sundararamayya, 1983; Hunter, 1989)



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Narrawallee catchment area. It is dominated by quartz rich, fine to medium grained, subangular to subrounded sandstones and quartzolithic siltstones with only minor conglomerates (McElroy et al., 1969; Hickey, 1978).

The Narrawallee catchment also features extensive outcrop of Milton monzonite that has intruded into the Conjola Formation. Milton monzonite occupies approximately 35% of the drainage area, including a significant proportion of the lower slopes (Hunter, 1989). Vallance (1969) notes that the invasion of the monzonite body, which took place in the early Triassic, did not cause any significant contact metamorphism. The monzonite is porphyritic consisting primarily of orthoclase, plagioclase and augite, with minor apatite and biotite (Vallance, 1969).

The remaining 25% of the Narrawallee catchment area consists of minor outcrops of Tertiary basalt (0.3%), Ordovician sedimentary rocks (2.5%), sandstone and siltstone of the Nowra, Wandrawandian and Berry Formations (6.2%), loosely consolidated Tertiary sediments (1.5%) and Quaternary sediments (14.5%) (Hunter, 1989).

2.2.3 General morphology of the coastal belt of southern New South Wales

Despite contrasting lithologies, the Lachlan Fold Belt and southern Sydney Basin display similar topographic traits and coastal valley dimensions. Appendix B lists the catchment and palaeovalley area for all south coast estuaries. The eastern highlands are within close proximity (<150 km) to the south coast and rise to between 1500 and 2000 metres at the highland summit, compared to 1000 metres for the central and north coasts (Bishop, 1988). The dividing line between north and south highland uplift areas lies inland at Goulburn. Figure 2.4 shows the highland contours of the south to be relatively closely spaced and parallel to the coast.

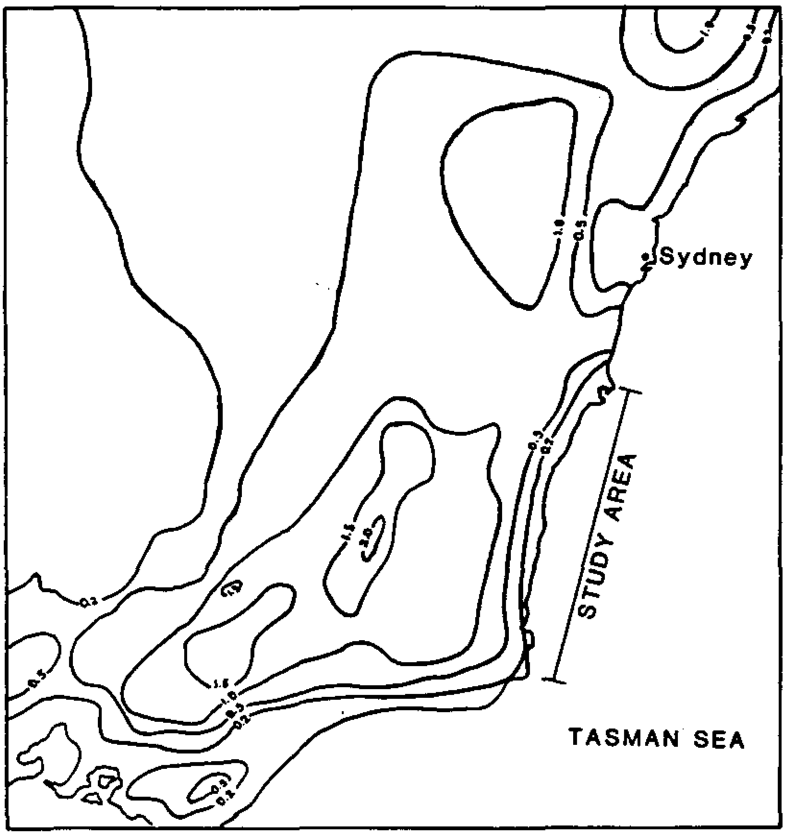


Figure 2.4: The southeast Australian highlands, showing contours of summit levels. Contours are 0.2, 0.5, 1.0, 1.5 and 2.0 kilometres above sea level. (modified from Wellman, 1979).

The upper reaches of south coast catchments, which are within 50 kilometres from the coast, rise relatively steeply to between 250 and 750 metres above sea level (Wellman, 1979). Consequently, the coastal lowlands are narrow (<2km) and the area available for deposition is limited in comparison to the broad plains of the central and north coasts of N.S.W. The most extensive deposit on the south coast is probably the prograded beach ridge plain at Moruya, which is 5.5 km in length and attains a maximum width of 3.9 km. By comparison, the Newcastle Bight Outer Barrier on the central coast is 38 km long and 9.5 km wide.

Furthermore, the south coast lowlands do not form a continuous coastwise strip. Rather, they are interrupted by numerous headlands and sections of rocky coast that mark the boundary between embayments. In general, each south coast estuary occupies a discrete embayment, although the larger embayments (Batemans Bay and Twofold Bay) contain several smaller bays of varying size. The area available for estuarine sedimentation at present sea-level is related to the dimensions of the incised river valley (see Appendix B). Several larger estuaries (e.g. Clyde, Tuross, Bega, Wallaga) penetrate tens of kilometres inland but even they are restricted in their lateral extent by bedrock valley sides.

In summary, the coast of southern New South Wales is characterised by a narrow coastal lowland with numerous headlands and sections of rocky coast that restrict deposition to small and narrow embayments. The streams and rivers of the coastal hinterland rise steeply to their headwaters that are within close proximity to the coast. Fluvial systems have incised narrow valleys into bedrock, resulting in comparatively restricted areas for estuarine sedimentation.

2.3 DEPOSITIONAL PROCESS FRAMEWORK

The present style of sedimentation within N.S.W. estuaries is a direct expression of the combined effects of a suite of depositional processes. The primary processes include: waves, tides and fluvial discharge. Attempts to understand the morphologic and sedimentologic character of estuarine deposits must, therefore, be made in the context of a process framework. In addition to specifying the general behaviour of waves, tides and river input, it is critical to have an understanding of spatial and temporal variability of each process and of the nature of interaction between processes within the confines of an estuary. The importance of process interaction and variability cannot be over emphasised because it is these properties that define the unique character of estuaries. Prior to discussing the characteristics of estuarine processes, the climate of the N.S.W. coast is first considered in order to establish the general environmental conditions influencing estuarine depositional processes.

2.3.1 Climate

Particular attention is given here to the wind and rainfall characteristics of the major air mass types that pass over the coast. Wind is important because it provides a driving mechanism for nearshore and estuarine water circulation, including wave activity. Rainfall is significant in terms of river discharge into estuaries.

(a) Meteorological Inluences: The weather patterns over southeast Australia undergo distinct seasonal variations. During the summer months (December to February) the coastal weather is dominated by Pacific subtropical maritime air masses. These air masses are associated with eastward moving anticyclones that deliver persistent moist warm winds from the east that in turn generate steep short period waves. When the moist air masses cross the coast, thunderstorms and intense rainfall events often occur as a result of the heat imbalance between land and sea (Gentilli, 1971; Thom, et al., 1973). The interaction of two adjacent anticyclonic cells can produce abrupt shifts in wind direction, typically in the form of a gale from the south and causing rough seas (Gentilli, 1971; Chapman et al., 1982). These conditions also prevail, though in weaker form, during spring (September to November) and early autumn (March). Summer weather conditions are also influenced by tropical cyclones situated off the Queensland coast.

Cyclones direct strong to gale strength north-east winds onto the N.S.W. coast and generate high (9-10 m) storm waves (Thom et al., 1973). Generally, summer conditions promote beach accretion, although cyclone generated waves can be destructional.

During winter (June to August) subtropical maritime air masses are less influential and are readily uplifted by sub-polar maritime air masses migrating from the southwest. High pressure systems are centered further north than in summer and the south coast experiences a westerly airflow. The offshore winds act to subdue ocean swell conditions and promote beach accretion. However, the sub-polar air masses are also associated with the regular passage of low pressure troughs and cold fronts from west to east. These systems produce weak to very strong, cold south to southeast winds which can result in storm wave and strong swell conditions, and hence major beach erosion (Chapman et al., 1982).

(b) Wind Conditions: One consequence of seasonal variations in meteorological conditions is a similarly varied wind regime. Annual wind data collected at Tathra and Nowra are presented as examples of the variable nature of the wind regime along the N.S.W. south coast. The Tathra wind rose in Figure 2.5 shows the dominant wind direction to be from the south to south west vector, with a frequency of 27%. The subordinate wind direction at Tathra is from the north to north-east vector with a frequency of 17%. The strongest winds also derive mainly from the south, with winds stronger than 33 knots occuring with a frequency of 1.2% (PWD, 1980). The velocity of winds from the north to north-east is somewhat less than the southerly winds with 10-20 knots dominating and the strongest winds (21-33 knots) having a frequency of only 1.6% (PWD, 1980).

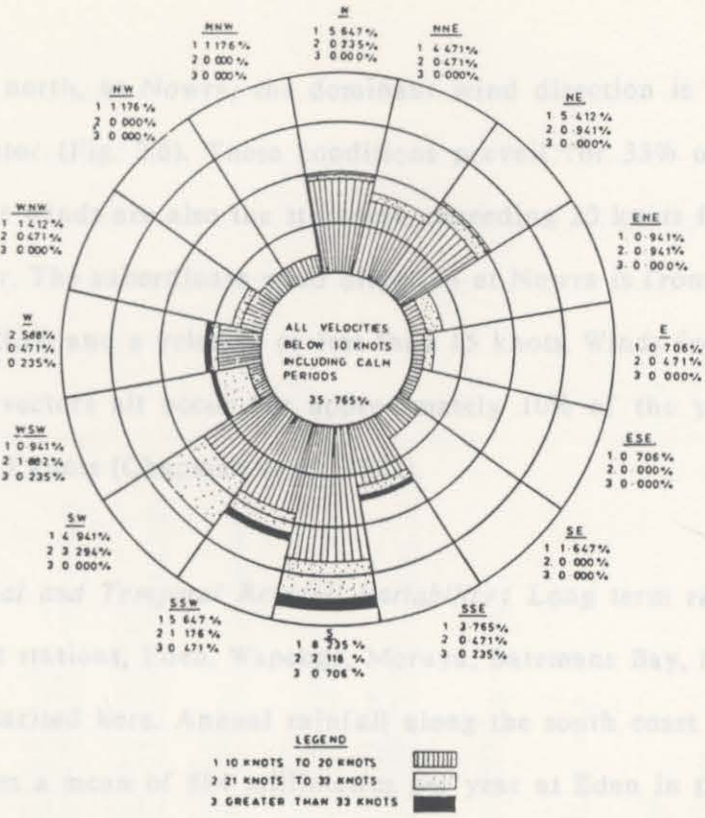


Figure 2.5: Wind rose derived from ships logs for offshore Tathra, 1975-1978 (source: PWD, 1980)

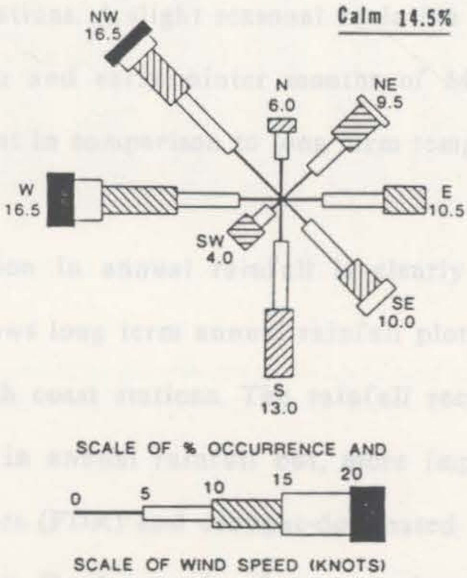


Figure 2.6: Annual wind rose for Nowra (source: Chapman et al., 1982).

Further north, at Nowra, the dominant wind direction is from the west to northwest vector (Fig. 2.6). These conditions prevail for 33% of the year . The most prevalent winds are also the strongest, exceeding 20 knots for approximately 3% of the year. The subordinate wind direction at Nowra is from the south with a frequency of 13% and a velocity of less than 15 knots. Winds from the north-east to south-east vectors all occur for approximately 10% of the year and are also weaker than 15 knots (Chapman et al., 1982).

(c) Spatial and Temporal Rainfall Variability: Long term rainfall data from six south coast stations, Eden, Wapengo, Moruya, Batemans Bay, Milton and Jervis Bay are summarised here. Annual rainfall along the south coast varies markedly, increasing from a mean of 884 millimetres per year at Eden in the south, to 1257 millimetres at Milton in the north, a distance of approximately 200 kilometres. Figure 2.7 shows that rainfall is evenly distributed throughout the year for all six south coast rainfall stations. A slight seasonal variation does exist, in the form of a peak in the autumn and early winter months of March to June, but this is considered insignificant in comparison to long term temporal variations.

Temporal variation in annual rainfall is clearly evident from long term records. Figure 2.8 shows long term annual rainfall plotted as deviation from the mean for the six south coast stations. The rainfall records indicate the lack of long term uniformity in annual rainfall but, more importantly, also reflect the flood-dominated regimes (FDR) and drought-dominated regimes (DDR) identified by Warner (1987) from flood records of coastal rivers north of Sydney. Each regime is characterised by a period of several decades of either relatively high or low flood activity. In summary, FDR prevailed for the periods 1857-1900 and 1947-1978 and DDR for the years 1821-1856 and 1901-1946 (Erskine and Warner, 1988). Rainfall records from south coast stations do not start until the early 1870s, precluding confident identification of the first DDR and FDR. The records do show, however, a consistent trend of below average rainfall for the 1900 to late 1940s period (second DDR) and above average rainfall from the early 1950s to early 1980s (second FDR).

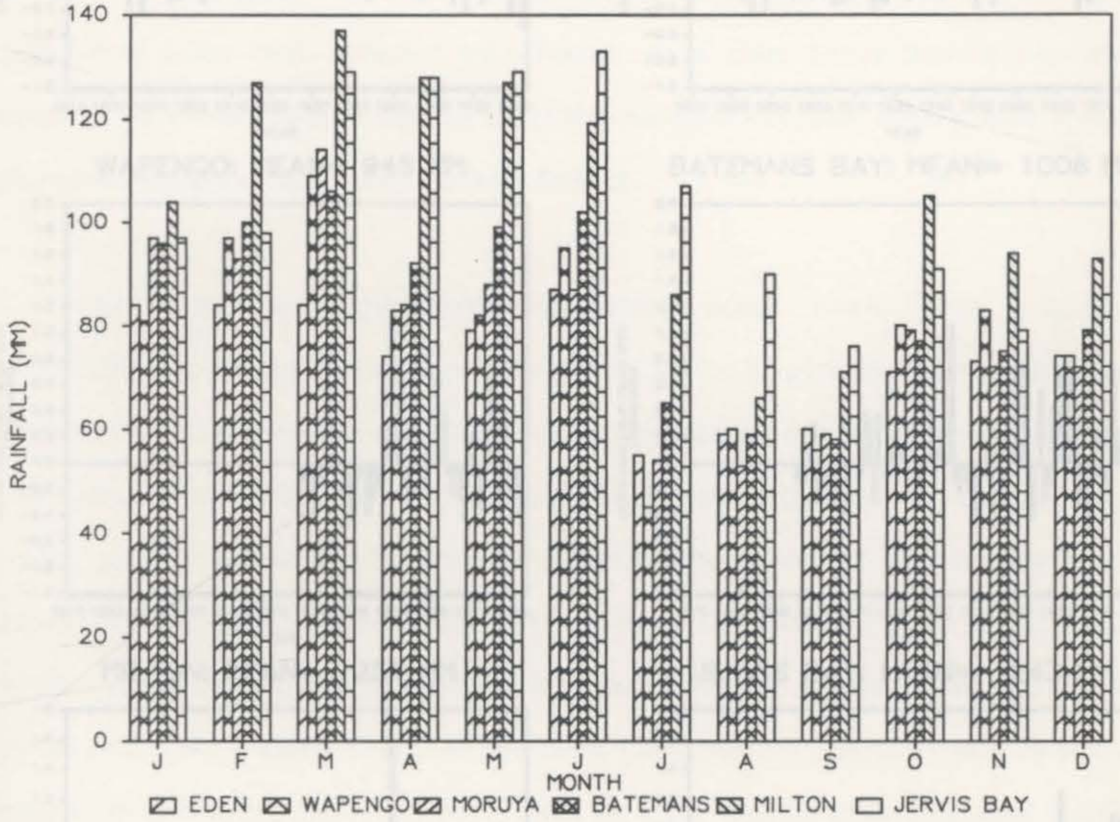


Figure 2.7: Long term monthly rainfall averages for six south coast stations. Station data plotted in order from south (Eden) to north (Jervis Bay) (source: Bureau of Meteorology, 1984).

Erskine and Warner (1988) identify major changes in river channel morphology and rates of fluvial sediment transport during FDR and DDR periods. It is therefore anticipated that temporal variations in rainfall will also impact upon the delivery of sediment to estuaries. The specific nature of river channel response to temporal rainfall variation will be discussed in section 2.3.4.

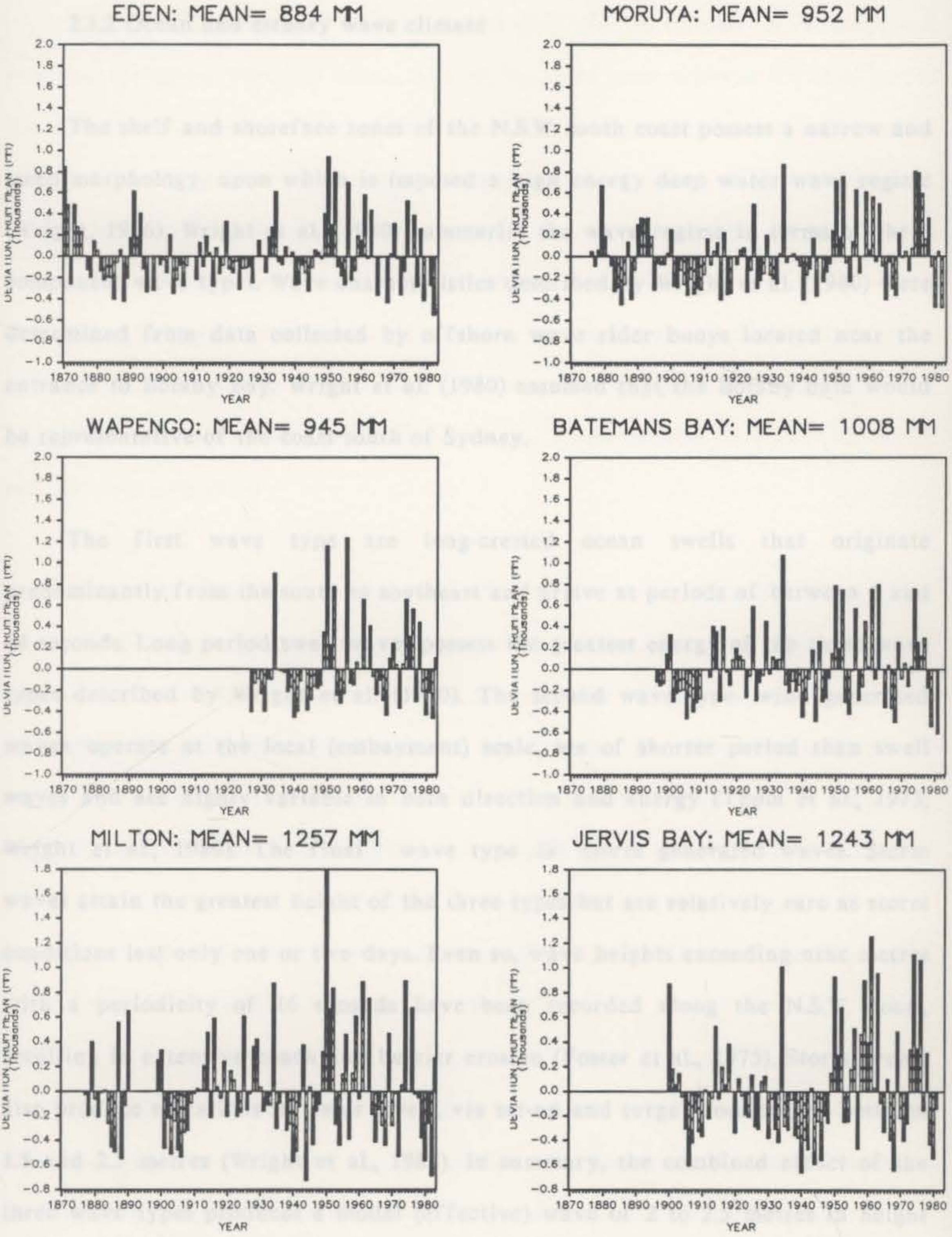


FIGURE 2.8: Long term annual rainfall trends plotted as deviation (mm) from the mean for six south coast stations. (source: Bureau of Meteorology, 1984).

2.3.2 Ocean and estuary wave climate

The shelf and shoreface zones of the N.S.W. south coast possess a narrow and steep morphology, upon which is imposed a high energy deep water wave regime (Wright, 1976). Wright et al. (1980) summarise the wave regime in terms of three component wave types. Wave characteristics described by Wright et al. (1980) were determined from data collected by offshore wave rider buoys located near the entrance to Botany Bay. Wright et al. (1980) assumed that the Botany data would be representative of the coast south of Sydney.

The first wave type are long-crested ocean swells that originate predominantly from the south to southeast and arrive at periods of between 6 and 14 seconds. Long period swell waves possess the greatest energy of the three wave types described by Wright et al. (1980). The second wave type wind generated waves operate at the local (embayment) scale, are of shorter period than swell waves and are highly variable in both direction and energy (Thom et al., 1973; Wright et al., 1980). The final wave type is storm generated waves. Storm waves attain the greatest height of the three types but are relatively rare as storm conditions last only one or two days. Even so, wave heights exceeding nine metres with a periodicity of 16 seconds have been recorded along the N.S.W. coast, resulting in extensive beach and barrier erosion (Foster et al., 1975). Storm events also produce elevations in water levels, via set-up and surge processes, of between 1.5 and 2.5 metres (Wright et al., 1980). In summary, the combined effect of the three wave types produces a modal (effective) wave of 2 to 2.5 metres in height with periods of 8.5 to 10 seconds from the south-southeast (Wright et al., 1980).

Kidd (1978) presented detailed wave data for a number of south coast beaches, including Wapengo beach, one of the field sites selected for this study. These data indicate that the shoreface wave climate at the study site is consistent with the characteristics of the modal wave described above. Waves arriving at Wapengo beach from the south and southeast are on average 2.5 metres and 2.2 metres high, respectively (Kidd, 1978). North-east waves (1.4m) and easterly waves (1.8m) are slightly smaller in size. The smaller waves are also significantly weaker in terms of wave power. The average deep water wave power of southerly waves is 42.2 kilowatts per metre, whereas north-east waves possess only 10.5 kilowatts per metre (Kidd, 1978).

Wright (1976) utilised two years of offshore wave rider data to calculate the mean significant deep water wave power and the extent of energy lost due to bed friction. Only 0.6 kilowatts per metre (3.4%) of the average wave crest power of 17.8 kilowatts per metre were lost via bed friction. In other words, 96.6% of incident wave power reaches the shoreface. The power loss was higher (16%) for high energy conditions (125 Kw/m), though the loss is low by comparison with power losses calculated for sections of the United States Atlantic coast. For example, the Georgia coast loses an average of 84% and the North Carolina coast 48% of respective incident wave energy (Wright, 1976).

The minimal power losses of the N.S.W. south coast are attributed to the nearshore zone bottom profile. The width of the zone of active sediment reworking by waves varies according to wave conditions prevailing at a given time. By weighting segments of the nearshore profile with the mean annual probability of sediment being redistributed by waves, Wright (1976) determined that the zone of reworking was less than one kilometre wide for over 50 per cent of the analysis time. The width of the zone exceeded 3.5 kilometres for only one per cent of time. The impact of these wave conditions upon the shoreface is marked, inducing severe erosion during storm events and slow recovery rates due to the narrow zone of active reworking of bottom sediment.

Given the high energy character of ocean swell waves arriving obliquely at the shoreface, it might be expected that strong longshore currents are generated and littoral sediment transport occur. Longshore currents certainly exist along the N.S.W. coast, flowing from south to north during winter and north to south in summer in association with seasonal shifts in prevailing wind direction. Sediment drift does occur along the north coast of N.S.W., where beaches are long and continuous. On the south coast, however, longshore current initiated drift is impeded by numerous bedrock headlands. Consequently, longshore processes are confined to individual embayments with negligible bypassing of sediment around headlands (Chapman, et al., 1982).

During fairweather conditions there is almost no transfer of incident wave energy into the estuary, due to the presence of subaerial barrier-spit complexes and subaqueous flood tidal deltas at the mouths of all N.S.W. estuaries. Waves should not, however, be discounted as an influential process in estuaries. It will be shown in chapters six and seven that storm swell waves and local wind generated waves have the potential to significantly influence the deposition of sediment in estuaries, particularly in the flood-tidal delta and estuary shoreline sub-environments.

2.3.3 Tidal regime

The absolute levels of tides and the average range between high and low water do not vary significantly along the N.S.W. coast (Wright et al., 1980). This is due largely to the uniform steep and narrow morphology of the shelf and nearshore. Mean tidal range is 1.6 metres. Under neap conditions, the range decreases to less than one metre and during springs it exceeds two metres (Chapman et al., 1982). Based on Davies (1964) classification of tidal types, the N.S.W. coast qualifies as microtidal (range <2 metres). Tides operate in a semidiurnal fashion with a diurnal inequality, denoting two high-water and two low-water stands each day, between which tidal range is not equal (Easton, 1970; Wright et al., 1980).

Within estuaries that are open to tidal exchange there is considerable attenuation of tidal range due to the presence of entrance shoals in the form of flood-tidal deltas and backbarrier flats. Measurement of tidal range within south coast estuaries has been undertaken in several systems, the results of which are summarised by Williams (1983). For example, in Lake Illawarra, tidal range decreased from 1.10 metres at the estuary mouth to 0.02 metres in the lake basin. In concert with the restriction of tidal range, occurs a landward loss in the energy of tidal currents (Williams, 1983). The exact magnitude of tidal energy loss within south coast estuary inlets and the sedimentological expression of spatial variation in depositional processes will be discussed in detail in chapter six.

2.3.4 Fluvial regime

The characteristics of streams and rivers draining into N.S.W. estuaries are considered here with specific regard to their relative sediment yield. Studies of rates of landscape evolution in southeastern Australia have shown that erosion rates, by world standards, are very slow (Young, 1981, 1983; Bishop, 1984). The evolutionary models for the eastern highlands (see section 2.2.1) that emphasise the great antiquity of the highlands, also imply that erosion rates were slow throughout the Tertiary and have remained so during the Cainozoic (Bishop, 1988). In addition, palaeo flow direction data indicate that the southeast drainage divide has been horizontally stable for at least the last 20 Ma (Bishop, 1986). Moreover, the Late Cainozoic has been a period of increased relative aridity, thereby further reducing the potential for highland denudation.

Rieger and Olive (1988) present a comparison of contemporary Australian sediment yields with those of other continents. Their data show Australia to be among the lowest sediment yielding continents of the world. One estimate, cited by Rieger and Olive (1988), ranks Australia last behind Asia, South and North America, Europe and Africa (Table 2.1). Estimates of annual sediment yield vary widely due to the use of different sampling and analytical methods. Therefore, Rieger and Olive (1988) urge caution when drawing conclusions from such data. Young (1983) makes an interesting point with regard to the claim that Australian sediment yields are below world averages. That is, the yields of the Asian, European and American continents may be unusually high because they drain areas that have experienced recent glaciation and, in some cases, are tectonically active.

Irrespective of specific values of continental sediment yield and the underlying causes, it is generally accepted that Australian drainage systems are inefficient agents for delivery of sediment to depositional sinks (Young, 1983; Bishop, 1984, 1988; Rieger and Olive 1988).

CONTINENT	AREA ($km^2 x 10^6$)	SEDIMENT YIELD ($t/km^2/yr$)
Asia	44.9	166
South America	18.0	93
North America	20.4	73
Europe	9.7	43
Africa	29.8	37
Australia	7.9	32

Table 2.1: Estimated annual sediment yield for the six main continents (from Strakhov, 1967).

The inefficiency of fluvial systems is attributed, not to a lack of source material, but to the marked temporal variability of discharge of Australian rivers (Rieger and Olive, 1988). Chapman et al. (1982, table 3.1) present discharge statistics for several N.S.W. coastal rivers which show that within a period of several months, daily discharge can increase from zero flow to hundreds of thousands of megalitres and then return to negligible flow. Further indication of the variable character of river discharge is provided by coefficient of variation statistics calculated by Finlayson and McMahon (1988). For example, for southeast Australian catchments that are less than 1000 km^2 in area, the coefficient for annual flow variability is 0.56. This value is significantly greater than the mean value of 0.27 for similar climatic regions of the world, with the exception of southern Africa where similar values were calculated. Peak discharge is also highly variable. The coefficient of variation for the southeast Australian and southern African catchments is 0.39, compared to 0.18 for the rest of the world (Finlayson and McMahon, 1988). The high flow variability in southeast Australian and southern African rivers is thought be a product of the lack of a strong topographic influence on rainfall (Finlayson and McMahon, 1988). However, the relationship between river flow and rainfall is not simple. By modelling relationships between streamflow variability and rainfall variability, Finlayson and McMahon (1988) demonstrated that streamflow variability is a function of *effective* rainfall. Effective rainfall is defined as the portion of total precipitation that contributes to runoff. The relatively ineffective transfer of rainfall to runoff in eastern Australia is attributed in part to high evaporation rates (Finlayson and McMahon 1988).

With regard to estuarine systems, the implications of high variability of runoff and streamflow are significant throughout an estuary. At the seaward end of estuaries, variable fluvial discharge is clearly evident in changes in the condition of estuary entrances, particularly in barrier estuaries and coastal lakes. During low river flow periods the estuary mouths may close. Reopening via barrier breaching usually requires a river flood (which is often associated with storm waves). The delivery of fluvial sediment to the central and lower fluvial portion of estuaries is also sporadic and dependent upon high flow regime conditions. Finally, at the landward limit of estuaries, distinct contrasts in channel morphology and bed behaviour exist during flood-dominated regimes (FDR) compared to drought-dominated regimes (DDR) (Erskine and Warner, 1988). During FDR, river channels widen and straighten. Bed accretion occurs where widening is greatest and bed erosion where channels are constrained by bedrock or vegetation. FDR do not appear to have caused lateral migration of channels. During DDR, channel changes are less dramatic, mainly involving a reduction in channel width where sufficient sediment is available for bank recovery (Erskine and Warner, 1988).

Estuarine systems on the south coast have the capacity to serve as highly effective sediment filters, trapping material derived from both land and sea. With the exception of those that are almost completely filled and which bypass sediment during floods, all estuaries in the study area are still actively filtering sediment. Therefore, it is expected that a detailed, though not necessarily complete, record of fluctations in fluvial flow is preserved within estuarine sediments. The character of the sedimentological signature produced by fluvial processes is described in detail in chapters seven and eight.

2.4 LATE QUATERNARY SEA-LEVEL HISTORY

Relative sea-levels along the southeast coast of Australia have fluctuated considerably throughout the Quaternary period and earlier. The most recent shift in relative sea-level occurred during the Late-Pleistocene and Holocene and is attributed primarily to the addition of glacial meltwater to the southern oceans. Postglacial crustal movements are believed to have been insignificant due to the fact that the Australian continent did not experience ice loading during the last glacial period (Nakada and Lambeck, 1989). In addition, slow rates of continental denudation throughout the Quaternary mean that the continent is in a state of relative isostatic equilibrium (Rieger and Olive, 1988; Nakada and Lambeck, 1989). Quaternary sea-level changes, therefore, have been driven by glacio-eustatic, not isostatic, forces.

Numerous studies of the Late Quaternary history of sea-level change along the N.S.W. coast have utilised relative and absolute dating methods to estimate the age of coastal deposits and associate those deposits with relative sea-level-highstands or lowstands (e.g. Langford-Smith and Hails, 1966; Langford-Smith and

Thom, 1969; Thom et al., 1969, 1972; Thom and Chappell, 1975, 1978; Marshall and Thom, 1976). A concise summary of the N.S.W. sea-level history over the past 15,000 years is presented by Thom and Roy (1983).

The most relevant sea-level fluctuations to the Quaternary evolution of coastal environments of N.S.W. are those associated with the Last Interglacial, Last Glacial and present Interglacial periods, spanning the last 140,000 years. Chronostratigraphic investigations of pre-Holocene marine deposits are few. Marshall and Thom (1976) published the first reliable numeric ages for Last Interglacial (c.120-140 ka) coastal deposits, using uranium series dating on buried corals at the Newcastle Inner Barrier and Evans Head on the central N.S.W. coast. More recently, thermoluminescence and uranium-thorium dating of coastal dunes on headlands in the Illawarra region has identified four distinct units that date from 25Ka, 45Ka, 125Ka, and 300-400Ka (Bryant et al., 1990). In addition, amino acid racemisation dating has been applied to shells preserved within Last Interglacial estuarine deposits on the central and southern coasts (Thom and Murray-Wallace, 1989; Nichol and Murray-Wallace, in press). These latter studies have relied upon calibration of analytical results with the Late Quaternary sea-level record, as determined by uranium series and radiocarbon dating of coral terraces in New Guinea (Chappell 1974, 1983) and oxygen isotope studies of deep sea cores (Shackleton and Opdyke, 1973). From their work, it could be concluded that the Last Interglacial (isotope substage 5e) was characterised by a sea-level situated between four and six metres above the present level (Fig. 2.9). However, Bryant et al. (1990) argue from uranium series dates of crusts sampled from rock platforms in the Illawarra that the elevation of the Last Interglacial highstand along the N.S.W. coast may have been only two metres.

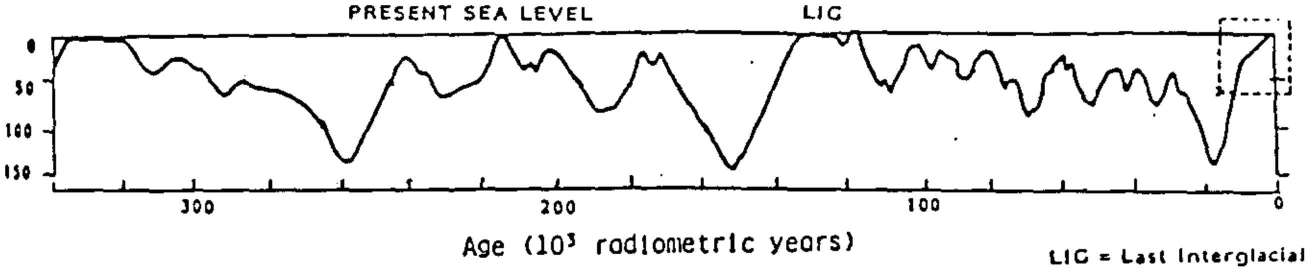


Figure 2.9: Late Quaternary relative sea-level curve for eastern Australia (from Chappell, 1983).

The Late Pleistocene and Holocene has featured major glacio-eustatic shifts in sea-level, involving fluctuations of up to 120 metres (Chapman et al., 1982). The Last Glacial period saw sea-level vary between lowstand levels below -70 metres and interstadial levels of -20 metres. Roy and Thom (1981) nominate the 20-70 metre zone as the modal zone for glacial sea-levels (Fig. 2.9).

Comprehensive radiocarbon dating of organic material recovered from backbarrier, lagoon, tidal flat, tidal delta and offshore marine deposits has provided for the construction of a reasonably accurate Late Pleistocene to Holocene relative sea-level envelope (Fig. 2.10.) (Thom and Roy, 1983). Dating results have not been sufficiently precise to permit plotting of a single sea-level curve. The envelope describes a transgressive rise from 60 metres below present sea-level between 12000 and 7700 years BP at the rapid rate of 1.3 metres/century, decelerating to 0.4 metres/century between 7700 and 6400 years BP (Thom and Roy, 1983). Several workers have speculated about the attainment of mid-Holocene (6500-5500 yrs BP) high sea-level (+1m) along the N.S.W. coast (Jones et al., 1979). Recently, evidence for a localised highstand of between one and two metres alomg the Illawarra coast, lasting from 6000 BP to 1500 BP has been put forward by Young et al. (1991). A late Holocene lowstand of about -1 metre may also have occurred; however the evidence for this is limited (one C-14 date of 3765+/-70 BP for peat sampled 80m offshore) (Thom and Roy, 1983).

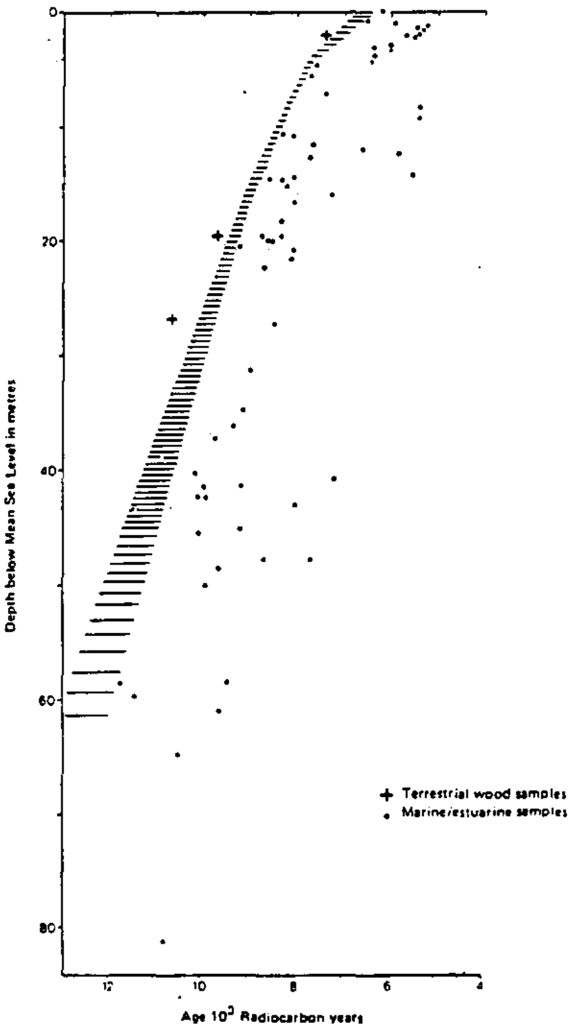


Figure 2.10: Late Pleistocene and Holocene relative sea-level envelope for southeast Australia. (reproduced from Thom and Roy, 1983)

Given the existing body of evidence related to mid- to late-Holocene sea-levels Thom and Roy (1983) conclude that since 6500 yrs BP sea-level has maintained a constant (stillstand) level, to within one metre of the present level

(Thom and Roy, 1983). The detailed sea-level history of the late Holocene period remains a subject of debate and an area for further investigation.

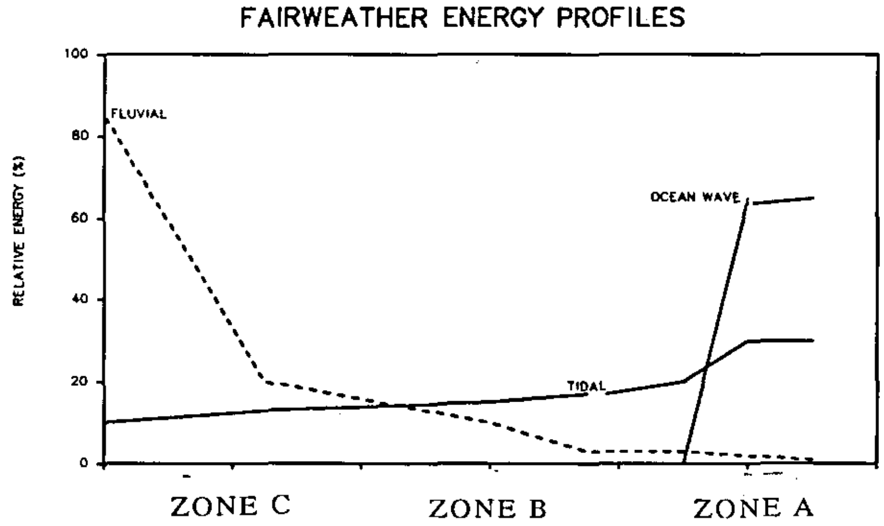
2.5 SUMMARY

In terms of the relative dominance of individual processes acting upon coastal depositional systems the N.S.W. coast qualifies as a wave-dominated coast. The characteristics of wave- and tide-dominated coasts are discussed by Hayes (1975, 1979), Heward (1981) and Davis and Hayes (1984) and in chapter one. To reiterate, dominance of waves or tides is not defined in absolute terms, such as wave power or tidal range. Rather, it is the relative dominance of one process over the other in controlling the morphology of coastal depositional systems that defines a coastal type.

The wave-dominated coast typically has sediment bodies oriented parallel to the shore. Barriers are straight and narrow with widely spaced inlets and flood tide deltas. Washover deposits may be present, but are not a pervasive feature. Davis and Hayes (1984) note that the number of inlets per barrier increases with tidal range. In tide-dominated estuaries, tidal processes prevent the formation of subaerial barriers and inlet deposits adopt a flow parallel orientation. The relationship between relative dominance of a process and depositional morphology points to the existence of a continuum between the extremes of wave-dominance and tide-dominance (Dalrymple and Zaitlin, 1989) (see chapter one).

Tidal processes are not entirely overwhelmed by wave-generated processes in wave-dominated systems. Indeed, on the landward side of barriers tidal currents and fluvial processes generally have greater direct influence on sedimentation than waves. As discussed in section 2.3.2, nearshore wave energy is almost completely absorbed by the barrier during fairweather conditions. However, storm swell waves and local small wind-generated waves do have some influence in N.S.W. estuaries. The first-order control on N.S.W. estuaries is waves because without wave-dominance the shore parallel barrier would not exist, nor would backbarrier environments and their respective depositional processes.

The characteristics of estuarine facies located landward of the barrier is largely the result of the interaction of tidal and fluvial processes along opposing gradients (Fig. 2.11). That is, tidal range is reduced and tidal currents weaken in a landward direction as they pass over the inlet shoals. Conversely, fluvial currents are dissipated in a seaward direction due to the presence of an open estuarine basin at the river mouth. This pattern is interrupted during extreme events such as storms and river floods. Under these extreme conditions tidal processes and fluvial processes penetrate further landward and seaward, respectively. Waves do influence estuarine deposits but in an irregular manner, as only large storm waves penetrate the estuary. Small wind waves can also influence shallow water deposits.



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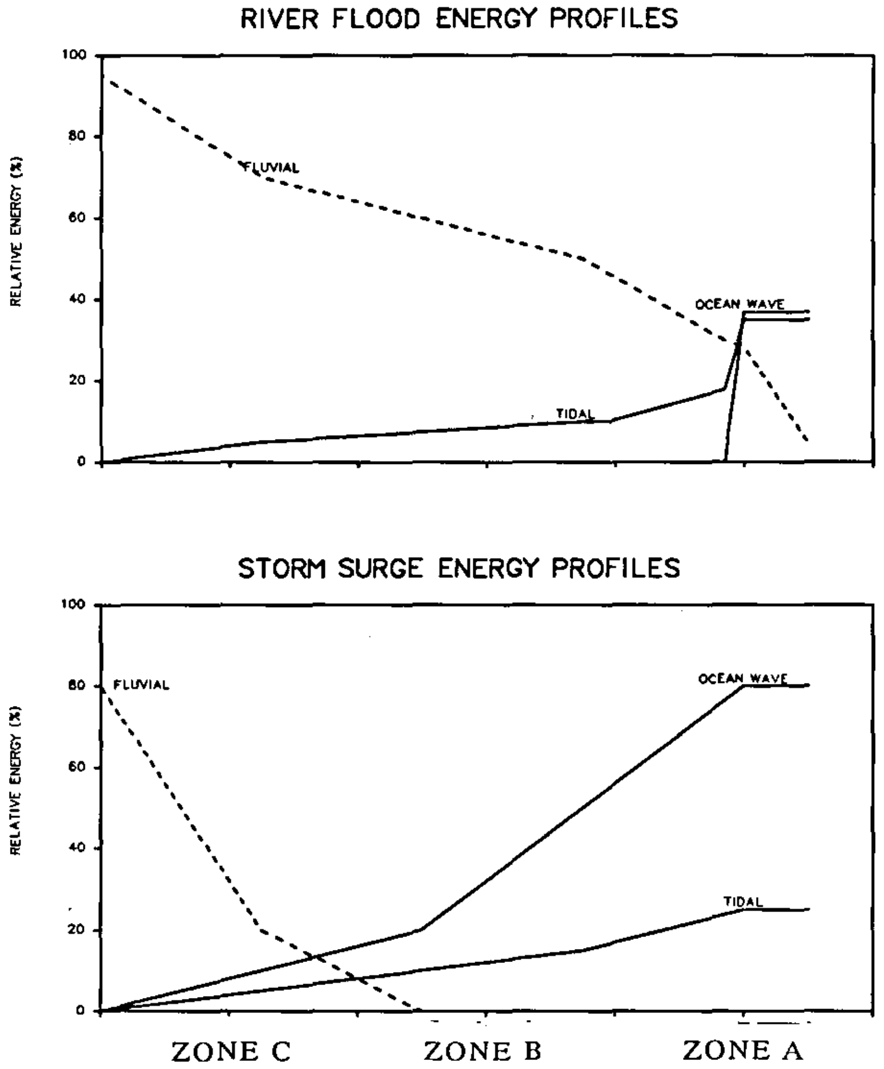

Figure 2.11: Plots showing the relationship between relative fluvial energy, tidal energy and ocean wave energy along the axis of wave-dominated estuaries during fairweather and extreme event conditions (modified from Dalrymple and Zaitlin, 1989).

The morphology of coastal deposits along the N.S.W. coast conforms to the wave-dominated coastal morphology described by Davis and Hayes (1984) (Fig. 2.12). N.S.W. represents the end-member position on the continuum between wave-dominated and tide-dominated coasts. End-member status is suggested because tidal processes maintain only one inlet through barriers, and in some barrier systems (e.g. saline coastal lakes) the inlet is merely an ephemeral feature. Inlet intermittency is also partly a function of antecedent topographic controls on barrier morphology and variable fluvial discharge. That is, the width and depth of some bedrock embayments is such that barrier sediments block the estuary mouth, preventing efficient tidal exchange.

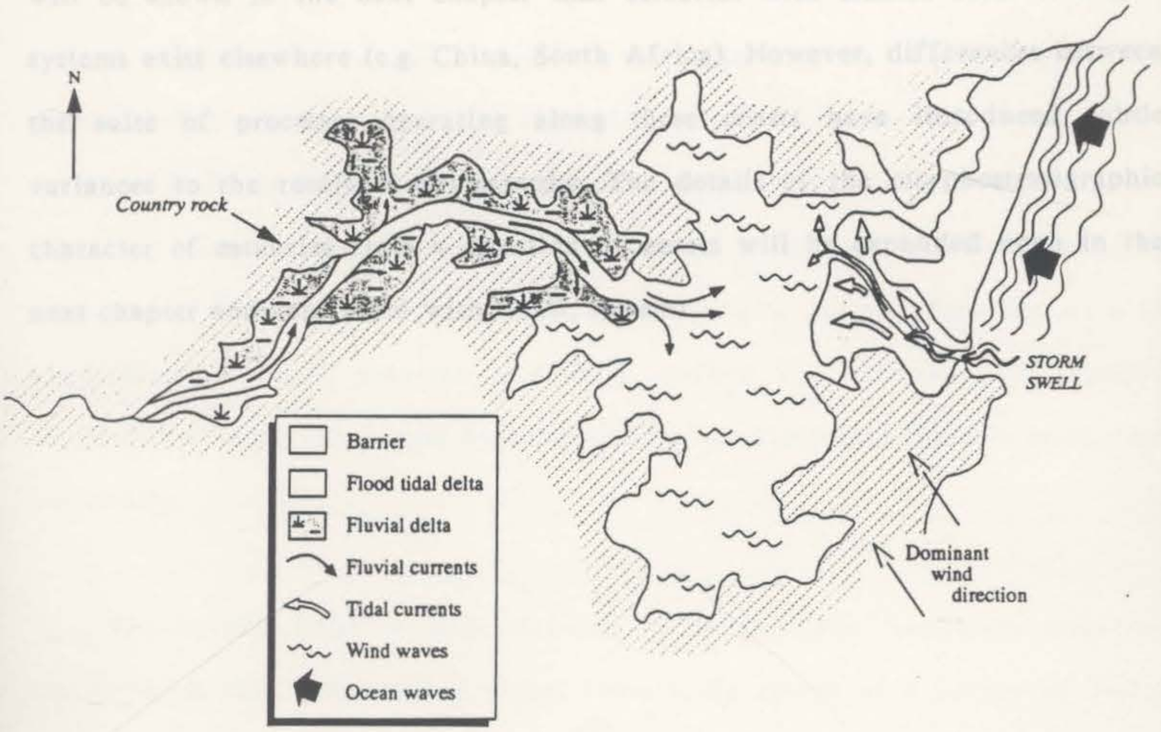

Figure 2.12: Sketch showing typical morphological character of N.S.W. south coast estuaries and the role of wave, tide and river processes.

Davis and Hayes (1984) discount wave-dominated high relief bedrock coasts with narrow shelves as sites for the accumulation and preservation of substantial coastal deposits. While it is recognised that narrow coastal plains provide limited accomodation space compared to broad coastal plain settings, the significance of the former must not be underestimated. The estuaries of the N.S.W. south coast do occupy a high relief bedrock coast abutting a narrow shelf but the depth of valley incision is such that sediment bodies up to 30 metres thick have accumulated. It is evident, therefore, that the N.S.W. south coast provides a setting for the development of excellent examples of wave-dominated estuaries. However, the morphological character of N.S.W. estuaries is not unique in global terms. It will be shown in the next chapter that estuaries with similar form to N.S.W. systems exist elsewhere (e.g. China, South Africa). However, differences between the suite of processes operating along these coasts have introduced subtle variances to the resultant stratigraphy. The details of the morphostratigraphic character of estuaries from a selection of coasts will be expanded upon in the next chapter and contrasted with N.S.W. systems.

CHAPTER 3: PREVIOUS RESEARCH IN NEW SOUTH WALES ESTUARIES : A GLOBAL CONTEXT

3.1 INTRODUCTION

A chronological review of previous estuarine research of a geological and geomorphological nature in N.S.W. is presented in this chapter. The theme of the review will be to highlight the development of concepts among earlier workers regarding estuarine sedimentation, as observed along the N.S.W. coast. The evolution of ideas is traced from the initial identification and documentation of physical properties of estuaries and their barriers, the recognition of regional variability of those properties and the eventual postulation of models explaining variability.

The current level of understanding of southeastern Australian estuarine complexes is then placed in a global context. By means of a review of select overseas literature, the uniqueness of the modern wave-dominated, microtidal incised valley estuarine setting of N.S.W. is highlighted. It is subsequently argued that the present study provides an important contrast to investigations of estuaries that have evolved under environmental settings different to N.S.W. The uniqueness of the N.S.W. setting and its attendant facies assemblage is also briefly assessed in the context of the geological record and shown to be something that is well represented in the rock record but which, until recently, was rarely included in palaeoenvironmental reconstructions.

3.2 EARLY IDENTIFICATION OF THE VARIABILITY OF ESTUARY AND BARRIER CHARACTERISTICS.

Preliminary research into the physical properties of Australian estuaries was carried out during the 1940's and 1950's by the C.S.I.R.O.[1] Division of Fisheries and Oceanography. This work focussed upon the hydrological properties of estuarine systems, including: tidal range and flow velocity; chlorinity/salinity; water temperature; phosphate and nitrate concentrations in bottom sediments; and the general textural character of bottom sediments (Rochford, 1951). These properties were later used to suggest a classification scheme that could be applied to all Australian estuaries (Rochford, 1959). From the limited data available, Rochford identified four estuarine hydrological zones: marine, tidal, gradient, and freshwater. Classification of individual estuaries was therefore intended to be based upon the observed dominance of a particular hydrological zone. One notable outcome of these early investigations was the observation that variation in the climatic and tidal regimes between coastal regions of Australia is reflected in a regional diversity of estuarine hydrological properties (Rochford, 1959).

Jennings and Bird (1967) acknowledged the value of hydrological work undertaken in Australian estuaries by Rochford (1951, 1959) and others (eg: Spencer, 1956) but lamented at the paucity of comparable geomorphological research. Consequently, they provided a significant contribution to the initial understanding of the geomorphic character of Australian estuaries (Bird, 1967a, 1967b; Jennings and Bird, 1967). The central theme to the observations of Jennings and Bird (1967) was of the strong role played by their suite of six "dynamic environmental factors" (Jennings and Bird, 1967:121) in determining the

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[1] Commonwealth Scientific and Industrial Research Organisation (Australia)

geomorphic character of Australian estuaries. These factors include: fluvial discharge; wave energy; tidal range; intertidal vegetation communities; lithology of estuary sediments, and; the neotectonic setting. There is considerable variation in these factors Australia-wide, resulting in distinct regional variations in estuarine geomorphology. In presenting examples of these variations, Jennings and Bird (1967) refer to estuaries of the NSW south coast emphasising the considerable variation in the degree of palaeovalley infilling. Jennings and Bird (1967) also recognised that the sediments had multiple sources, terrestrial and marine. In particular they refer, among others, to Narrawallee Inlet as an example of a completely infilled estuary and the adjacent Burrill Lake as an example of a partially infilled system (Fig. 1.4). Apart from suggesting that the combined influences of local geology and antecedent valley topography are important in determining the degree of infilling, Jennings and Bird (1967) concluded that the specific nature of such relationships was not readily apparent. Therefore, accounting for variations in estuary infill was nominated as a primary research problem, a challenge taken up recently by Hunter (1989) and also addressed in this thesis.

Bird (1967a; 1967b) presented the first detailed geomorphic descriptions of estuarine depositional environments for systems located along the N.S.W south coast and north-eastern Victoria. Bird (1967a; 1967b) furthered his previous observations concerning the significance of apparent relationships between patterns in estuarine morphology and local geologic and geomorphic characteristics. This entailed identifying direct associations between the degree of estuary infilling and catchment lithology for a number of south coast estuaries. Thus, systems draining catchments featuring lithologies that are relatively susceptible to weathering and erosion (eg: weathered granite of Murrah Lagoon catchment, weathered monzonite of Narrawallee Inlet catchment) were found to be infilled to a greater extent than systems draining erosion resistant catchments (eg: metasediments of Wagonga catchment) (Fig. 1.4). Recognition was given, however, to the need to consider infilling in volumetric terms rather than simply areal extent (Bird 1967a). Volumetric calculations require detailed geophysical and stratigraphic data, both of which were unavailable to Bird (1967a, 1967b).

The barrier component of N.S.W. estuaries received considerable attention from a separate group of workers, including Thom (1965), Hails (1968), Hails and Hoyt (1968) and Langford-Smith and Thom (1969) but with a focus on the central coast region. The primary outcome of these early barrier studies was the identification of an Inner Barrier of Pleistocene age and a Holocene Outer Barrier in central coast embayments. In addition, both regressive (prograded) and transgressive (receded) barrier morphologies were recognised. However, the origin of the different barrier types was unclear (Langford-Smith and Thom, 1969).

3.3 ESTUARY AND BARRIER MAPPING: DOCUMENTING VARIABILITY

In describing the morphological character of the N.S.W. coast, Langford-Smith and Thom (1969) noted that the coast south of Sydney had suffered from lack of attention from researchers. Existing detailed studies included the work of Walker (1962) on the age of floodplain deposits of the lower Shoalhaven River and the investigations of Wright (1967, 1970) on the morphology and evolution of the Shoalhaven barrier complex and river delta. The problem of scant estuarine and barrier research was partially redressed through the efforts during the 1970's of Roy and Peat (1973, 1975a, 1975b, 1976), Thom (1974, 1978) Reinson (1973, 1977), Kidd (1978), Thom et al. (1978), Eliot (1979) and later Wright et al. (1980), Wearne (1984), Hann (1985), Bradshaw (1987), Klepetko (1988) and Hunter (1989) who set about the task of documenting in relative detail the morphostratigraphic characteristics of individual N.S.W. estuaries and barriers, which included numerous south coast systems. In essence, the work involved mapping the surface distribution of major sediment types and associated depositional environments. The investigations served to reinforce the polygenetic nature of estuarine sediments observed by earlier workers. In general terms, this character incorporated the following depositional environments: (i) fluvial channel and associated floodplain and delta; (ii) estuarine lake basin, and; (iii) seaward entrance channel and associated flood tide delta and barrier complex (Roy and Peat, 1973, 1975a, 1975b). Each environment was found to feature a distinct sediment type, which reflected the focussing of sediment from disparate sources into environments with contrasting depositional energy levels. Thus, floodplain and fluvio-deltaic environments feature terrestrially sourced sediments, mainly poorly sorted angular sands and sandy gravels of mixed mineralogy. The estuarine basin is typified by terrestrially derived muds and sandy muds. The seaward portion is characterised by well sorted, rounded, quartzose sands of marine origin (Roy, 1984a).

Through the collective efforts of those undertaking mapping, the morphologic and sedimentologic character of estuaries at different stages of infill emerged. The areal dominance of a particular depositional environment over one or both of the others in a particular estuary was recognised as defining the degree of infilling experienced by that system. For example, a geologically mature estuary features an areal dominance of floodplain and fluvial delta deposits over estuarine basin deposits. Once the physical properties of estuaries at various infill states had been documented, it became possible for models of estuary and barrier evolution to be postulated.

3.4 MODELS OF ESTUARY AND BARRIER EVOLUTION: EXPLAINING VARIABILITY.

An important conceptual contribution toward solving the dilemma of variability in depositional morphologies along the NSW coast was made by Davies (1974) with the application of the notion of the 'coastal sediment compartment'. The compartment concept had previously been developed by Shepard and Inman (1951) and Bowen and Inman (1966) for the Californian coast in the context of sediment budget studies within embayments bound by submarine canyons. At present sea-level there exists a discrete sediment store that occupies a compartment that extends from the seaward limit of effective wave reworking of bottom sediments to the landward limit of dunes. Davies (1974) argued that if store activity is thought of in geological time scales (e.g.: glacial-interglacial cycles) then the net volume of the store will not change if there are changes in sediment input and/or output. Rather, such changes merely bring about either a landward (shoreface erosion) or seaward (shoreface progradation) shift in position of the store.

The validity of this model for the N.S.W. coast must be questioned because it requires that the embayed morphology of interglacial times is maintained during glacial periods. The mid-shelf and outer shelf of south-eastern Australia has a low gradient and lacks the relief that characterises the present coast (Ferland, 1990). Therefore, the coast during lower sea-levels may be considered an open compartment in which sediment is free to be transported along the coast.

Davies (1974) proposed that the coastal compartment is analogous in its application to the stream catchment in terrestrial geomorphology insofar that it provides for the definition of a discrete area that may be considered an exclusive system, with negligible exchange of sediment between adjacent compartments (Davies, 1974). Clearly, the analogy does not apply during lower sea-levels when the coast was an open sediment compartment. Nevertheless, the compartment concept may be used to assist in the explanation of *existing* patterns of sediment distribution and transport through the terrestrial-marine transition zone, within individual compartments.

Concentrating on the southeast coast of Australia, Davies (1974) evaluated the relative significance of possible sources of sediment input and output to compartments in the context of the Late Quaternary period (Fig 3.1).

Of the inputs it was concluded that:

(i) coastal headland erosion is negligible due to the resistant lithologies that constitute headlands of the N.S.W. coast;

(ii) river input of eroded material from catchments has been important in the geologic past (lower sea-levels), but *appears* insignificant at present, with a few exceptions (e.g. Shoalhaven River);

(iii) onshore transport from the shelf has also been important in the past (mid-Holocene), but is no longer due to the establishment of a shoreface equilibrium profile;

(iv) littoral drift is generally negligible due to the strongly compartmentalised nature of the present-day coast, though varies from region to region. Presumably, littoral drift was far more important during lower sea-levels;

(v) autochtonous biological production provides only a minor contribution.

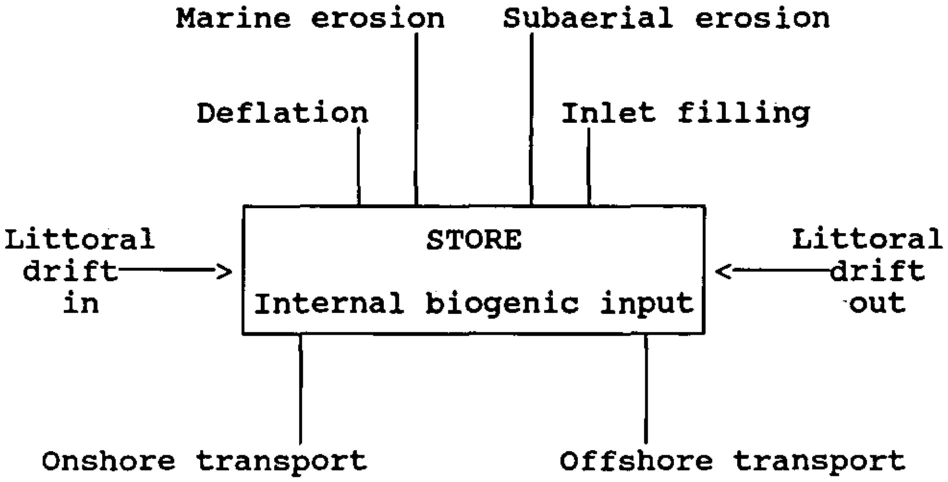


Figure 3.1: Inputs and outputs for coastal sediment compartments. (reproduced from Davies, 1974).

Of the outputs:

(i) offshore transport is insignificant, due to the strength of the onshore southeast and easterly swell;

(ii) movement into coastal inlets and estuaries is important;

(iii) movement inland by deflation of dunes is important;

(iv) littoral drift is again negligible but variable.

Davies (1974) postulated a general sediment transport budget by comparing the combined inputs to the total outputs and extended the budget in a temporal sense to formulate an evolutionary cycle of change in the budget. In this way, it is possible to demonstrate compartments at different points in the sediment budget cycle which are responding at different rates to the Postglacial Marine Transgression (PMT). A major factor in determining at which point in the cycle a compartment is at, is the infill state of the adjoining inlet or estuary. In the context of the most recent glacial to interglacial transition, four phases of estuary infilling were thus defined (Davies, 1974).

The first phase involved deposition of fluvial sediment on the continental shelf during the glacial low sea-level period. Phase two incorporated the early period of the high-stand (7000-4000 yrs BP) during which onshore movement of reworked sediments was relatively rapid and continuous, whereas delivery from rivers was low due to the elevation of river base levels associated with the PMT. By phase three (c. 4000 BP), the shelf had attained equilibrium with the new sea-level and the offshore supply of sediment became virtually depleted. Also, estuaries had achieved partial infilling by this time. The final phase is characterised by complete estuary infilling, allowing sediment to be delivered to the coastal compartment store (Davies, 1974).

Davies (1974) notes that few rivers supply significant volumes of sediment to the coast today, an observation supported by the work of Roy (1977) in the Hunter River. This has been largely attributed to the effective sediment trapping ability of estuaries, particularly the deeper basin portion and indicates that they are at phase three in Davies (1974) scheme. As noted previously, not all systems are at the same infill stage. There are examples of almost complete palaeovalley infilling (phase four) in systems now characterised by channels traversing the prior basin surface, such as the Shoalhaven River and Narrawallee Inlet. Yet these systems appear not to be delivering coarse sediment (traction load) to the coast, suggesting that in these cases phase four of Davies (1974) scheme has not come into full effect.

3.4.1 The estuary model

In attempting to explain the varied morphology of N.S.W. estuaries Roy et al. (1980) and Roy (1982; 1984a) devised an evolutionary model which incorporates a broad estuarine classification system. Roy (1982, 1984a) acknowledged that earlier estuarine stratigraphic, morphologic and hydrologic investigations had identified the absence of a common evolutionary path and suggests "...that different types of estuaries arise from the initiation of characteristic entrance conditions at the time the estuaries formed" (Roy, 1982). The condition of the estuary entrance is regarded by Roy (1984a) as a critical forcing factor in determining the general physical characteristics of a particular estuary. The entrance configuration and orientation, with respect to the prevailing onshore swell direction, is in turn a function of long term marine processes which are often overprinted by local geological factors (Roy, 1982). Belknap and Kraft (1985) also recognise the role antecedent topography plays in determining the nature of estuarine sedimentation in an ongoing transgressive setting on the Delaware coast.

Three types of estuary have been recognised on the basis of overall basin morphometry and condition of the seaward entrance (Roy, 1982, 1984a) (Fig. 3.2). The three types are:

Type I. Deep, open ocean entrance with full tidal range= Drowned river valley estuary.

Type II. Narrow entrance channels with attenuated tides= Bay-mouth barrier estuary.

Type III. Closed entrances= Saline coastal lake/lagoon.

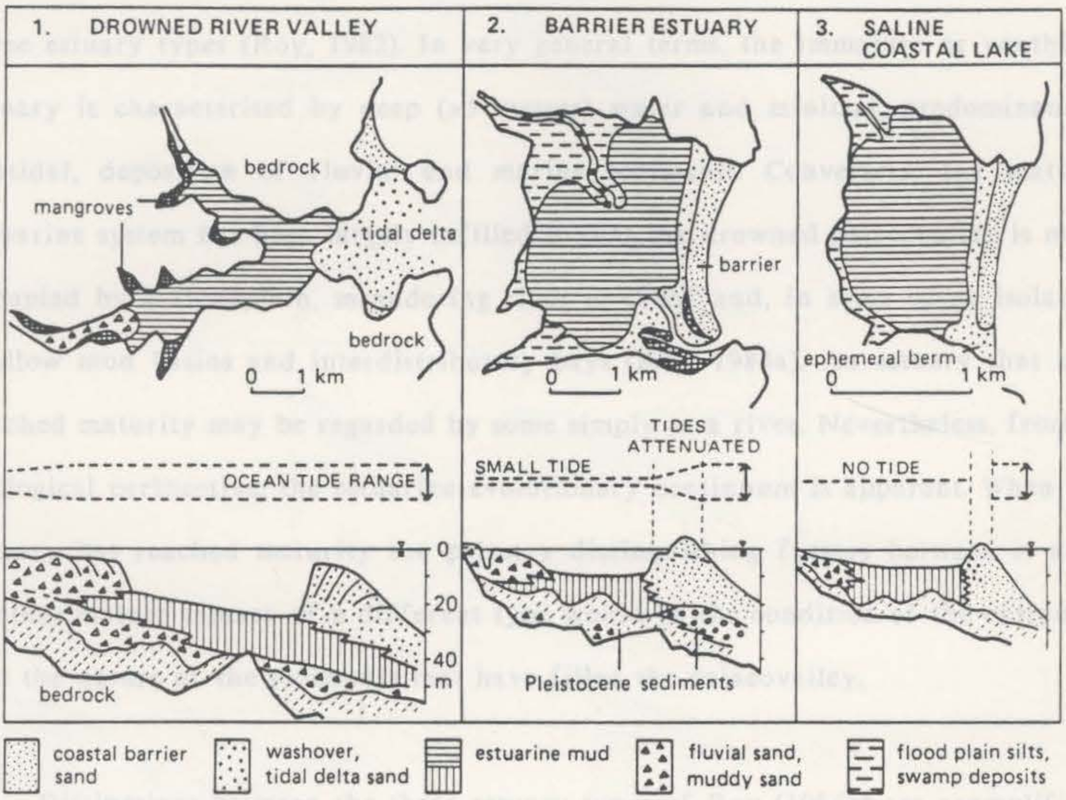


Figure 3.2: Three N.S.W. estuary types recognised by Roy (1984a).

The present day form of a particular estuary will determine what type of estuary it is classed as. It is too simplistic, however, to view estuarine systems as static. Roy (1982, 1984a) therefore, incorporates the concept of evolutionary change, whereby an estuary will evolve as a certain type through several stages as it approaches maturity. Implicit to this model is the concept that the different estuary types each feature distinguishable styles of sedimentation (Roy, 1984a).

The general stages of physical evolution of each estuary type have been postulated from observations of estuaries that are seen to be of the same type but are at different stages in their evolution. Identification of the stage of evolution, defined by the degree of palaeovalley infilling, allows for subgrouping of the three estuary types (Roy, 1982). In very general terms, the immature or youthful estuary is characterised by deep (>5 metres) water and minimal, predominantly subtidal, deposition of fluvial and marine sediments. Conversely, the mature estuarine system has been largely infilled so that the drowned palaeovalley is now occupied by a floodplain, meandering river or creek and, in some cases, isolated shallow mud basins and interdistributary bays (Roy, 1984a). An estuary that has reached maturity may be regarded by some simply as a river. Nevertheless, from a geological perspective, the estuarine evolutionary continuum is apparent. When an estuary has reached maturity the primary distinguishing factors between it and another mature estuary of a different type would be the condition of the entrance and the nature of the sediments that have filled the palaeovalley.

Distinctions between the three estuary types of Roy (1984a) are exemplified by the morphology of major sediment units and the internal characteristics of respective valley fills. Figure 3.3 illustrates three evolutionary stages (corresponding to phases two, three and four of Davies (1974)) for each estuary type. Roy (1984a) details the characteristics of each stage, suffice to note here that the most striking contrasts in depositional style are found at the seaward and landward portions of estuaries. All three types have a central lagoon or basin environment.

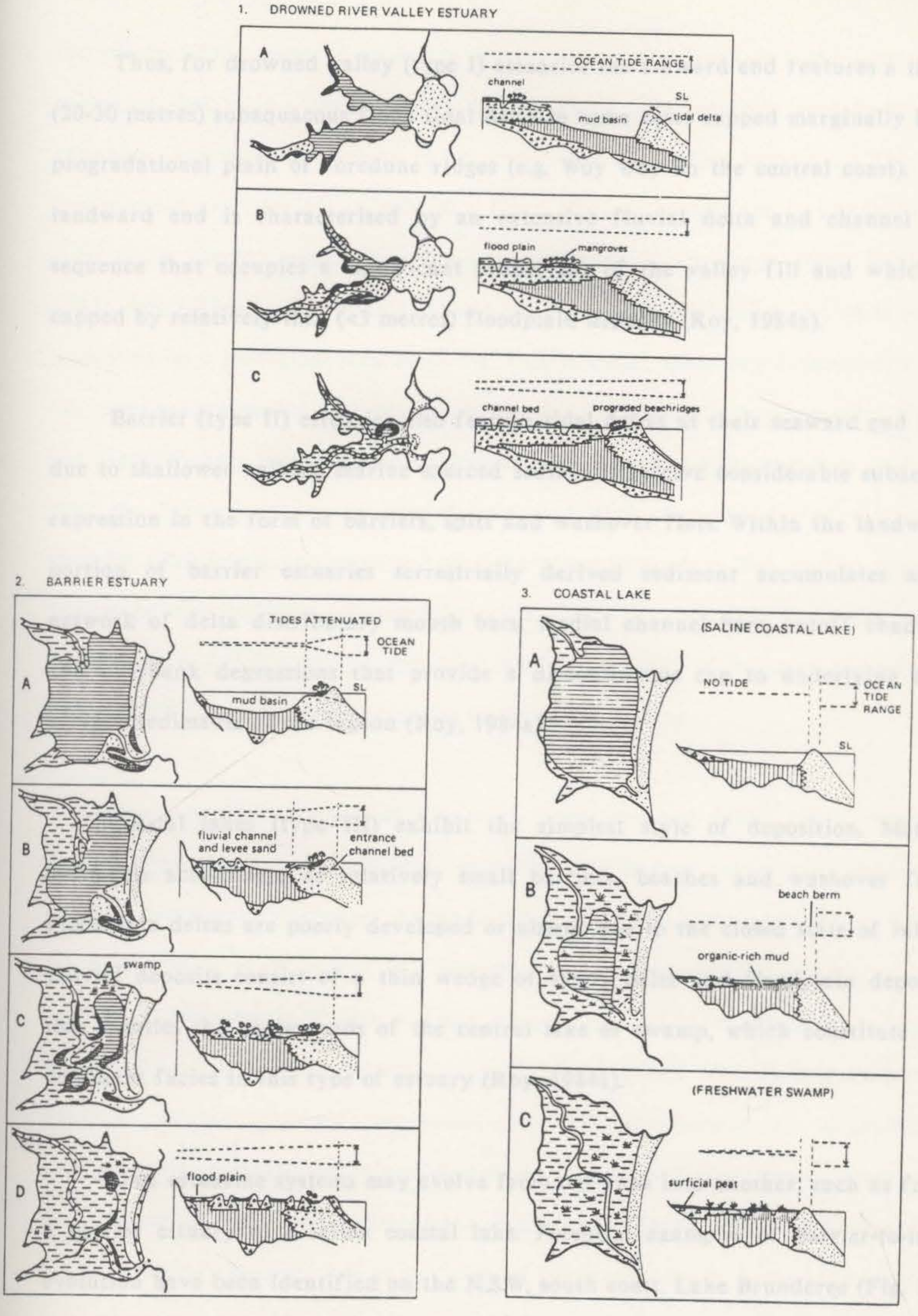


Figure 3.3: Evolutionary stages of the three types of N.S.W. estuaries (reproduced from Roy, 1984a).

Thus, for drowned valley (type I) estuaries the seaward end features a thick (20-30 metres) subaqueous flood tidal delta in some cases capped marginally by a progradational plain of foredune ridges (e.g. Woy Woy on the central coast). The landward end is characterised by an extensive fluvial delta and channel fill sequence that occupies a significant proportion of the valley fill and which is capped by relatively thin (<3 metres) floodplain deposits (Roy, 1984a).

Barrier (type II) estuaries also feature tidal deltas at their seaward end but, due to shallower valleys, marine sourced sediments receive considerable subaerial expression in the form of barriers, spits and washover flats. Within the landward portion of barrier estuaries terrestrially derived sediment accumulates as a network of delta distributary mouth bars, medial channel bars, cutoff channels and overbank depressions that provide a discontinuous cap to underlying fine grained sediments of the lagoon (Roy, 1984a).

Coastal lakes (type III) exhibit the simplest style of deposition. Marine sediments accumulate as relatively small barriers, beaches and washover fans. Flood tide deltas are poorly developed or absent due to the closed state of inlets. Fluvial deposits consist of a thin wedge of sandy delta and floodplain deposits that mantles the peaty muds of the central lake or swamp, which constitute the dominant facies in this type of estuary (Roy, 1984a).

Some estuarine systems may evolve from one type into another, such as from a barrier estuary to a saline coastal lake. Potential examples of barrier-to-lake evolution have been identified on the N.S.W. south coast. Lake Brunderee (Fig. 1.1) for example, is currently a coastal lake but was once open to regular tidal exchange, as evidenced by the infilled tidal channel extending from the basin to the barrier. This mode of evolution was not predicted by Roy (1984a) yet it is suggested that it is a result of the dissipation of tidal energies associated with changing entrance conditions, a process that Roy did recognise. That is, longitudinal and vertical growth of a flood tidal delta will act to attenuate the tidal prism thereby weakening tidal currents, hence scour (Roy, 1984a; Williams, 1983). Roy (1984a) refers to this process as a 'feedback mechanism' which is as yet unproven on a geological time scale. For this to occur, there is a requirement that sediment supply exceed the accommodation space available in a given inlet. Given the rapid onshore movement of sediment during the mid-Holocene it is probable that the barrier estuary to coastal lake transition occurred during this time, thereby establishing the estuary type soon after formation. The reverse process, lake to barrier evolution, requires that a tidal inlet be established and maintained. A mechansim for this will be presented later for barriers of the coast of southern Ireland and assessed for applicability to the N.S.W. setting.

The evolutionary model of Roy et al. (1980) and Roy (1982, 1984a) provides for the classification of individual estuaries into several sub-groups within the three major estuary types (see Appendix in Roy, 1982). The classification system of Roy (1982) as it stands is, however, entirely subjective, relying on the classifiers assessment of the relative amount of infilling achieved for each estuary. There is a need, therefore, for the development of a firm quantitative base to enable absolute expression of the significance of depositional environments in terms of their contribution to estuary filling. Such a base may also indicate a need for revision of the existing classification system. As stated in the introductory chapter, one of the aims of the present study is the generation of a database incorporating the quantitative information necessary for an objective classification. Chapter five presents the results of the statistical analysis of that database.

3.4.2 The barrier model

N.S.W. barrier and beach ridge complexes have received considerable attention from previous workers, with morphologic and stratigraphic studies making significant contributions to the formulation of coastal evolutionary models (Thom et al., 1978; Roy et al., 1980 Thom et al., 1981). Four barrier types have been recognised along the N.S.W. coast: (i) prograded; (ii) stationary; (iii) receded; and (iv) episodic transgressive (Thom et al. 1978). As for the estuary types, sub-types of barrier are also perceived and these are illustrated in Figure 3.4. In addition, composite barrier types exist but these are not discussed here.

Prograded barriers (Type 1) display a morphology that consists of a series of vegetated sub-parallel to parallel swash aligned foredune ridges. With the exception of the seaward ridge, all beach-ridges display a degree of podzolization. The most well developed podzol profiles are found in the older, landward ridges (Thom et al., 1978, 1981). Where present, the beach-ridge plain occupies the greater part of Zone A (eg: Moruya River estuary- 69.71%; Wonboyn River estuary- 70.2%; Narrawallee- 58.9%). The number of ridges varies between barrier systems, with approximately 40-50 at Moruya, 10 at Narrawallee and up to 60 in Wonboyn. Ridge height is typically between four and five metres above sea level, though the youngest ridge can be up to 10m asl (Thom et al. 1981).

Detailed drilling in the Moruya and Wonboyn beach-ridge plains has identified five lithostratigraphic units, including: (i) a basal Pleistocene deposit of estuarine organic clay with lenses of fine sand; (ii) a transgressive moderately sorted medium to coarse sand with gravel and minor shell; (iii) a regressive upward coarsening nearshore shelly medium to coarse sand; (iv) an upward fining well sorted and leached dune and beach sand; and (v) mobile sands of the modern foredune and shoreface area (Thom et al., 1978, 1981).

Type 2 (stationary) barriers are less complex than the prograded type. As implied by their name, stationary barriers possess a morphology that does not suggest either progradation or landward migration since the end of the PMT. Thus, they are defined by a single dune ridge that may be vegetated and well stabilised (Type 2a) or partially vegetated with a high dune (Type 2b). Both sub-types merge landward with backbarrier washover flats. These two sub-types are by far the most common barrier form along the N.S.W. coast. Type 2c barriers are relatively rare and have a tombolo morphology (Fig. 3.4) (Thom et al. 1978).

Stationary barriers typically comprise four stratigraphic units. These include: (i) basal Pleistocene sands with lenses of gravel and organic clays; (ii) transgressive slightly shelly sands of variable texture and mineralogy; (iii) regressive (nearshore) shelly sands; and (iv) capping aeolian dune and beach sands. The upper three units interfinger landward with thick back barrier sand deposits (Thom et al., 1978). The main difference between the stationary and prograded barrier stratigraphy is the absence of a thick backbarrier sand lithofacies from the latter barrier type.

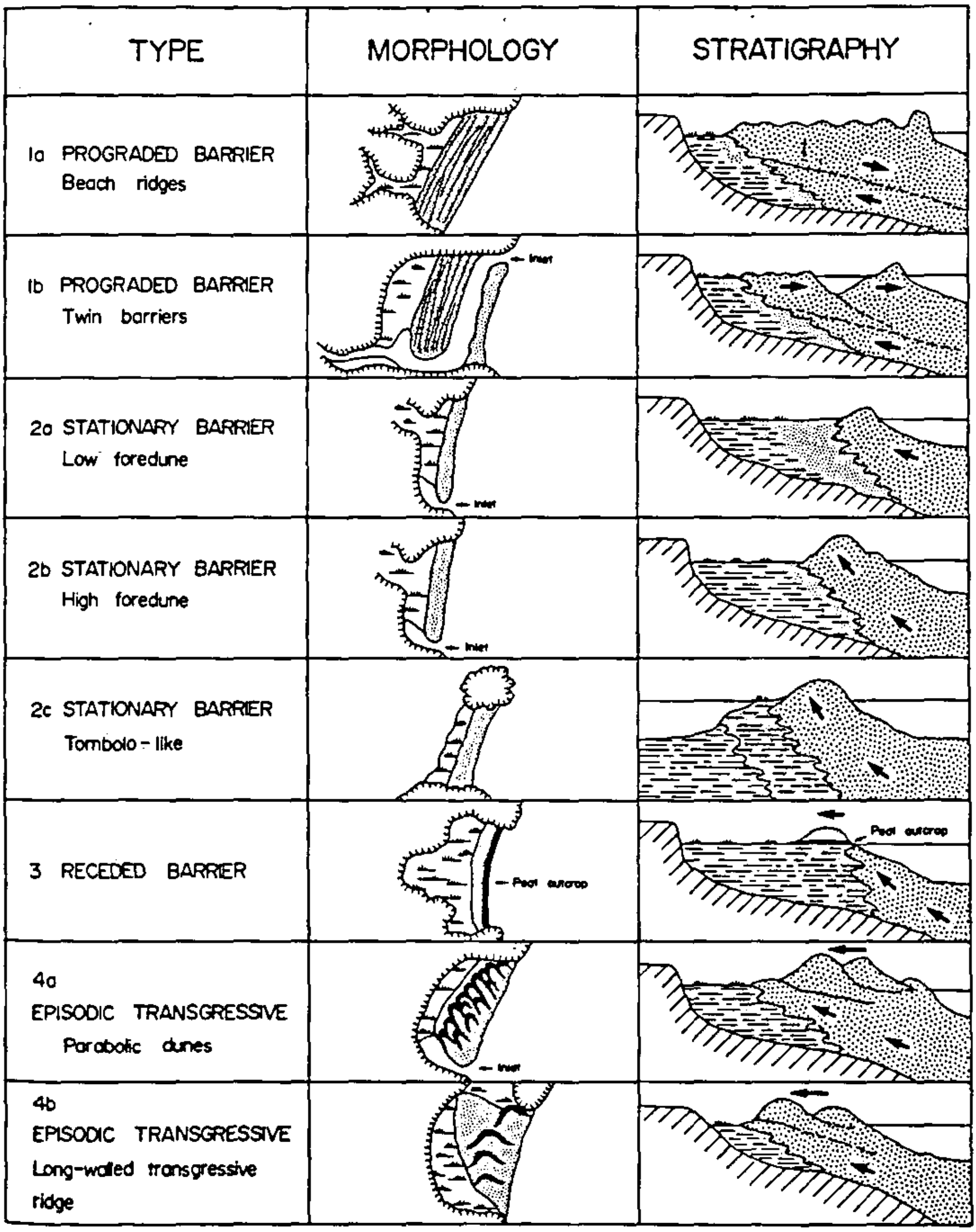


Figure 3.4: Barrier types of the N.S.W. coast, showing the Holocene (Outer Barrier) portion only. (reproduced from Thom et al., 1978).

Type 3 barriers are receded barriers that are characterised by a low ridge of aeolian sand with an eroding seaward face, as evident from outcrops of lagoon clay or peat (Fig. 3.4) (Thom et al. 1978). Barriers of this type are rare in N.S.W. The implication from this morphology is that the dune is moving landward in the manner described for many barriers of the Atlantic coast of North America. The stratigraphy of receded barriers is relatively simple, comprising a shallow (<10m) basal Pleistocene sand unit overlain by remnant Holocene backbarrier peats and capped by dune and beach sands.

The final barrier type, episodic dune barriers (Type 4) qualify as the largest and most impressive of the N.S.W. barriers. They exist as very high (>100m) fields of parabolic (Type 4a) and long-walled transgressive dunes (Type 4b) (Fig. 3.4) (Thom et al., 1978). The mobilisation of dunes appears to occur on an episodic basis. Due to their size, Type 4 barriers are restricted to the larger embayments along the coast (e.g. Bherwerre barrier at St.Georges Basin). These barriers may possess a Pleistocene core but the greater part of the stratigraphy consists of a thick aeolian unit, incorporating palaeosols and peat lenses, that can extend to below present sea-level. Where the aeolian sands do not continue below sea-level a basal transgressive-regressive sand sequence, similar in character to that in Type 1 and 2 barriers, is preserved (Thom et al., 1978).

3.5 NEW SOUTH WALES ESTUARIES IN A GLOBAL CONTEXT

A review of a representative portion of the vast international literature concerned with aspects of estuarine and barrier-lagoon sedimentation highlighted two features of prior research. First, the majority of investigations have been carried out along a few coastlines, notably the east coast of North America (see

Leatherman, 1987). Second, notwithstanding the bias toward certain coastlines, the enormous variability in depositional styles manifest among the estuaries of the world is well recognised. The scope of that variation, which exists at both the temporal and spatial scales, is succintly discussed by Wolfe and Kjerfve (1986) who attribute variablity to the fact that estuaries occupy the inherently stressful land-sea transition zone.

Following from the above, there is the real danger that facies models for estuarine complexes based on detailed local studies, may be insensitive to variation from conditions set by the study area(s) on which they are based and are probably no more than case examples of one point on a continuum (Boyd and Penland, 1984). A true generalised facies model must be flexible to allow application at the global scale (Walker, 1984). Nevertheless, construction of facies models requires detailed local and regional investigations because collectively they will define the limits of estuarine variability. Because estuaries themselves are probably an endmember of a tripartite group of landforms (deltas, barriers and estuaries), variability may be expressed as a continuum between different estuary types and it is important that the full extent of variability is recognised. The present study of sedimentation in N.S.W. estuaries represents a single estuary type (wave-dominated, micro-tidal) along the continuum. The purpose of this section is to distinguish N.S.W. estuaries in the context of the spectrum of variation that is apparent on a global scale. Further, it will be argued that N.S.W. estuaries are significant in global terms because they represents an end-point on the continuum that is not adequately represented in the literature.

A frequently used benchmark for placing a particular study area in a global context and for comparing coastal depositional systems in disparate geographical settings is provided by the suite of factors that influence depositional conditions at a given location (e.g. Berelson and Heron, 1985; Boyd and Penland, 1984; Hails and Hoyt, 1968; Kelley et al., 1986). These forcing factors include the relative importance of wave, tide and fluvial energy, combined with local sea-level history. Clearly, the specific character of each factor will be an expression of geologic and climatic conditions at a particular site, so they must also be considered when comparisons are drawn. As discussed in chapter one, these factors may be conceptually modelled to define a spectrum of potential process conditions. The present review of contrasts between southern N.S.W. estuaries and those found along coastlines elsewhere will therefore be made in the context of that process spectrum. In addition, comparisons require consideration of the relative importance of available sediment sources and sinks and associated transport mechanisms operating at a location, because they collectively influence the style and evolution of coastal depositional systems.

In the interests of brevity, the review will be confined to embayed coasts where estuarine sedimentation is strongly influenced by antecedent topography, otherwise termed an incised valley setting. The contrast in depositional style between incised valley estuaries and coastal plain lagoonal systems has been dealt with previously (e.g. Emery, 1967; Davies, 1974, 1980; Kraft and Chrzastowski, 1985) and is recognised as important in terms of overall variability of paralic environments but not central to the present task.

The focus of discussion regarding variability of incised valley estuarine deposition will be upon the coastlines of North America, southern Ireland, China, Brazil and South Africa. These were chosen primarily because they incorporate a broad range of environmental conditions. In addition, having received considerable attention from researchers, they are among the most understood of the world's coasts, thereby providing a sound base for comparative analysis.

3.5.1 North America

3.5.1.1 United States and Canadian Atlantic coast

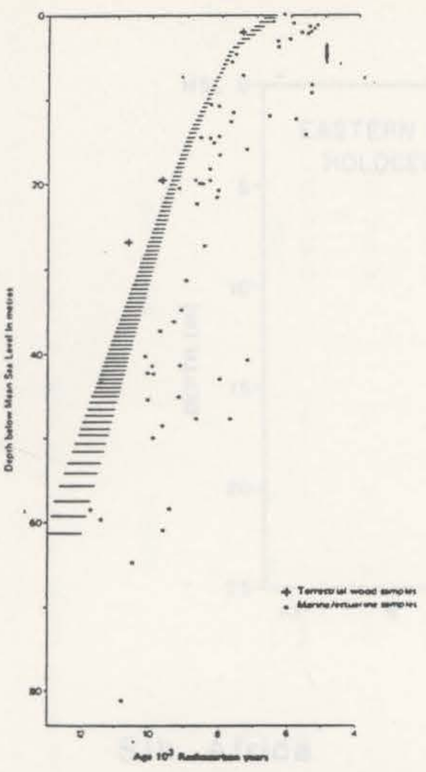
Much of the Atlantic coast of North America is characterised by a broad, low gradient coastal plain suitable for barrier island formation (Leatherman, 1979). It is only along the central and northern sections of the United States coast and southern Canadian Atlantic coasts that an incised valley estuary setting exists. Three sections of the northern United States. and Canadian coast will be reviewed: Delaware; Maine, and; Nova Scotia. Each provide interesting and relevant contrasts to the N.S.W. coast.

Whilst general similarities in wave and tidal regimes may be found, the primary contrast between the eastern Australian and eastern North American settings lies in the relative sea-level (RSL) history since the last glacial period. The configuration of bedrock valleys also differs but it is argued that RSL history is probably the more important factor. Late Quaternary sea-levels along the eastern Australian coast were detailed in chapter two. To reiterate, the east coast experienced a uniform rapid rise in RSL during the post-glacial transgression culminating in a highstand at c.6500 yrs. BP that has since remained essentially unchanged (Thom and Roy, 1983). Rates of RSL rise along northeastern North America have varied from being relatively slow (11 cm per century for southern Maine) (Belknap et al., 1987) to fast (40 centimetres per century for Nova Scotia) (Boyd et al., 1987) and is ongoing. Figure 3.5 shows Late Quaternary RSL curves for the coasts discussed below. The differing sea-level scenarios are reflected in the morphology and stratigraphy and evolution of respective estuarine systems.

(a) Delaware: The Delaware coast is one of the most studied sections of coast in North America (e.g. Kraft, 1971; Sheridan et al., 1974; Halsey, 1979; Kraft et al., 1979; Belknap and Kraft, 1985; Kraft et al., 1987; Fletcher et al. 1990). The antecedent topography is characterised by a dendritic drainage network incised into a low gradient, low relief coastal plain and shelf by rivers and glaciers during the Quaternary (Halsey, 1979; Belknap and Kraft, 1985). The tide regime is comparable to that of the N.S.W. coast, with tides varying between microtidal and low mesotidal. Wave energy, however, is significantly less than N.S.W. and is classed as moderate. The mean annual wave height along the Delaware coast ranges between 0.4 and 0.8 metres (Belknap and Kraft, 1985). In terms of Davies (1974) coastal sediment compartment, the Delaware coast also possesses a sediment store that is efficiently recycled via input and output paths during and after shifts in RSL. The relative importance of inputs and outputs, however, differ from Davies (1974) eastern Australia model (Table 3.1).

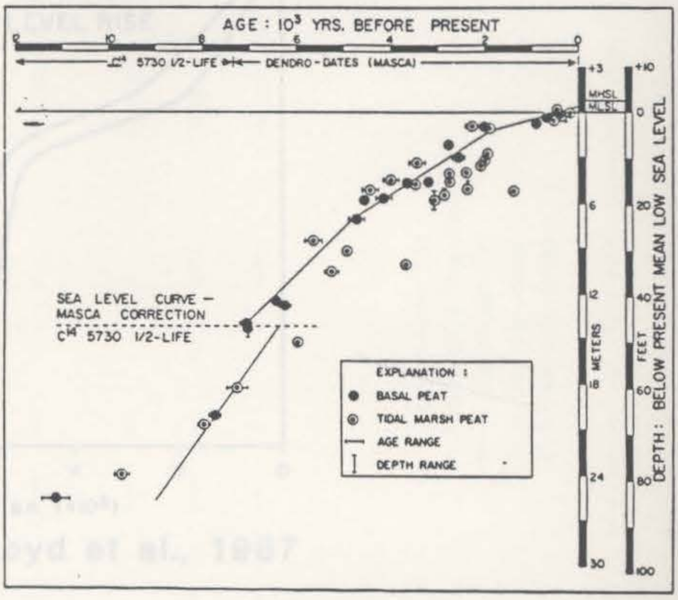
Erosion of headlands and onshore transport of sediment via processes of shoreface erosion act as the primary sediment input sources (Kraft et al., 1987). Input from the inner shelf, littoral drift and estuary catchments via rivers is relatively minor. The Delaware coast is allochthonous, hence autochthonous bioproduction of sediment is assumed by Kraft et al. (1987) to be minor.

S.E. Australia

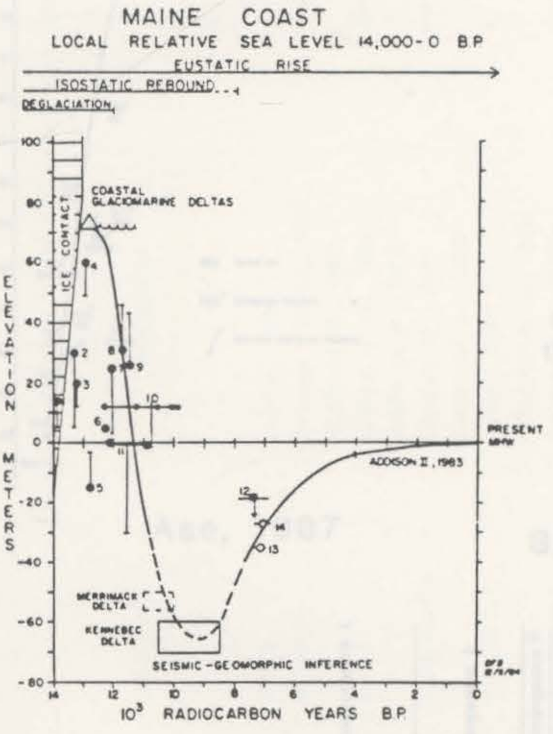


Roy and Thom, 1983

Delaware



Belknap et al. 1987



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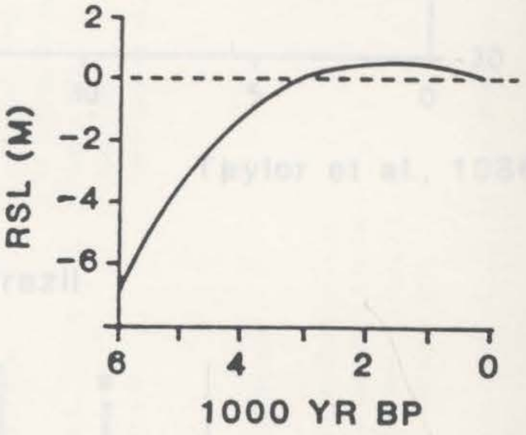
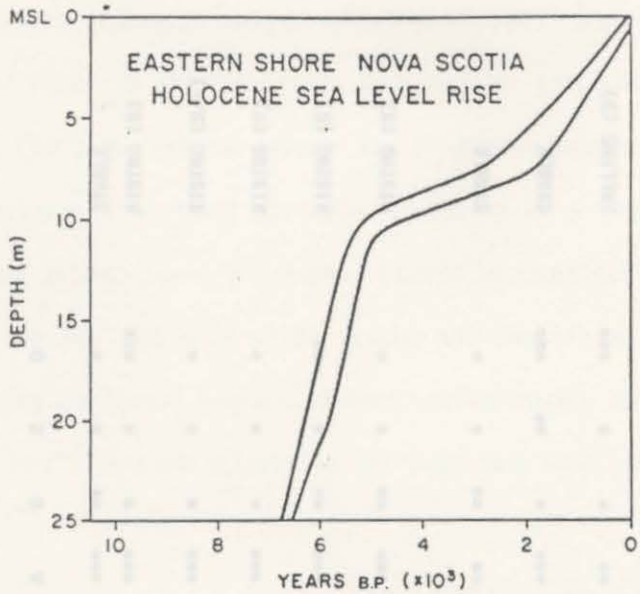
N.W. U.S.A.



Clark and Lingle, 1979

Figure 3.5: Late Quaternary RSL curves for coasts discussed in the text.



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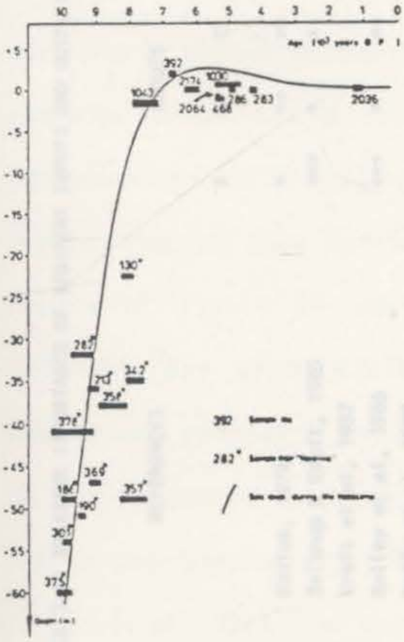
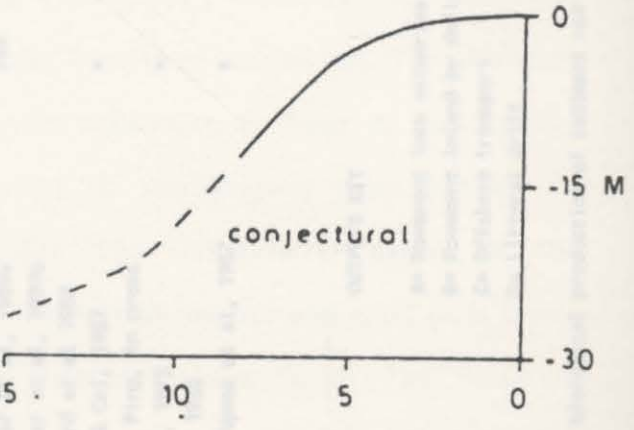


Ase, 1987

S.E. Ireland



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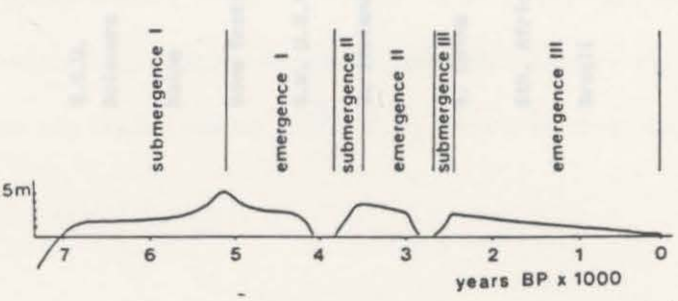


Dominguez et al., 1987

TABLE 3.1: RELATIVE IMPORTANCE OF SEDIMENT INPUTS AND OUTPUTS FOR SELECT INCISED VALLEY COASTLINES OF THE WORLD

COASTLINE	REFERENCES	INPUTS				OUTPUTS				RSL STATUS
		A	B	C	D	A	B	C	D	
N.S.W.	Davies, 1974	*	**	**	*	***	**	*	*	STABLE
Delaware	Belknap & Kraft, 1985 Kraft et al, 1987	***	*	*	***	***	*	*	***	RISING (S)
Maine	Kelley et al, 1986 Duffy et al, 1989	***	*	**	*	***	*	*	*	RISING (S/F)
Nova Scotia	Boyd et al, 1987 Carter et al, 1989	***	*	*	*	***	*	*	*	RISING (F)
N.W. U.S.A.	Anima, 1989 Peterson et al, 1984	*	***	*	***	***	**	*	**	RISING (S)
S. Ireland	Carter et al, 1989a Carter et al, 1989b Orford et al 1988	***	*	*	*	***	**	*	*	RISING (S)
N. China	Cai & Cai, 1987 Li & Ping, in press	*	***	*	*	**	**	*	*	STABLE
Sth. Africa	Orme, 1973 Ase, 1986	*	***	**	***	***	*	**	***	STABLE
Brazil	Dominguez et al, 1987	*	**	*	***	**	*	*	***	FALLING (S)

INPUTS KEY

A= Headland erosion
B= Catchment erosion
C= Onshore transport
D= Littoral drift

OUTPUTS KEY

A= Movement into estuaries and inlets
B= Movement inland by deflation
C= Offshore transport
D= Littoral drift

* = insignificant I/O
** = moderately important I/O
*** = significant I/O
(S) = slow RSL change
(F) = fast RSL change

n.b. Input via autochthonous biological production of sediment not included because it is minor for all siliclastic coastlines considered here

The primary sediment output pathways include movement via littoral drift and landward flux via tidal currents into barrier spit and tidal delta complexes (Kraft et al., 1987). Aeolian processes are of minor importance. Wave and littoral transport dominate over tidal processes resulting in a relatively straight barrier coast with few inlets. These processes operate in conjunction with the continued RSL rise (33 cm per 100 yrs) which erodes the shoreface to a mean depth of 10 metres, ensuring continual reworking and redistribution of the sediment store via littoral drift and landward migration via overwash and inlet filling (Kraft et al., 1987).

Kraft et al. (1987) note that barrier morphology and evolution is generally consistent but that there is considerable variability in barrier dimensions due to variation in antecedent topography. Thus, barriers are widest (4-6 km) where they comprise a barrier-spit and tidal delta ("sea-island" barriers), and narrowest (approaching 0 m) at headlands ("linear" and baymouth barriers). Barrier thickness ranges from less than 5 metres to 25 metres, depending on depth of palaeovalley incisement. Figure 3.6 reproduces a series of stratigraphic cross sections of Rehoboth Bay from Kraft et al. (1987). The transgressive nature of the depositional complex is clear in cross section A, with barrier and tidal inlet facies in erosive contact with the underlying Holocene lagoon facies. The Delaware barrier stratigraphy is closely similar to that described for N.S.W. receded barriers (Thom et al. 1978). The control of antecedent topography is illustrated in cross section B where thickest accumulations of lagoon and barrier sediments are preserved in pre-Holocene stream valleys. Where the pre-Holocene surface is shallow, preservation of lagoon facies is poor, the barrier facies being in direct contact with the pre-transgression surface, as shown in cross section C (Fig. 3.6).

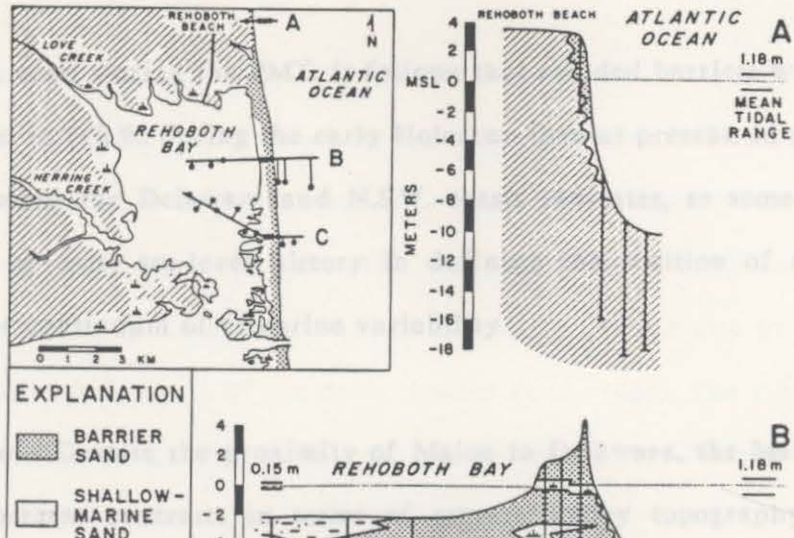


Figure 3.6: Barrier-lagoon stratigraphy, Rehoboth Bay, Delaware. (reproduced from Kraft et al., 1987).

Antecedent topographic control has been nominated as the primary factor in determining the evolution and, ultimately, the preservation style of Delaware's barrier deposits (Belknap and Kraft, 1985; Halsey, 1979; Kraft et al., 1987). That the Delaware coast is not as embayed as the N.S.W. coast is attributed to the fact that the level of maximum transgression has yet to be attained. The Delaware coast, therefore, provides a possible modern analogy for the general morphology of the N.S.W. coast during the PMT. It follows that receded barriers were probably more common in N.S.W. during the early Holocene than at present. In addition, the contrast between the Delaware and N.S.W. coasts indicates, to some degree, the significance of local sea-level history in defining the position of an estuarine setting on the continuum of estuarine variability.

(b) Maine: Despite the proximity of Maine to Delaware, the Maine coastline exhibits important contrasts in terms of estuary valley topography. Thus, the general geological setting of the Maine coast is such that it is strongly embayed and compartmentalised. Duffy et al. (1989) divide the Maine coast into four compartments on the basis of geological structure and topography. These compartments are characterised, respectively, by broad arcuate embayments, broad estuary valleys with bedrock islands and, two compartments of narrow deeply incised estuary valleys (Duffy et al., 1989). There is considerable contrast in bedrock type between compartment types, including low grade and high grade metasediments, metavolcanics and plutonic rocks.

Tidal range, wave energy and the rate of sea-level rise along the coast of Maine all increase toward the northwest. Tidal range increases from 2 metres (mesotidal) in the southwest to over 6 metres (macrotidal) in the northwest. Wave energy increases from low (0.39m) in the S.W. to moderate (0.44-0.61m) in the N.W., though this pattern is interrupted by high energy storm events. Rates of RSL rise also increase in the same direction from 11 cm per century to 32 cm per century, rates which are comparable to the Delaware coast (Belknap et al., 1987; Duffy et al., 1989).

With respect to sediment sources and sinks, the primary inputs derive from erosion of glacial headlands and onshore transport of reworked sediment as sea-level continues to rise. Being of glacial origin, the sediments comprising the barriers of Maine are coarse and poorly sorted. Delivery of sediment, via rivers, from the hinterland is minor and littoral drift insignificant due to the strongly compartmentalised structure of the coast (Kelley et al., 1986). The major sediment sink is deposition in estuaries and inlets, with negligible offshore loss, inland deflation, or littoral drift (Table 3.1).

Five barrier-lagoon types were recognised for the Maine coast by Duffy et al. (1989) on the basis of barrier morphology. They include: (i) barrier spit; (ii) looped barrier; (iii) cuspate barrier; (iv) double tombolo, and; (v) pocket barrier. The terms employed by Duffy et al. (1989) allude to the general nature of barrier form along the Maine coast. The specific traits of each barrier type are detailed by Duffy et al. (1989), suffice here to note that all types are anchored at one or both ends to bedrock headlands, emphasising the strongly embayed character of the coast. In terms of N.S.W. estuary types recognised by Roy (1984a), the Maine estuaries and lagoons appear to equate with Type II (bay-mouth barrier estuary) and Type III (saline coastal lake).

The distribution of barrier types varies among the four coastal compartments, with no preferred pattern. Although, Kelley et al. (1986) demonstrated different styles of valley infill in two adjacent estuaries that mark the boundary between an arcuate embayment compartment and a narrow incised valley compartment. In essence, the different infill styles result from contrasting source rocks, granite and fine grained metamorphics, respectively.

Stratigraphic investigations of backbarrier environments revealed four types of sequence that correlate strongly with the presence or absence of inlets through the barrier (Duffy et al., 1989). The influence of inlets is recorded in the type of backbarrier marsh (low salt marsh or brackish to freshwater marsh) preserved in the subsurface. Salinity variations, hence inlet opening or closure, are inferred from marsh type (Duffy et al., 1989). Thus, the four vertical sequences include: (i) a uniform freshwater marsh sequence for barriers lacking inlets; (ii) a saline to brackish to freshwater marsh upsequence transition, recording lagoon infilling with decreasing marine influence; (iii) a freshwater to brackish to marine transition, formed in response to increased marine influence due to rising sea-levels, and; (iv) a variable brackish to fresh to brackish vertical sequence associated with fluctuating marine influence due to ephemeral inlets (Duffy et al., 1989). Of the four sequences, the fresh to marine type is by far the most common along the Maine coast (Duffy et al., 1989). Types one and four display a stratigraphy that may be found in the coastal lakes of N.S.W., whereas type two may equate with mature barrier estuaries.

There is no clear association between backbarrier stratigraphy and coastal compartment, though there is a weak relationship between stratigraphy and barrier morphology. Figure 3.7 shows a typical stratigraphic cross section for a coarse clastic barrier-lagoon system on the north-west coast of Maine (Duffy et al., 1989). The sequence is not unlike that reconstructed for the Delaware coast and for N.S.W. receded barriers, insofar that it records the landward migration of the barrier facies over lagoon and marsh facies. The absence of a permanent inlet means that flood tide delta deposits are not preserved. Interestingly, the Maine sequence is analogous to the sequence predicted for Delaware, given continued sea-level rise (Kraft et al., 1987, Fig. 9). The predicted Delaware sequence would occupy an embayed coast of similar shape to the modern Maine coast.

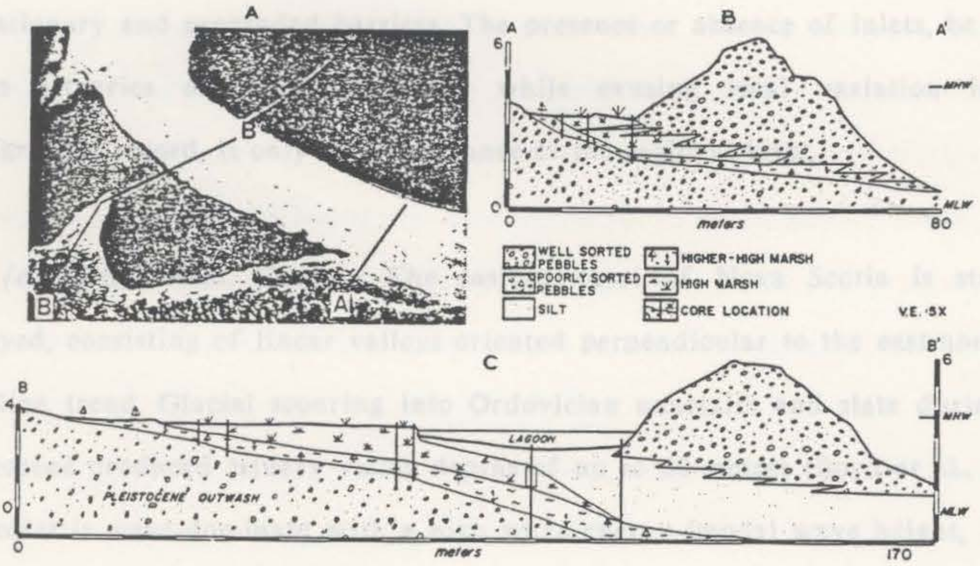


Figure 3.7: Barrier-lagoon stratigraphy, Maine (reproduced from Duffy et al., 1989).

In summary, the evolution and resultant stratigraphy of Maine estuary valley deposits is closely linked with the condition of the estuary mouth. The influence of regional variation in bedrock, valley morphology and processes such as tidal range and RSL rise are recognised but considered of secondary importance by Duffy et al. (1989). These findings are in accord with the significance placed on estuary entrance condition as a factor influencing modes of estuary evolution by Roy (1984a) for N.S.W. estuaries. Further, the recording of variable salinity conditions in lagoon stratigraphy along the Maine coast corresponds in a general fashion to the barrier estuary (type II), coastal lake (type III) contrast for the N.S.W. coast. In a broader context, however, the RSL setting must be ranked as the primary factor in determining the overall character of coastal depositional sequences. For Maine, the RSL setting is transgressive resulting in a receded barrier-lagoon type stratigraphy that records the retreat of barriers. In contrast, the stillstand conditions of N.S.W. result in a preponderance of stationary and prograded barriers. The presence or absence of inlets, be it for Maine estuaries or N.S.W. estuaries, while causing local variation in the stratigraphic record, is only of significance at the regional level.

(c) Nova Scotia, Canada: The eastern coast of Nova Scotia is strongly embayed, consisting of linear valleys oriented perpendicular to the east-northeast shoreline trend. Glacial scouring into Ordovician quartzite and slate during the Pleistocene produced estuary valley depths of up to 60 metres (Boyd et al., 1987). The coast is wave-dominant with a high wave energy (modal wave height, 1.5-2.0 metres) that peaks during winter storms and a spring tidal range of 2.1 metres (low mesotidal) (Boyd et al., 1987; Carter et al., 1989b).

The Holocene evolution of the coast has been characterised by continual landward shoreline migration at a rate of approximately 1 metre per year as RSL has risen by 35-40 centimetres per century and is accelerating (Boyd and Penland, 1984; Boyd et al., 1987; Carter et al., 1989b; Scott et al., 1987). The eastern Nova Scotia coast thus qualifies as having the most rapid ongoing RSL rise under consideration here. Although, similar rates of transgression are postulated for the PMT of southeastern Australia (Thom and Roy, 1983).

The primary source for sediment input to coastal depositional systems has been erosion of unconsolidated coarse grained glacial till and drumlin fields deposited on the shelf during low sea-level and reworking of drowned barrier systems formed in the early to mid Holocene (Boyd and Penland, 1984; Boyd et al., 1987) (Table 3.1). Till and bedrock headlands provide anchor points for barriers. Input via catchment erosion is restricted to the upper limit of estuaries due to the effect of the continued RSL rise. Onshore transport is of moderate importance due to the pace of RSL rise which causes offshore sediment accumulations to become stranded and reworked by shelf currents (Carter et al., 1989b). The significance of littoral transport as an input pathway is also minor because of the deeply embayed shoreline shape (Boyd and Penland, 1984). Within compartments, however, longshore transport of sediment is the primary mechanism for the transfer of material from headlands to barriers (Boyd et al., 1987).

Routes for sediment ouput are as limited as inputs. Movement into estuaries and inlets is the principal manner for sediment to adopt a sink position. Rising sea-level coupled with tidal currents, storm overwash and limited aeolian processes provide the mechanisms for movement into estuaries. Clearly, given the sea-level setting, offshore losses from the present sediment store are negligible. As mentioned above, sediment exchange between embayments via littoral drift is not effective for the Nova Scotian coast.

The resultant style of estuarine deposition consists of bay-mouth barriers composed of sand and gravel with permanent tidal inlets and associated flood tide delta deposits. These complexes are continually adjusting to the marine transgression by retreating landward, which in turn causes river base levels to elevate, thereby preventing significant volumes of terrigeneous sediments to accumulate in lagoons. Boyd and Penland (1984) note that the transgressive lag on the shelf is only 1-2 metres thick indicating that barrier migration is efficient and complete. There are examples of lagoon filling (e.g. Black Island lagoon) but sediments are of marine origin deposited as flood tide deltas which provide a sufficiently shallow lagoon for marsh colonisation (Carter et al., 1989b). Given continued RSL rise, such basin environments will be shortlived, though they are well preserved in the stratigraphic record due to the rapidity of the transgression, as predicted by Davis and Clifton (1987).

Variations in barrier morphology exist according to the evolutionary stage attained by the barrier, which is in turn a function of variations in the volume of sediment supplied to the barrier (Carter et al., 1989b). Thus, in areas of sediment abundance, mature barriers develop either progradational features such as beach ridges or large flood tide delta and washover in addition to the main barrier-spit (Carter et al., 1989b). Where the source of sediment becomes depleted (i.e. a drumlin is consumed) barriers respond by stretching and thinning through local drift and swash processes. Ultimately, such barriers become over extended and are breached and partially destroyed (Carter et al., 1989b). Changes of this nature are rapid and have been observed in historical times (Boyd et al., 1987).

The diversity of barrier and lagoon morphology along the east coast of Nova Scotia has allowed the formulation of a six stage evolutionary model (Fig. 3.5) (Boyd et al., 1987; Scott et al., 1987). The model does not incorporate stratigraphic information, presumably because of the difficulty in obtaining such data from coarse clastic barriers. Nevertheless, the contrasts between the Nova Scotian model and the models of Davies (1974) and Roy (1984a) for the N.S.W. coast are marked. The former is characterised by instability of coastal depositional systems initiated by a transgressing sea, the latter by relative sea-level stability enabling depositional systems to develop fully. The Nova Scotia model is detailed by Boyd et al. (1987), suffice here to note that it emphasises the efficient recycling of sediment through barrier migration with rising sea-level. Reworking of sediment is so complete that it includes the drumlin headlands to which barriers are attached. A subtidal shoal of boulders is all that remains of former drumlins (Boyd et al., 1987; Scott et al., 1987). The Nova Scotia barrier-lagoon coast, therefore, provides a setting where the legacy of the glacial period is striking, yet the sea-level scenario remains the primary forcing factor in the evolution of coastal depositional systems.

3.5.1.2 United States Pacific coast

The Pacific coast of the United States, considered briefly here, provides an active-margin incised valley estuary setting that contrasts the passive-margin setting of the Atlantic coast and southeast Australian coasts. The Pacific Northwest, including northern California to Oregon and Washington, is characterised by numerous small high-gradient drowned river valley estuaries evolving under a (storm) wave-dominant process regime (Peterson et al., 1983). The tides are low mesotidal (2 metres) and the wave energy is moderate (Davis and Clifton, 1987). Being an emergent coastline, the Holocene RSL history is complex but may be summarised as having risen from -130 metres at a relatively rapid rate in the early Holocene due to eustatic submergence, slowed by 7000-6000 years BP and has continued to rise at a decreasing rate to the present level (Davis and Clifton, 1987; Clark and Lingle, 1979).

The primary sources of sediment are fluvial input and littoral drift, with the former dominating. Headland erosion and onshore transport of sediment are less important sediment inputs (Anima, 1989; Clifton, 1989; Peterson et al., 1984) (Table 3.1). Output routes from the coastal sediment compartment are primarily via tidal current transport into inlets and deflation of dunes into estuaries. Losses by littoral drift processes also occur.

Variation in barrier and lagoon morphology appear to be minimal, with barriers anchored to bedrock headlands and cut by a single tidal inlet. Inlet width ranges from tens of metres (e.g. Salmon River estuary) (Peterson et al., 1983) to several kilometres (e.g. Willapa Bay) (Clifton et al., 1989). Variability in estuarine character is expressed primarily by differences in the relative significance of sediment derived from marine and fluvial sources (Peterson et al., 1983). In general terms, Peterson et al. (1983) found in six Oregon estuaries that those with a low ratio of mean tidal prism volume to mean annual fluvial discharge were dominated by fluvial sediment (>70 per cent of estuary surface). Given, sufficiently low tidal to fluvial ratio it is expected that such systems would eventually deliver fluvial sediment to the coastal sediment store (Peterson et al., 1983). Conversely, a high ratio of tidal prism to fluvial discharge correlates with a dominance (>50 per cent of estuary surface) of marine sourced sand in estuaries. Estuaries of this type are acting as primary sinks of sediment from the coastal store.

It appears, therefore, that the Oregon estuaries examined by Peterson et al. (1983) are at an evolutionary stage whereby fluvial processes are leaving a clear sedimentological signature. Sea-levels have not realised a stillstand position but the gradient of coastal rivers is steep enough to ensure delivery of catchment derived sediment to estuaries. Unfortunately, the significance of fluvial deposits in the stratigraphic record is not known because Peterson et al. (1983) do not present subsurface data. Nevertheless, Peterson et al. (1983) postulate from their observations of variations in the relative abundance of fluvial sediment that a trend toward greater volume of fluvial sediment and increased mean grain size may be indicative of the latter stages of estuary infill, if sea-level were stable. Sea-level stillstand conditions do exist along the N.S.W. coast and many estuaries display a significant fluvial component. The N.S.W. estuaries, therefore, provide evidence to support the hypothesis put forward by Peterson et al. (1983). Furthermore, the importance of the N.S.W. setting in global terms is underlined.

3.5.2 Southern Ireland

The southern coast of Ireland presents an interesting and important contrast to transgressive coastlines discussed thus far. The detailed RSL history for the southern Irish coast remains unclear but the general pattern is one of an ongoing yet decelerating transgression and is considered close to adopting a stillstand position (Carter et al., 1989a). In the RSL context, therefore, southern Irish estuaries lie somewhere between the extremes of the N.S.W. stillstand setting and the Nova Scotian rapid transgression setting. The coast is wave-dominant with a mean tide range of about 1.5 metres (microtidal) (Orford et al., 1988, Fig. 6) and a wave climate of high to moderate energy but strongly influenced by the southwest long period swell (Carter et al., 1989b).

Barrier-lagoon systems occur within glacially scoured embayments and present a range of morphological and evolutionary traits that are controlled by the presence or absence of tidal inlets. Four barrier-lagoon types are recognised by Carter et al. (1989b), including two types of freshwater lagoon that drain seaward either by seepage through the barrier or surface channel flow, brackish lagoons with ephemeral entrances and, permanently open saline lagoons.

Sediment held in the coastal store is sourced principally via erosion of sand and gravel from glacial till sea cliffs that is subsequently transported by longshore currents, and to a lesser extent from input of catchment derived fluvial material (Orford et al., 1988). Onshore transport of sediment from the shelf is thought to have ceased in the mid-Holocene once the rate of RSL slowed (Carter and Orford, 1984). Littoral drift also became insignificant as barrier systems retreated into their respective embayments, thereby dissecting transport pathways with bedrock headlands (Carter et al., 1989b; Orford et al., 1988).

Sediment output routes vary depending on barrier morphology. Thus, for barriers lacking tidal inlets, sediment is delivered to lagoon sinks by both aeolian and storm overwash processes. Alternatively, barriers with permanent inlets provide a tide generated path for movement of material into lagoons. Ephemeral inlet barriers experience a composite of all three processes. Losses from the coastal store through offshore and littoral transport are negligible for the Irish coast (Carter et al. 1989b; Orford et al., 1988).

An interesting relationship exists between the condition of estuary mouths (open, ephemeral or closed) and the stability of barriers. This relationship is seen to be integral to the evolution of barrier-lagoon complexes under conditions of slow to negligible RSL rise (Carter et al., 1989b). Thus, for lagoons permanently open to tidal exchange, barriers comprise multiple spits anchored at one end to headlands, ebb and flood tide deltas and dunes. Tidal processes have sorted the barrier sediment into discrete textural elements. That is, the coarsest fraction (gravel and cobbles) occurs as a basal lag deposit in barriers upon which the finer material (sand) accumulate to form the various subtidal to subaerial barrier components (Carter et al., 1989b). There is considerable reworking and exchange of sediment between ebb and flood tide deltas and beaches and dunes via tidal and aeolian processes. Such a process is regarded by Carter et al. (1989a) as critical for barrier survival under a transgressive (albeit slow) RSL regime.

Barriers lacking tidal inlets continue to transgress at a rate of approximately 0.05 metres per year, despite the continuing decline in the pace of RSL rise. The forcing factors for migration are overwash and deflation processes, the relative significance of each being dependent upon barrier dimensions and geometry (Carter et al. 1989b). The response of closed lagoons to invasion by the barrier is to raise water levels to the point where barrier breaching may occur. The material removed to accommodate the new inlet is added to the nearshore zone and beach. Breach closure is rare due to the lack of littoral transport along the Irish south coast to supply sediment for closure. Carter et al. (1989b) note that barrier breaching does not necessarily require landward barrier migration to bring about an increase in the hydraulic head of the lagoon. Infilling of the lagoon with sediment delivered from the catchment will lead to the same result. For the south Irish coast this scenario appears not to have yet occurred. There are examples, however, of closed lagoon shoaling on the N.S.W. south coast (e.g. Nadgee Lagoon, Curalo Lagoon) which, while not completely infilled, are able to breach their barriers intermittently.

Ephemeral inlets along the south Irish coast are, by definition, hydraulically unstable due to the comparatively coarser sediments making up their barriers (Orford et al. 1988). Barrier breaching is not permanent because inlet processes are not capable of completely redistributing the liberated sediment into the nearshore and beach. Rather, inlet opening and closure is accompanied by the formation and destruction of inlet bedforms such as ebb and flood tide deltas and swash bars. Variation in the state of inlet bedforms influences the nearshore wave regime. During inlet opening bedforms act to dissipate wave energy thereby limiting washover deposition and hence promote barrier stability. With inlet closure, inlet bedforms are destroyed and a reflective barrier profile results (Orford et al., 1988). A reflective morphology is conducive to storm overwash and barrier instability which, when coupled by river flooding, may bring about inlet reopening.

The significance of estuary entrance status as a factor in determining barrier morphology and the manner in which the barrier interacts with the estuary lagoon is clear. Moreover, it is a relationship that appears to be common, though variable in strength, to estuaries in the different geographic settings considered thus far. The primary contrast between those settings is the rate of RSL rise. Given the continued slow RSL rise along the south Irish coast it is not likely that the present coastal deposits will be preserved (Carter et al., 1989b). Nevertheless, such a scenario is important because it provides a contrast to the stillstand RSL setting of N.S.W. and the rapid RSL rise of Nova Scotia.

3.5.3 China

The morphology, stratigraphy and regional distribution of barrier-lagoon systems along the coast of China is reviewed by Li and Ping (in press). Four types of barrier-lagoon are defined, including: transgressive; stable; local transgressive; and regressive. The distribution of each type along the coast is interpreted to be a function of regional variation in the tectonic setting. The Chinese coast is divided into subsidence belts and uplift belts formed during the Quaternary. Uplift belts occupy over 70 per cent of the coastline (Fig. 3.8). Despite the dominance of uplift belts, the great majority of fluvial discharge and suspended sediment load (94%) is delivered to the subsidence belt coast (Li and Ping, in press). The subsidence coast is, therefore, a broad coastal plain setting fed by China's main rivers, including the Yangtze and Yellow rivers. In contrast, the uplift belts are characterised by a wave-dominated embayed coast with a narrow coastal plain and sea-level stillstand conditions. The uplift coast setting is considered closely analogous to the estuary setting of the N.S.W. south coast.

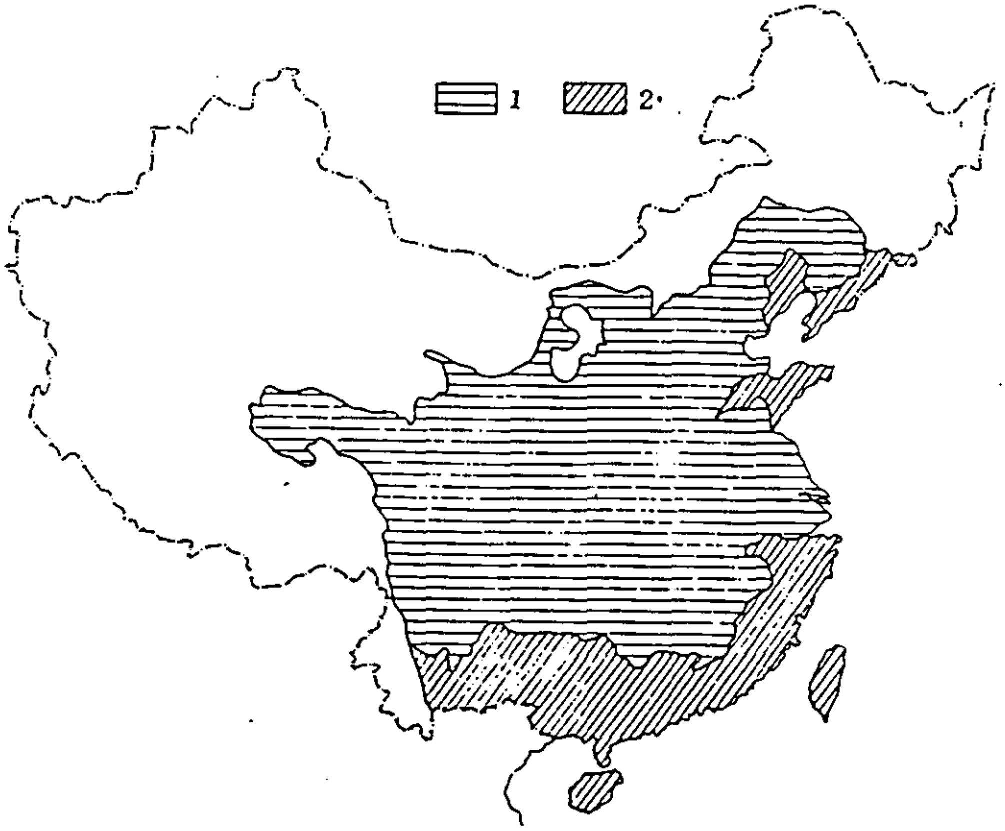


Figure 3.8: Distribution of subsidence belts (1) and uplift belts (2) and respective drainage areas along the Chinese coast (reproduced from Li and Ping, in press).

Along the subsidence coast barrier-lagoon systems are limited in occurrence but, where present, are of the transgressive type, reflecting the subsiding nature of the coast. Stratigraphically, the transgressive systems record an upward transition from terrestrial to marginal marine to open marine depositional conditions, not unlike the transgressive sequences of the central and southern Atlantic coasts of the United States.

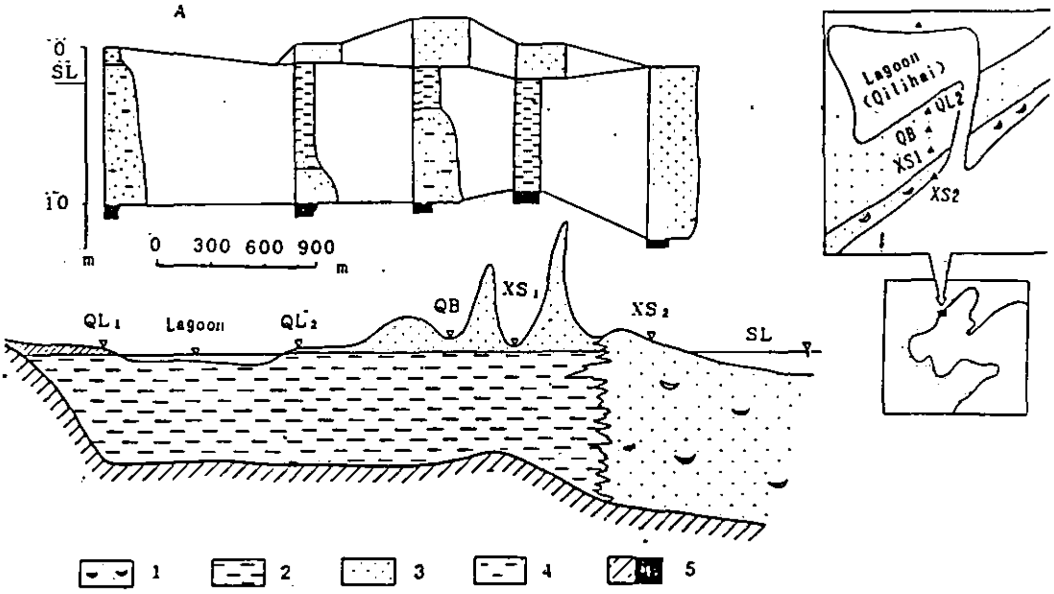


Figure 3.9: Example of stratigraphy for the stable barrier-lagoon type. Key to symbols: 1= Barrier sand with shells; 2= Lagoon silty clay; 3= Aeolian sand; 4= Fluvial silty sand; 5= Pre-Holocene clay or bedrock (reproduced from Li and Ping, in press).

The barrier-lagoon systems of the uplift belts are typically of the stable and local transgressive types (Li and Ping, in press). Stable barrier-lagoon systems have developed in areas of relative sea-level stability and lie near the landward limit of maximum transgression. They are considered to be analagous to N.S.W. stationary barrier estuaries. A typical stratigraphic sequence consists of a basal unit of lagoonal clays interfingering at the seaward end with barrier sands that are capped by a regressive (progradational) facies of dune sands (Fig. 3.9). Given the low fluvial input to the uplift coast (two orders of magnitude less than the subsidence coast), the deposition of a regressive fluvial facies over the lagoon facies in stable systems is limited and river deltas are rare.

The local transgressive barrier-lagoons of the uplift belts consist of a landward migrating barrier and is considered to be a reworked stable barrier-lagoon type (Li and Ping, in press). They have similar morphostratigraphic characteristics to receded barrier estuaries along the N.S.W. coast, but the cause of migration is slightly different (Fig. 3.10). Barrier retreat along the Chinese coast is initiated by a decrease in fluvial sediment supply resulting in shoreface erosion. Both natural (seasonal variation of fluvial flow) and artificial (dam construction) causes are invoked to account for the drop in sediment supply (Li and Ping, in press). Migration of N.S.W. barriers is also due to a poor sediment supply, but the deficiency is attributed to a small budget of marine sands, relative to stable and prograded barriers (Thom et al. 1978).

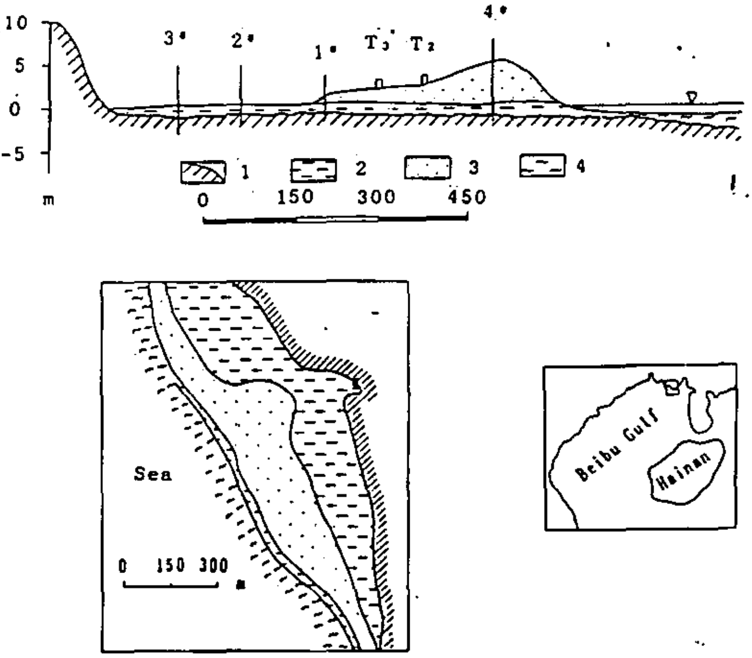


Figure 3.10: Example of stratigraphy and plan-form for the local-transgressive barrier-lagoon type. Key to symbols: 1= Pre-Holocene clay; 2= Lagoonal clay; 3= Barrier sand; 4= Tidal flat mud (reproduced from Li and Ping, in press).

In contrast to the stable barrier-lagoons, regressive barrier-lagoons do possess a substantial prograded fluvial facies. These systems occur in areas of transition between uplift and subsidence belts where fluvial supply is of sufficient magnitude to provide sediment for deposition of a regressive capping facies. One such transition area is the Shandong Peninsula of northern China. Cai and Cai (1987) classify the lagoons of the Shandong Peninsula into three broad types: (i) sandy coastal lagoons; (ii) silty lagoons, and (iii) estuarine lagoons. Of these, only estuarine lagoons (Type III) occupy incised valleys and are possible equivalents to partially filled N.S.W. barrier estuaries (Cai and Cai, 1987). Type I lagoons are equated by Cai and Cai (1987) with the coastal plain lagoon systems of the United States Atlantic coast. Type II lagoons are described in terms that suggests they are simply closed interbarrier depressions (Cai and Cai, 1987).

The estuarine lagoons of the Shandong Peninsula commonly exhibit a coarsening upward stratigraphic sequence. Thus, fine grained lagoon sediments are erosively overlain by barrier sands recording the migration of barriers earlier in the Holocene. Lagoons are currently being infilled at their landward end with fluvial sediments, which is consistent with a regressive depositional style. In some cases, aeolian processes contribute to lagoon infilling (Cai and Cai, 1987; Li and Ping, in press).

In sum, the depositional style in barrier-lagoon systems of the Chinese coast is primarily an expression of antecedent topography, exemplified by clear differences between the coastal plain coast and the embayed coasts. A similar relationship was observed by Schubel et al. (1986) for estuaries of the west coast of Korea. However, within a tectonic region the relative sea-level history and to a lesser extent, variations in sediment supply, assume primary importance in determining depositional style. The uplift belt coast experiences stillstand conditions and three types of barrier-lagoon have resulted. Significantly, the apparent extent of variation in depositional style among barrier-lagoons of the Chinese uplift coast is comparable to that among N.S.W. south coast estuaries.

3.5.4 Brazil

The south-east coast of Brazil has previously been classified a wave-dominated delta coast (Coleman and Wright, 1975; Galloway, 1975). The delta classification probably derives from the fact that the present shoreline is characterised by broad prograded beach ridge plains cut by rivers that are currently delivering limited amounts of sediment to the coast. Recent studies indicate, however, that the Holocene coastal depositional complexes of the Brazilian coast are mature barrier-lagoon systems that have evolved rapidly in response to multiple sea-level submergence and emergence episodes during the Holocene (Suguio and Martin, 1976; Dominguez et al., 1987; Ireland, 1987; Martin and Suguio, 1989).

The rivers draining the southeastern margin of Brazil are incised into Precambrian basement rocks and late Tertiary alluvial fan deposits (Dominguez et al., 1987). Beyond the limit of their incised valleys the rivers traverse relatively broad coastal plains occupied by freshwater lakes, swamps, floodplain deposits, dunes and beach-ridge terraces (Dominguez et al., 1987). Tidal range at the coast is small, increasing from one metre to 1.5 metres, south to north. The critical factor in the overall setting of the Brazilian coast appears to be the Holocene relative sea-level history.

Detailed morphostratigraphic investigations, supported by abundant radiocarbon dating, have produced a high resolution sea-level curve with the following characteristics. As for most of the worlds coastlines, sea-level rose rapidly to a level close to present by about 7000 years BP. Along the southern Brazilian coast, the rise continued to a peak of +4-5 metres by c.5100 BP. An emergence period followed, with sea-level marginally lower than present by 3800 BP. The elevation to which sea-level dropped is not known. A second rapid transgression occurred, peaking at +3 metres by 3500 BP. A second lowstand, of similar yet unknown elevation to the first, was achieved by 2700 BP and this was soon surpassed by a third transgressive episode during which sea-level reached +2.5 metres at 2500 BP. Sea-level has since been in a gradual regressive phase (Dominguez et al., 1987; Martin and Suguio, 1989) (Fig. 3.5).

With respect to the mechanism driving the rapid Holocene sea-level fluctuations, Martin and Suguio (1989) concede that the magnitude of sea-level change is too great and fast to be of glacio-eustatic origin. Therefore, they suggest that the driving mechanism may be a combination of neo-tectonic activity and regional deformation of the geoid surface. Evidence for neo-tectonic uplift of coastal blocks along the southeast Brazilian coast exists for certain sections of coast (e.g. the coast of Rio de Janeiro). However, other areas appear not to have been uplifted in Holocene times (e.g. coast of Sao Pauo State). Moreover, the ubiquitous Last Interglacial (c.120 ka) raised marine terrace does not vary in elevation between tectonically active and inactive areas. If the mid-Holocene high sea-level was a tectonic product then the Last Interglacial terrace should be vertically displaced (Martin and Suguio, 1989). Therefore, neo-tectonic activity is not the favoured explanation.

Deformation of the geoid surface is, invoked by Martin and Suguio (1989) as the primary mechanism for Holocene sea-level fluctuations. Specifically, the mid-Holocene high sea-levels may have resulted from regional sinking of the geoid surface following a period of uplift that ended before 5100 years BP (Martin and Suguio, 1989). Whether this mechanism is valid remains to be full tested. Of particular concern is the question relating to the late-Holocene sea-level fluctuations that require geoid displacements on a time scale of centuries. Despite uncertainties regarding the validity of the geoid model, the Holocene sea-level perturbations are real and moreover, the impact upon coastal depositional environments appears to have been dramatic.

Four stages in the evolution of the Brazilian coast have been postulated by Dominguez et al. (1987) based on an analysis of four modern beach-ridge plains and associated rivers (the Sao Francisco, Jequitinhonha, Doce and Paraiba do Sul rivers). Thus, stage one incorporates the Pleistocene glacial lowstand period, during which the rivers incised channels into Pleistocene inner shelf sediments that had been redistributed to form beach-ridge plains. The second stage saw the drowning and partial reworking of the lowstand plains that attended the Late Pleistocene postglacial marine transgression. A barrier island-lagoon coast morphology, with lagoons occupying the Pleistocene drainage network, is suggested for this early period of the Holocene. Barriers were anchored to bedrock headlands and there is evidence for multiple tidal inlets, suggesting a less embayed setting than the N.S.W. coast. Both the barrier and lagoon deposits of the first highstand period are preserved today. Moreover, there is stratigraphic evidence for their landward migration during the transgression, indicated by lagoon clays preserved below barrier sands (Dominguez et al., 1987). The third stage preceded the first Holocene emergent period and involved the progradation of river deltas into the lagoons. This stage is equated by Dominguez et al. (1987) with the modern barrier-lagoon systems of the United States Atlantic coast. Interestingly, Dominguez et al. (1987) note that the river deltas are well preserved in the modern depositional complexes, indicating negligible reworking during the ensuing brief lowstands.

The final stage in the evolution of the Brazilian coast involved the formation of freshwater lakes and swamps and beach-ridge plains as sea-level dropped by up to 5 metres. Intervening highstand episodes caused the drowning of river mouths and reformation of lagoon and barrier systems as well as partial reworking of beach ridge terraces. Bio-stratigraphic investigations of estuaries on the southern coast of Brazil revealed marked changes from marine to brackish to fresh water lagoon environments preserved as transgressive and regressive overlap sequences which correlate with the Holocene sea-level record for the east Brazilian coast (Ireland, 1987).

Dominguez et al. (1987) stress that the primary source of sediment for coastal progradation was inner shelf sands, not river sediment. The multiple Holocene lowstand episodes initiated conditions suitable for wave-generated longshore and onshore transport of inner shelf sediments. It is this dominance of longshore transport over river processes as a mechanism for coastal progradation that distinguishes the Brazilian coast from a true delta coast (Dominguez et al., 1987). The rivers do supply sediment to the coast today, but are a secondary source only. That fluvial sources are not the primary source is attributed by Dominguez et al. (1987) to the frequent fluctuations in sea-level which introduce disequilibrium conditions to river systems thereby reducing their competence to transport sediment, though the ongoing drop in sea-level is likely to rejuvenate fluvial systems.

3.5.5 South Africa

The coast of South Africa suffers from a lack of comprehensive geomorphic research, although it is clear from ecological work carried out in estuarine systems over 20 years ago (e.g. Brown, 1959; Day, 1951; Day and Morgans, 1956; Day et al. 1952, 1954; Day, 1967) that South African estuaries occupy a high energy, incised valley coast. The following description of South African estuarine and barrier environments focuses upon the sector of the coast for which published geomorphic research is available, namely the southern and east facing portions (Orme, 1973; Reddering, 1983; Ase, 1986).

North of Durban the coast experiences a mean spring tidal range of 1.8m and 0.5m for neap tides (Orme, 1973). Tidal range within estuaries is about 1.5m within the entrance channel and decreases to zero in the lagoons. Deep water wave height on the coast ranges from 0.9m to 4.0m with a periodicity of between six and 18 seconds (Orme, 1973). The Late Pleistocene and Holocene sea-level history is unclear, though a sea-level curve from nearby Mozambique suggests a trend somewhat similar to that for southeastern Australia (Fig. 3.5). That is, the PMT was initially rapid, rising from 100 metres below present level between 10,000 and c.7000 years BP. The 7000 to c.5000 year BP period saw sea-level peak at +c.3 metres and then fall gradually to its present level (Ase, 1986). Therefore, the stillstand period along southeastern Africa appears to be shorter than that for the N.S.W. coast. In sum, the South African coast may be described as microtidal, wave-dominated and under relative stillstand conditions (Reddering, 1983).

In terms of sediment inputs and outputs, the most important coastal process is offshore and longshore transport of sand. When waves have a shore normal approach an extremely energetic nearshore circulation system is generated, characterised by rip currents spaced every 600m that flow up to 800m offshore with velocities up to 1m/sec (Orme, 1973). In opposition to offshore circulation, a unidirectional longshore current is generated when wave approach becomes oblique in response to strong shore parallel winds. Longshore currents are characterised by velocities that exceed 1m/sec that have the ability to entrain significant volumes of sediment, including coarse sands and pebbles (Orme, 1973).

An added influence to coastal depositional conditions is provided by the Agulhas Current that flows in a persistent southerly direction near the edge of the continental shelf and parallel to the coast. The Agulhas Current interacts with nearshore waters to produce eddy circulation and reversing currents located up to five kilometres offshore but with a significant onshore-offshore component that directly affect the coast (Orme, 1973).

Fluvial discharge into estuaries and the coastal zone also has a significant influence on sediment distribution patterns. South African rivers display strong seasonal variations in discharge, with over 80 percent of mean annual discharge and sediment transport taking place during summer. Flood events are of sufficient magnitude to transport coarse sandy sediment into the surf zone and project a suspended sediment plume several kilometres offshore (Orme, 1973). The winter months are a low discharge period during which sediment yield is significantly diminished. Consequently, river mouths are closed by littoral drift processes and the estuary isolated from tidal processes. In fact, of the 289 inlets along the South

African coast only 37 are permanently open and many display evidence for longshore inlet migration (Reddering, 1983).

The barrier complexes along the eastern coast of South Africa are not unlike those of southeastern Australia, to the extent that they comprise an inner Pleistocene and an outer Holocene component (Orme, 1973). However, barrier morphology is somewhat different to N.S.W. barriers. Beach-ridge type barriers do exist in areas of relative sediment abundance, but they are the product of longshore drift and not the progradational conditions operating in N.S.W. embayments (see section 3.4.2). Consequently, the South African beach-ridge systems are narrow and long. For example, immediately north of Durban a beach-ridge barrier extends for 45 km as a one kilometre wide unbroken strip. Longshore drift is particularly prevalent along this section of the coast. Lagoons have not formed behind the beach-ridge systems, although estuarine conditions do exist within the few small rivers that flow to the coast. The rivers are themselves affected by littoral processes by having their mouths diverted several kilometres northward (Orme, 1973).

Estuarine lagoons are present behind the barriers located north of the beach-ridge section of coast, in the vicinity of Richards Bay. Littoral drift processes are not as consistent, in terms of current direction and duration, as the beach-ridge coast. As a result, barriers display a morphology not unlike the stationary and episodic-transgressive barriers of N.S.W. That is, they consist of a weathered Pleistocene core and inner barrier mantled by Holocene medium sized sands of the outer barrier that together form a 60m high, 2km wide, 8km long complex, fronting a broad lagoon (Orme, 1973). Despite the variability of littoral drift, the

Richards Bay lagoon entrance is an ephemeral feature that relies on high river discharge to maintain a breach through the barrier.

Backbarrier and lagoon sedimentation in South African estuaries occurs primarily through fluvial processes. Transport of sediment via aeolian processes and tidal and washover processes are minor in comparison (Orme, 1973; Reddering, 1983). Contributions from eroding Pleistocene cliffs are locally significant in some systems. However, it is the episodic high discharge river floods that impart the clearest signature on lagoon deposits. Orme (1973) measured the surface area of the nine lagoon along the northeastern coast of South Africa and determined that all lagoons have filled to the extent that they occupy less than 40 percent of their original Holocene area. Much of the reduction in area has been via swamp encroachment and the segmentation process, described later in chapter seven.

River deltas of the type described from N.S.W. estuaries appear not to have formed in South African lagoons. The seasonal nature of river discharge and sediment delivery may explain the absence of deltas. That is, delta levees that may form during high discharge periods are destroyed by wind waves during low discharge periods and redistributed along the lagoon shoreline, thereby contributing to the reduction in lagoon area and segmentation.

Lagoon sediments are typically fine-grained and rich in organics. In the larger estuaries (e.g. Lake St. Lucia) lagoon deposits are more than 16m thick (Orme, 1973). Fluvial sands are delivered to the estuary mouth and beyond during floods and it is assumed here that some sand is also deposited in the lagoons. The great majority of sand and gravel sized sediment is deposited upstream from the lagoon (Orme, 1973). The fluvial portions of most estuaries occupy incised Pleistocene channels and now bear between ten metres and 40m of Holocene sediment. It is evident, therefore, that under stillstand sea-level conditions the fluvial systems feeding South African estuaries have been able to equilibrate to the change in base level and deliver appreciable quantities of sediment to the lagoons and to the nearshore zone.

Published studies of barrier and estuarine stratigraphy for South African systems appear to be relatively scarce. However, given the general sea-level and depositional process setting described above it is possible to offer a speculative stratigraphic sequence for the sector of the South African coast characterised by high barriers and lagoons. Briefly, the sequence is likely to be dominated by a lagoon muddy facies that interfingers on the seaward side with a barrier/inlet sandy facies. Fluvial delta deposits should be poorly represented at the landward side of the lagoon, although the depth of valley incision achieved by South African rivers implies that a fluvial channel facies is preserved at the landward end of the estuary valley. The resultant valley fill stratigraphy should not be dissimilar to that described for N.S.W. barrier estuaries.

3.6 SUMMARY AND DISCUSSION: THE NEED FOR FURTHER WORK

The foregoing review of variability of the gross sedimentologic character of modern incised valley estuaries at the global scale highlighted the relative importance of individual factors that, collectively, force the style of deposition at a given location. Carter et al. (1989) argue that these factors operate in a stochastic fashion, whereby depositional processes are arranged in a "nested heirarchy" (Carter et al., 1989: 222). The heirarchy of controlling factors includes:

the rate of relative sea-level change; antecedent topography; sediment inputs to and outputs from the coastal sediment store; the relative dominance of wave and tide regimes, and; textural properties of barrier and lagoon sediments (Carter et al., 1989). At the top of the heirarchy is the rate of sea-level change. As coastal systems adjust to RSL change, lower order depositional controls take effect. The rate of sea-level rise and the proximity of RSL to the maximum level of transgression along a coastline will therefore determine the relative significance of other controls in the heirarchy. These relationships are best explained by way of a summary of the barrier-lagoon coasts already discussed.

With respect to N.S.W. estuaries, the relatively early termination of the PMT allowed antecedent topographic controls and entrance conditions to influence depositional style during the early stages of estuary and barrier formation. Antecedent topography and entrance form, set up when barriers formed, are recognised by Roy (1984a) as critical variables in the style of estuary evolution, hence the three N.S.W. estuary types discussed in section 3.4. It is suggested here that basement controls are no longer the primary control over deposition in N.S.W. estuaries and that other controls of the heirarchy have assumed prominence since the PMT. These include, sediment input from the hinterland via rivers affecting lagoon sedimentation and secular variation in the storm wave climate affecting barrier form. Delivery of sediment to barriers from the shelf has become negligible because the shoreface profile has attained an equilibrium form in response to the sea-level stillstand. Adjustments by drainage networks to the Holocene shift in base level have been achieved, allowing rivers to deliver sediment to lagoons thereby imparting a strong fluvial signature to the valley fill. This does not contradict Davies (1974) assessment of catchment erosion being an unimportant sediment source for the coastal sediment store. Rather, it supports Davies (1974) claim by highlighting the sediment trapping ability of estuaries.

With respect to barrier form, Thom (1978) identifies secular variation in barrier stability since c.6500 years BP, including phases of barrier progradation and landward dune migration and periods of beach and dune stability. Given the stillstand setting, it appears that these variations are controlled by short term (10^1-10^2 years) and long term (10^3 years) climate induced changes in storm wave activity, not sea-level change (Thom, 1978). All of the characteristics of the N.S.W. coastal setting discussed herein are assumed to provide support for the end-member status of N.S.W. estuaries.

The stable barrier-lagoons of the uplift belts along the coast of China and to a certain extent the South African estuaries, are a close match to the N.S.W. estuaries. That is, they lie close to the level of maximum transgression and approximate a stillstand setting. Lower order controls on deposition such as fluvial inputs are not reported in the published descriptions of stable barrier-lagoons of the uplift belts of China. The lack of a regressive fluvial deposit is a function of particularly low fluvial discharge in uplift areas. Toward the boundary between uplift and subsidence coastal belts of China fluvial discharge is higher and the regressive type of barrier-lagoon occurs. These systems do exhibit a stratigraphic sequence that records the adjustment of fluvial systems to the Holocene high sea-level in the form of a prograded fluvial deposit. It is therefore concluded that lower order fluvial controls have assumed a level of importance for regressive type barrier-lagoons.

The barrier-lagoon systems along the east coast of South Africa also display a clear fluvial signature, albeit seasonally variable. Indeed, fluvial systems have adjusted sufficiently to the PMT to be able to occasionally deliver appreciable amounts of terrigenous sediment to the nearshore zone. The orientation of the east African coast with respect to the dominant winds and deep ocean currents is such that longshore currents are an important process influencing the distribution of sandy sediment along the coast. The most evident expression of littoral drift processes is the closure of tidal inlets. In sum, the South African coast is no longer adjusting to changes in sea-level and the lower order controls of fluvial discharge and littoral drift have both assumed major roles in shaping barrier-lagoon character.

Further along the spectrum of sea-level scenarios, the southern coast of Ireland is taken here to represent a setting where sea-level is continuing to rise but at a sufficiently slow rate that it has relinquished the status as the primary control over coastal deposition. Regional variation in barrier-lagoon morphology are attributed to the presence or absence of a tidal inlet and explained in terms of storm overwash, tidal inlet processes and lagoon overflow- all lower order controls in the heirarchy. Sea-level is, nevertheless, rising along the southern Irish coast and barriers are migrating landward. Estuaries, therefore, remain in a mild state of disequilibrium and lower order controls have yet to impact upon coastal depositional systems to the extent seen on the N.S.W. coast.

The Northwest Pacific coast of the United States, while in an active tectonic setting, displays estuarine characteristics of a similar nature to the southern Irish coast. That is, sea-level is continuing to rise but at a decreasing rate, allowing lower order controls to begin to influence depositional style. This is recorded primarily as an incipient signature of fluvial facies development.

The relatively rapid sea-level rise occurring along the coasts of Delaware and Maine places them toward the end-member of almost complete sea-level control on the spectrum of sea-level scenarios. Lower level depositional controls are evident on these coasts, notably antecedent topography. The morphology of the pre-existing surface interacts with the retreating barrier-lagoon systems in a manner that controls the deposition and preservation of component facies. In simple terms, the deeper the incised palaeovalley, the thicker and more diverse is the transgressive stratigraphic sequence. Along the coast of Maine, barrier morphology and estuary stratigraphy appear related to estuary entrance conditions, suggesting some degree of topographic control, but the exact nature of these relationships is not clear.

The end-member opposite to N.S.W. on the sea-level spectrum is the coast of eastern Nova Scotia, where RSL is rising rapidly. Sea-level remains the primary control over the evolution of the Nova Scotia barrier-lagoon coast. Even to the extent that the pre-existing periglacial topography (drumlin headlands) is partially destroyed by the migrating shoreline. Barrier-lagoon systems are in a constant state of disequilibrium and local variations in barrier morphology are a function of continual adjustments (erosion or aggradation) of sediment budgets to the encroaching sea. Despite the stressful conditions imposed upon estuaries by rapid sea-level rise, Carter et al. (1989) note that lagoon basins in receipt of overwash and tidal delta sediment, infill rapidly and are well preserved.

Finally, to complement the relatively clear-cut suite of sea-level scenarios considered thus far, the Brazilian coast provides a rather complex RSL history. That is, since the mid-Holocene, back and forth switching in depositional controls has occurred. Three shortlived yet significant Holocene highstands and intervening lowstands have meant that sea-level has assumed, relinquished and resumed dominance over estuary evolution several times. The Brazilian coastal and inner shelf setting is such that main lower order control operating at low sea-level was wave induced longshore transport. It appears that the shifts in sea-level were too short in duration to allow fluvial systems to reach equilibrium. Because of this, the south-east Brazilian coast is not considered to be a true delta coast. This is supported by the character of estuary stratigraphy, which records lagoon and barrier facies. Instead, it may represent a point on the continuum between deltas and estuaries.

A consistent characteristic of all estuarine systems considered here is the tripartite nature of facies assemblage. That is, facies reflect the transition from fluvial to estuarine (lagoonal) to marine environments. This tripartite character is recognised in both modern and ancient estuarine valley fills (e.g. Nichols et al., 1989; Rahmani, 1988; Reinson, 1984). In a comparative study of eastern Australian and Atlantic coast barrier-lagoon systems Hails and Hoyt (1968) refer briefly to the backbarrier and lagoonal portions and fail to consider the fluvial environment of estuarine systems. Reinson (1984) presents a detailed discussion of facies models for barrier-island lagoon systems but also neglects the fluvial portion of the complex. This neglect is seen to stem from the fact that fluvial facies development is at a relatively immature stage in estuaries still subject to sea-level rise, the first order control in the stochastic process of coastal evolution. Estuaries in a rising sea-level regime are continually having to adjust to a negative shift in base level. Sedimentation in lagoons is, therefore, in a "deficit" state and the lagoon is overwhelmed by the retreating barrier. Some lagoons are able, however, to keep pace with sea-level rise and survive while migrating landward (Nichols, 1989). This is in contrast to the estuaries of eastern Australia where a prolonged stillstand has enabled fluvial and lagoon systems to adjust to the post-glacial rise in sea-level and adopt a sediment "surplus" (Nichols, 1989) status, evidenced by deposits of seaward prograding floodplain and fluvio-deltaic facies.

It has already been stated that many of the published facies models for barrier and associated lagoon systems are based upon comprehensive research along the Atlantic coastline of North America. It is evident from the preceeding discussion that the North American coast does not represent the full spectrum of depositional conditions. Thus, as emphasised by Boyd and Penland (1984), the models are no more than detailed regional studies. The need to recognise the scope of variation of estuarine depositional character that can occur in diverse environmental settings cannot be overemphasised. The present study should contribute to the understanding of variation because the N.S.W. setting defines an end-member on the continuum of variability at the global scale as well as providing an interesting and necessary contrast to prior studies of incised valley estuarine systems.

3.6.1 Applications of modern estuarine studies to interpretations of ancient deposits

Given the multitude of sea-level advances and retreats over geological time it is to be expected that estuarine incised valley fill deposits are preserved in the rock record. However, in a review of literature concerned with the hydrocarbon reservoir properties of ancient estuarine deposits, Zaitlin and Shultz (1990) observe that few studies have recognised their true character. This has been generally attributed to a poor appreciation of the specific facies character of incised valley fills (Zaitlin and Shultz, 1990). The number of published examples of ancient incised estuarine valley fills is limited (e.g. Buffin, 1989; Reinson et al., 1988; Sloan, 1987; Zaitlin and Shultz, 1984). It is evident from these studies that the preservation potential of incised valley highstand deposits is excellent. Reinson et al. (1988), for example, describe a multiple stillstand estuary fill sequence from the Lower Cretaceous Viking Formation, Southern Alberta. Moreover, ancient estuarine deposits are increasingly proving their economic worth as petroleum bearing entities featuring both hydrocarbon source rocks and reservoir sand bodies (Reinson et al., 1988; Zaitlin and Shultz, 1990).

There is a clear need for more modern analogues of ancient deposits in order to provide the geologist with a fuller appreciation of the nature of facies variability possible within estuarine fills. Zaitlin and Shultz (1984) present a stratigraphic model for a hydrocarbon bearing wave-dominant transgressive estuarine deposit in the Lower Cretaceous Lloydminster Formation of west-central Saskatchewan. Their model conforms generally to that for modern N.S.W. estuaries developed by Roy et al. (1980) and Roy (1984a), with the exception that a lagoonal facies was not recognised in the ancient deposit. Clearly, a primary avenue of investigation that will provide information pertinent to the interpretation problem is the detailed documentation of facies character in modern estuarine systems (Heward, 1981). The value of this approach is demonstrated by Reinson et al. (1988) who draw an analogy between the Viking Formation and the modern Miramichi estuary on the New Brunswick coast. Knowledge of the spatial distribution and geometry of facies in the modern system provided for more accurate prediction of the position of reservoir bodies in ancient deposits (Reinson et al., 1988). In recent years, the linking of modern studies with ancient interpretations has led to the recognition of a tripartite facies zonation in both modern and ancient deposits, thereby providing a common conceptual framework for the spatial organisation of estuarine facies (Nichols et al., 1989; Rahmani, 1988; Reinson, 1984).

In reference to macrotidal estuaries Dalrymple et al. (1985) note the paucity of detailed facies models necessary for paleo-environmental reconstruction. Frey and Howard (1986) make a similar observation about estuarine research in general, stressing the requirement for an improved understanding of facies relationships. Such models have recently been proposed by Dalrymple and Zaitlin (1985), Dalrymple et al. (1985), and Zaitlin (1987) for macrotidal systems and by Frey and Howard (1986) for mesotidal complexes. In an extensive review of wave-dominated clastic depositional environments Heward (1981) acknowledges the morphostratigraphic work of Kraft et al. (1973), Kraft and John (1979) and Roy et al. (1980) in transgressive barrier-lagoon (palaeovalley fill) settings. However, Heward (1981) identifies the notable absence from the literature of detailed sedimentologic studies of modern palaeovalley infills.

The estuaries of the N.S.W. coast provide excellent modern analogues of ancient incised valley fills for the following reasons. The various infill styles that exist among N.S.W. systems provide a useful guide for the potential range of character of ancient deposits associated with a stillstand, wave-dominant setting. The transgressive to highstand conditions under which N.S.W. estuaries have evolved is important insofar that many of the estuarine deposits recognised in the rock record are inferred to have accumulated under similar sea-level scenarios (e.g. Clifton, 1989; Reinson et al., 1988). This also serves to indicate the good preservation potential of transgressive/highstand deposits. A study of N.S.W. estuaries also enables confident definition of component facies and respective sedimentological properties of incised valley fills because they are readily accessable and suited to controlled field sampling.

CHAPTER 4: RESEARCH METHODS

4.1 INTRODUCTION

This chapter sets out in detail the methods employed during the various phases of research for this thesis. The overall research program was divided into three phases. The first phase entailed mapping depositional environments in all south coast estuaries, generation of facies morphometric data and statistical analysis of that data. Phase two involved field sampling in the two field sites, Wapengo Lagoon and Narrawallee Inlet. The final phase consisted of laboratory processing and analysis of field samples.

4.2 ESTUARINE MORPHOSTRATIGRAPHIC MAPPING

In order to document the organisation of facies in individual estuaries along the N.S.W. coast it was necessary to define a set of geomorphic features common to all systems. The morphostratigraphic unit of Frye and Willman (1962) was adopted as the basic mapping unit. Morphostratigraphic units may be considered analogous to depositional sub-environments and are recognised as having a distinct surface morphology and unique lithological properties. A suite of thirteen morphostratigraphic units were defined and mapped from colour aerial photographs at a scale of 1:25000 (1981 Coastal Wetland Series) for 68 southern N.S.W. estuaries. Criteria for unit definition from air photos included colour, texture, shape and location. Interpretation of remotely sensed physical form was based upon prior knowledge and ground truthing of morphostratigraphic maps. Definitions of the 13 units are presented in Table 1.1. Clearly, not all estuarine systems possess the entire range of units defined in Table 1.1. On a gross scale, however, it is possible to identify in all systems at least two of three facies zones that comprise an assemblage of some or all of the morphostratigraphic units. These zones (A,B,C) are defined and discussed in detail in chapters five through eight.

Mapping of estuary catchments was also carried out. Catchment boundaries were defined from 1:25000 topographic maps with the intention that an analysis of catchment dimensions would contribute to the interpretation of facies morphometric data, specifically the extent of floodplain and fluvial delta development in palaeovalleys.

4.3 MORPHOMETRIC ANALYSIS OF MORPHOSTRATIGRAPHIC UNITS

4.3.1 Morphometric data generation

In this study, morphometric data consists of areal measurements of every mapped morphostratigraphic unit and respective catchments in each of the 68 estuaries. Areal data were captured via electronic digitising of map polygons using ERDAS (Earth Resources Data Analysis Systems) micro-computer software. Appendix A lists all estuarine morphometric data.

Measurement of the areal extent of the three primary facies zones and component morphostratigraphic units allows for accurate characterisation of the proportion of each zone and unit in each valley. Furthermore, the collective morphometric data for the 68 south coast estuaries describe the different modes and stages of infill among those estuaries. The task of identifying the various modes and stages of estuary infill is achieved through the classification of estuaries, on the basis of their gross morphometric characteristics, using multivariate statistical procedures.

Calculation of sediment volumes requires an estimate of sediment thickness to supplement known surface area data. Since accurate drill data for the estuarine systems under investigation is limited, volume calculations have not been made for all 68 sites. It is possible to extrapolate palaeovalley slopes to provide a rough estimate of depth to basement, but this involves the assumption that the whole sediment body is Holocene in age. Subsurface investigations in Wapengo and Narrawallee suggest that this assumption is not correct, with both sites featuring remnants of Pleistocene valley fills. Therefore, volume calculations were made for Wapengo and Narrawallee only, where the thickness of Holocene sediment is known.

4.3.2 Statistical analysis of morphometric data

Facies area data were subjected to three fundamentally different classification techniques: (i) ENTROPY maximisation, a nonparametric, nonheirarchical agglomerative grouping programme that maximises the differences between classes while maintaining within class homogeneity (Johnston and Semple, 1983); (ii) Classification and Regression Trees (C.A.R.T.), a non-parametric recursive splitting technique that provides a set of decision rules to account for the creation of a particular pre-existing class (Briemann et al., 1984); and (iii) Principal Components Analysis (P.C.A.), a data transformation technique that extracts two or more primary variables from a data set and identifies relationships between groups of observations (estuaries) and the primary variables

(Wright, 1985). A flow chart showing the classification methodology developed for this study is presented in Figure 4.1.

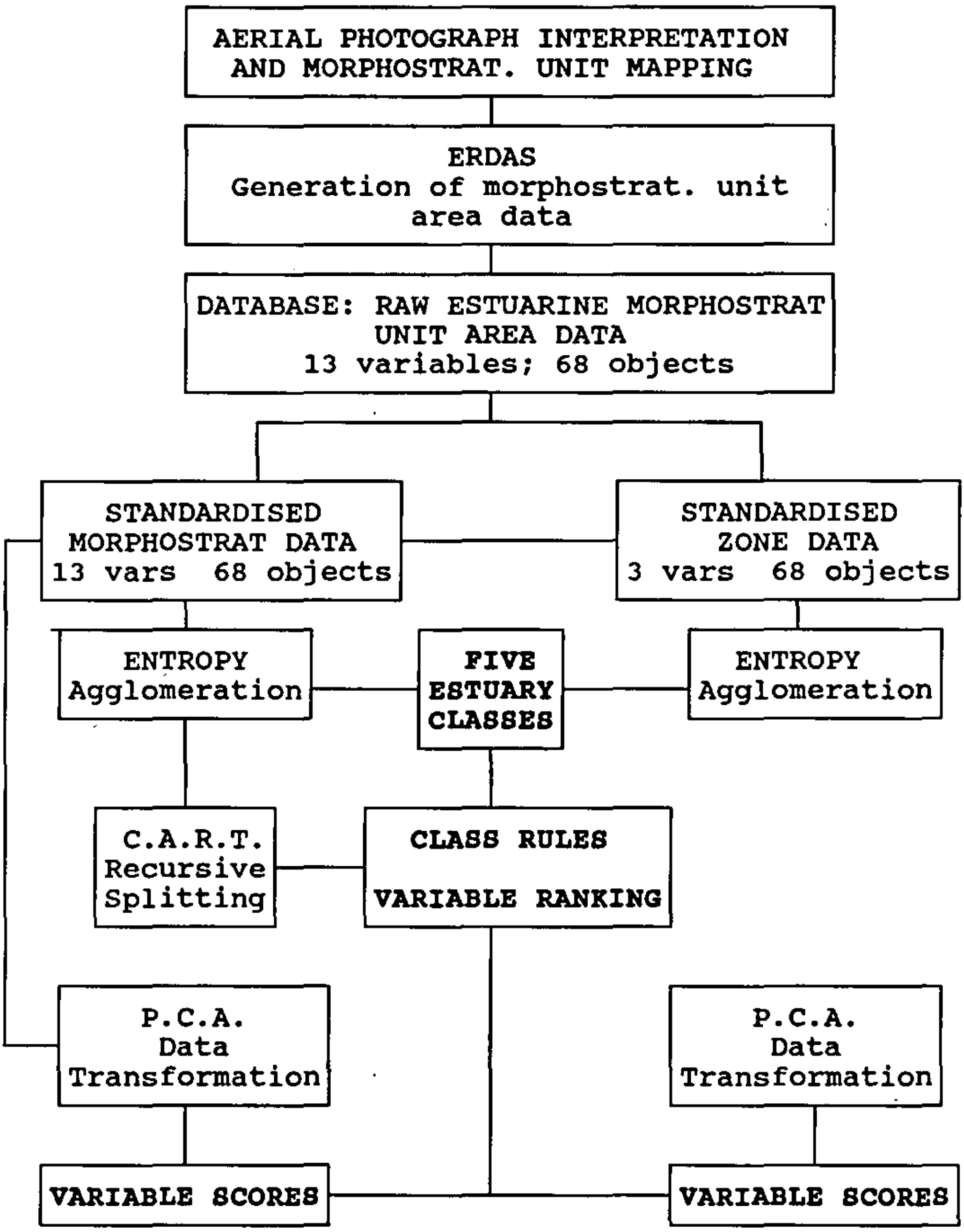


Figure 4.1: Flowchart showing the estuarine classification method developed for this study.

The purpose of employing three statistical techniques was to allow for the development of a rigorous classification. ENTROPY is used as the primary method for classification. C.A.R.T. supplements the ENTROPY output by taking the ENTROPY result and characterising the unique properties of each class. It is important to stress that C.A.R.T. does not independently validate or disprove the ENTROPY classification because it utilises the ENTROPY output in order to operate. However, P.C.A. is used to test the output of the combined ENTROPY and C.A.R.T. result. In addition, both C.A.R.T. and P.C.A. provide variable importance ratings that assist in the interpretation of the overall classification.

Prior to applying the three statistical techniques, the raw area data (km^2) were transformed into a dimensionless (standardised) form to allow comparison between estuaries. That is, the area of each morphostratigraphic unit was expressed as a percentage of the total palaeovalley area. These data were subsequently merged manually into three variables, representing the three primary estuarine zones: Zone A; Zone B; and, Zone C.

4.3.2.1 ENTROPY maximisation: The principal of entropy is reviewed by Full et al. (1984), who perceive a level of uncertainty pertaining to the entropy concept. This is seen to stem from the use of the term in several disciplines including chemistry, physics and mathematics. Full et al. (1984) refer to the measure called "information entropy" introduced by Shannon (1948) and cite it as the form of entropy relevant for geological application. Shannon's entropy measure (E) is dimensionless and is defined through the following formula:

$$E = -\sum_{i=1}^{n} P_i \log_a P_i \qquad (1)$$

where, P_i= proportion of the distribution in the ith component (variable);

n = number of variables in the distribution;

a = any base of logarithm (taken here as 2);

P_i is derived by dividing the frequency within a variable i, by the total frequency in the data set. Here that entails converting each raw unit area to a proportion of palaeovalley area, for each estuary (Full et al., 1984; Johnston and Semple, 1983).

In addition to the measure of information within a distribution, it is possible to calculate a measure of the inequality (I) within that distribution via the formula:

$$(2) \qquad I = \sum_{i=1}^{n} P_i \log_2(nP_i)$$

The value of I increases as the inequality within the data set increases (Johnston and Semple, 1983).

In the context of multi-variate data grouping, Johnston and Semple (1983) present a detailed review of the task of deriving methods for determining the variations within a group and between groups. As the total variation (I) for a data set will be equivalent to the sum of the within and between group variations, it is only necessary to calculate the between group variance, $I_B(P)$:

$$(3) \qquad I_B(P) = \sum_{j=1}^{J} P_j \sum_{r=1}^{R} P_{jr} \log_2\left(\frac{P_{jr}}{N_r/N}\right)$$

where,

P_j = proportion of total distribution in column j

J = number of columns (variables) in data matrix

P_{jr}= proportion of total distribution in column j and group r

R = number of groups

N_r = number of observations in group r

N = total number of observations (Johnston and Semple, 1983).

The aim of ENTROPY analysis, therefore, is to arrive at a classification scheme of n classes that maximises the between class variability, or inequality, and simultaneously minimises within class variability (Johnston and Semple, 1983). By achieving this, observations assigned to a class will have similar distributions for all variables.

The degree of between and within class variability is assessed through the calculation of a test statistic, R_s, which describes the between-class variability as a percentage of the total variability (Johnston and Semple, 1983). R_s is calculated by the formula:

$$Rs = [I_B(P)/I(P)]*100 \quad (4)$$

where, I(P) = inequality for all observations, eq. (2)

$I_B(P)$= between class inequality, eq. (3)

Clearly, as the number of classes increases so does the between-class variance and the value of R_s approaches 100 per cent. Thus, successful use of ENTROPY requires balancing maximum R_s with minimum number of classes.

The actual process of assigning observations to a class is agglomerative (Johnston, 1976). That is, at the outset each observation is treated as a separate class. Observations are then paired via the location of the nearest neighbour in the sample space. As pairing continues, classes are established. The R_s measure produced by ENTROPY provides for determination of the appropriate cut-off point in the classification process.

The ENTROPY programme also computes a Z statistic, which is a measure of the difference between the mean of a given variable for a particular class and the mean of that variable for the total population (in standard deviation units). The Z statistic is given by the formula:

$$Z = (\bar{x} - \mu)/(\sigma/\sqrt{N}) \qquad (5)$$

where,

$\bar{x}$ = mean of group

μ = mean of total population

σ = standard deviation for total population

N = number of observations (Johnston and Semple, 1983).

The greater the difference between the two means the larger the Z statistic. A positive Z statistic signifies that the class mean for a variable is larger than the population mean. The converse applies for a negative statistic. The Z statistic, therefore, may be used to assist in the interpretation of a classification since it identifies variable behaviour that is peculiar to a certain class.

The number of classes produced by ENTROPY is defined by the user. Typically, a range of class numbers will be defined, allowing for graphical assessment of a range of R_S values. Figure 4.2 presents a sample plot of classification levels against Rs values. The point at which the curve begins to flatten out represents a shift to diminishing returns from the creation of additional classes. As noted earlier, the procedure is non-heirarchical insofar that an n+1 level of classification is not influenced by the prior n level grouping. Ultimately, selection of a particular level of classification requires a subjective decision by the user, guided by Rs values and an assessment of the 'real world' significance of the classification in terms of the data under analysis.

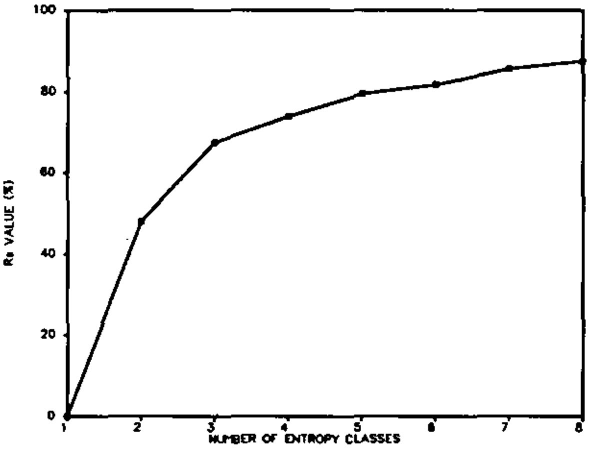


Figure 4.2: Plot of Rs value versus ENTROPY classes.

4.3.2.2 Classification and Regression Trees (C.A.R.T.): In contrast to the agglomerative methodology employed by the ENTROPY programme, C.A.R.T. approaches classification via a recursive splitting technique. The concept of divisive classification is not a recent one (Williams and Lambert, 1959, Johnston, 1976). Early applications involved use of nominal (presence/absence) data and as such were limited in their application to detailed analysis of spatial data

(Williams and Lambert, 1959). C.A.R.T. is a powerful extension of prior divisive techniques, representing recent theoretical developments in classification methodology (Breiman et al., 1984).

Starting with all observations, C.A.R.T. splits the data into two nodes (or classes) on the basis of associations between variables. The two nodes (t_{Left}^*, t_{Right}^*) each possess a degree of internal variation, termed impurity. The first node, containing all observations and classes, is the most impure as it will possess maximum internal variation. The most pure node is one which represents one class of observations. C.A.R.T aims to maximise the decrease in node impurity with each successive split of the data. Node splitting continues until groups possessing minimal impurity (i.e. maximum homogeneity of variable characteristics) are achieved, thereby producing terminal nodes.

The technique requires that each observation be associated with a pre-determined class. This does not necessarily mean that the same classification will result, rather C.A.R.T. will identify misclassed observations and, more importantly, identify class properties. Here the pre-determined classes used by C.A.R.T. were those produced by ENTROPY. As previously noted, this requirement for pre-existing classes prohibits C.A.R.T. from being used to independently validate or disprove the ENTROPY result. Rather, it is used to complement the ENTROPY output.

The programme constructs a classification binary tree diagram, depicting successive stages of splitting, with terminal nodes of the tree representing classes. In addition, a set of decision rules is created detailing the variable(s) and their respective properties that were used to define a class of observations.

Consequently, variables are assigned an importance rating, relating the relative performance of each variable in producing the classification.

C.A.R.T. also produces a variable ranking which is directed toward determining which variables provide the second -best, third-best, ...n-best node split. In doing so, C.A.R.T. identifies surrogate, or second-best, variables (Breiman et al., 1984). The surrogate being the variable that best reproduces the split of the primary variable. The purpose of using a surrogate variable derives from the possibility that the influence of the primary variable (x_1) at a particular decision level may be such that it unnecessarily 'masks' the significance of other variables ($x_2, x_3 \ldots x_n$). Surrogate variables are identified by C.A.R.T. and used to produce a tree that is the best alternative to the original. Use of the surrogate variable creates two nodes ($t_{Left}{}^{\sim}, t_{Right}{}^{\sim}$) from node t that are less accurate alternatives to $t_{Left}{}^{*}$ and $t_{Right}{}^{*}$, having higher node impurity and containing different proportions of observations.

The performance of each variable, with respect to the decrease in node impurity it yields as a surrogate, is used to rank the variables. The importance of a variable x_m is defined by the expression,

$$M(x_m) = \sum_{t \in T} \ast I(s_m{}^{\sim}, t)$$

where,

t= individual nodes in the decision tree;

T= total number of nodes in tree;

$\ast I(s_m{}^{\sim}, t)$= decrease in impurity resulting from the surrogate split of node t. (Briemann, et al. 1984).

In sum, C.A.R.T. identifies important variables in the data set, ranks all variables in terms of relative importance and specifies the values of the critical variables that define boundaries between classes.

4.3.2.3 Principal Components Analysis (P.C.A.): The P.C.A. procedure involves transforming, or summarising, multi-variate data into a set of *uncorrelated* primary variates known as principal components (Daultrey, 1976; Wright, 1985). If each of the variables from the original data are considered as one dimension (axis) in the N-sample space (scatter distribution), then each principal component is an axis that maximises sample variance. With respect to the estuarine morphometric data, three principal components were generated from 13 variables. Given that data are transformed in this manner the method is certainly the most abstract of data analysis techniques employed here. Nevertheless, use of P.C.A. is important because it allows for independent testing of the combined ENTROPY and C.A.R.T. result.

Unlike the two classification programmes, P.C.A. does not group data. However, groups may be identified by the user when scatter plots of principal component data are drawn up. The aim here is to determine whether groups on P.C.A. plots correspond with groups identifed by ENTROPY and C.A.R.T. In addition, by manually merging the output of the different methods, further information relating to the behaviour of variables in the data set is obtained.

P.C.A. produces variable scores and object scores. Variable scores provide a measure of the level of correlation between each variable and each principal component. In essence, the variable score can be regarded as the equivalent to the r^2 correlation measure of linear regression analysis. Thus, the closer the variable score is to 1, the stronger the relationship between a variable and a principal component.

Object scores indicate the extent to which an individual object (observation) contributes to each principal component. The further the object score is from zero, in an either positive or negative direction, then the greater the contribution of that object to the particular component.

Interpretation of variable and object scores is, therefore, directed toward identifying relationships between a particular principal component with groups of objects (estuaries) and one or more of the original variables. In this study, the groups of estuaries and critical variables identified by P.C.A. are compared to the classes defined by ENTROPY and the critical variables recognised by C.A.R.T.

4.3.2.4 Catchment dimension analysis: The nature of relationships between estuary catchment area and the extent of palaeovalley infilling was examined through a non-dimensional analysis of the relevant variables. Expressing variables such as Zone C area and catchment area in a non-dimensional (standardised) form is essential to facilitate comparisons between estuaries and their respective catchments. Zone C area and catchment area were standardised by expressing both in terms of a common factor, palaeovalley area: in the case of Zone C, as a percentage of palaeovalley area; and then, palaeovalley area as a pecentage of catchment area.

Such an approach will provide a first-order measure of the significance of catchment area as a factor influencing estuary infilling. A comprehensive analysis demands quantification of fluvial channel gradient and catchment slope gradients, stream runoff, erodability of catchment lithology and sediment transport pathways. Furthermore, accurate quantification would only be realised via a sub-catchment analysis. An analysis of this type was considered beyond the scope of the present research, given that the focus here is upon the sedimentological character of estuarine facies.

4.4 FIELD SAMPLING METHODS

The central task to this thesis is to develop an understanding of the sedimentological character of select estuarine systems. Therefore, it was necessary to design a field sampling program that would provide data pertinent to this task. A field program directed toward collection of sediment at a variety of scales was undertaken. Sampling scales ranged from bedform coring to drilling an entire valley fill.

4.4.1 Box-coring

Fifty-two box-cores were collected from specific bedforms in the intertidal to supratidal portions of the inlet to Wapengo Lagoon. Figure 4.3 shows the location of sample sites in Wapengo. Box-cores were not collected from Narrawallee Inlet due to the advanced stage of infill and consequent paucity of active intertidal depositional environments. For each bedform sampled, two cores were collected, one oriented parallel to the inferred flood flow direction and the other positioned normal to the flood flow. The purpose of sampling in this manner was to allow reconstruction of the three-dimensional internal structure of bedforms. The box-corer provides an undisturbed sample 20 centimetres wide by 34 centimetres deep, allowing for complete sampling of small-scale bedforms.

Medium-scale and large-scale bedforms required separate sampling on stoss and lee faces.

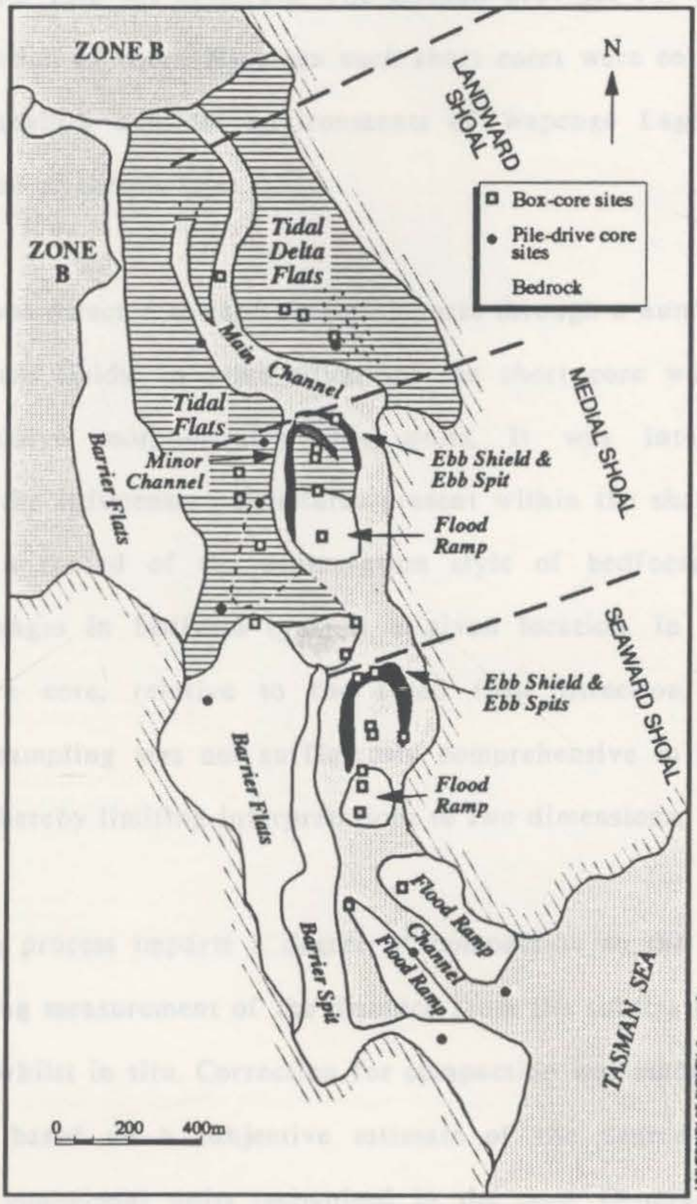


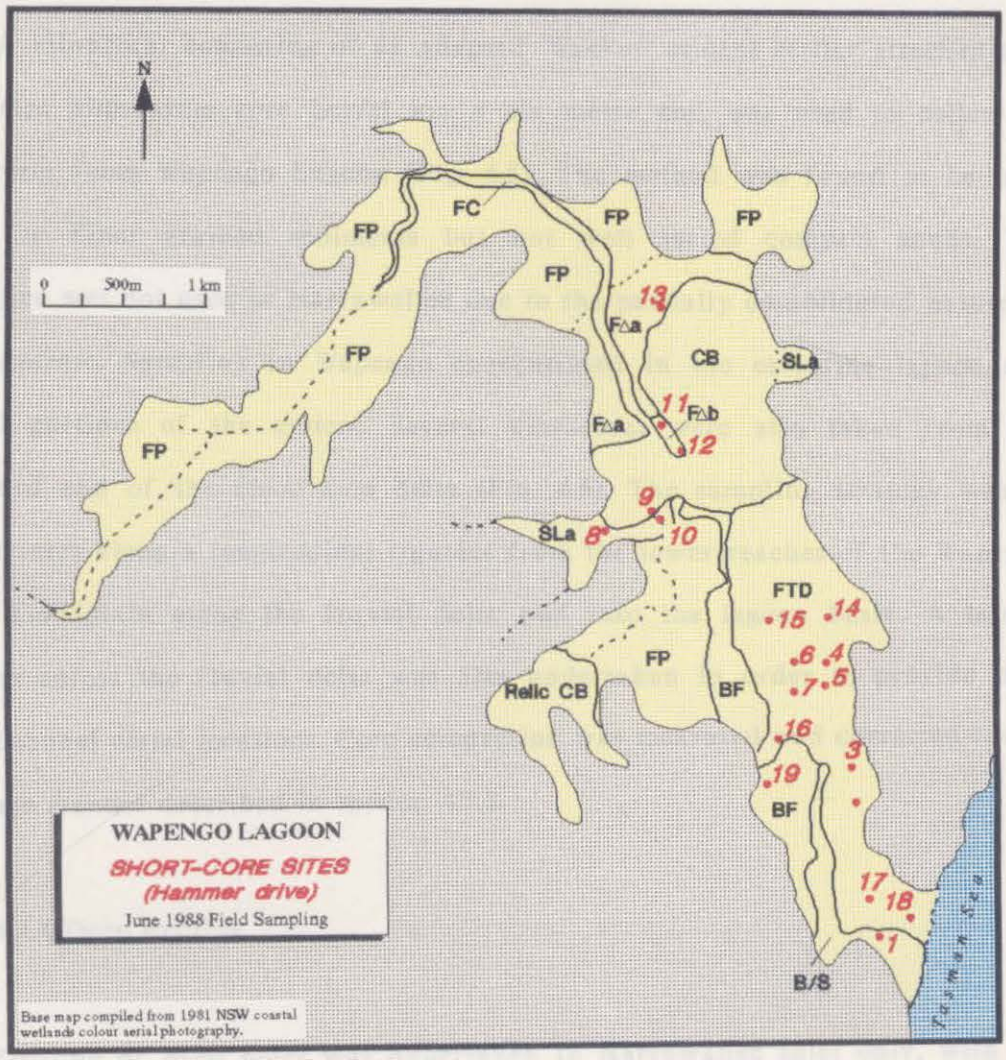
Figure 4.3: Location of box-core sites in the Wapengo Lagoon inlet.

4.4.2 Hammer-coring

The hammer-coring technique involves manually penetrating a two metre plastic core barrel into the substrate. The method provides for relatively rapid and cheap collection of cores. Nineteen such short cores were collected from the intertidal and shallow subtidal environments of Wapengo Lagoon. Figure 4.4 shows the location of sample sites.

Sampling was directed toward obtaining cores through a number of locations in active bedform fields. In some situations the short core was sufficient to penetrate successive morphostratigraphic units. It was intended that an examination of the sedimentary structures present within the shallow subsurface would provide a record of the preservation style of bedforms and possibly evidence of changes in bedform type at a given location. In most cases the orientation of a core, relative to the flood flow direction, was recorded. Unfortunately, sampling was not sufficiently comprehensive to provide a flow normal record, thereby limiting interpretations to two dimensions.

The coring process imparts a degree of compaction to the sediment being sampled, requiring measurement of the distance from the substrate surface to the top of the core whilst in situ. Correction for compaction was made following core logging and is based on a subjective estimate of the degree of compaction experienced by component units recognised in the core. Generally, well sorted sands are assumed to compact by less than five per cent whilst organic rich muds and silts compact by up to 40 per cent.



Note: Refer to figure 2 for detail on sub-environments.

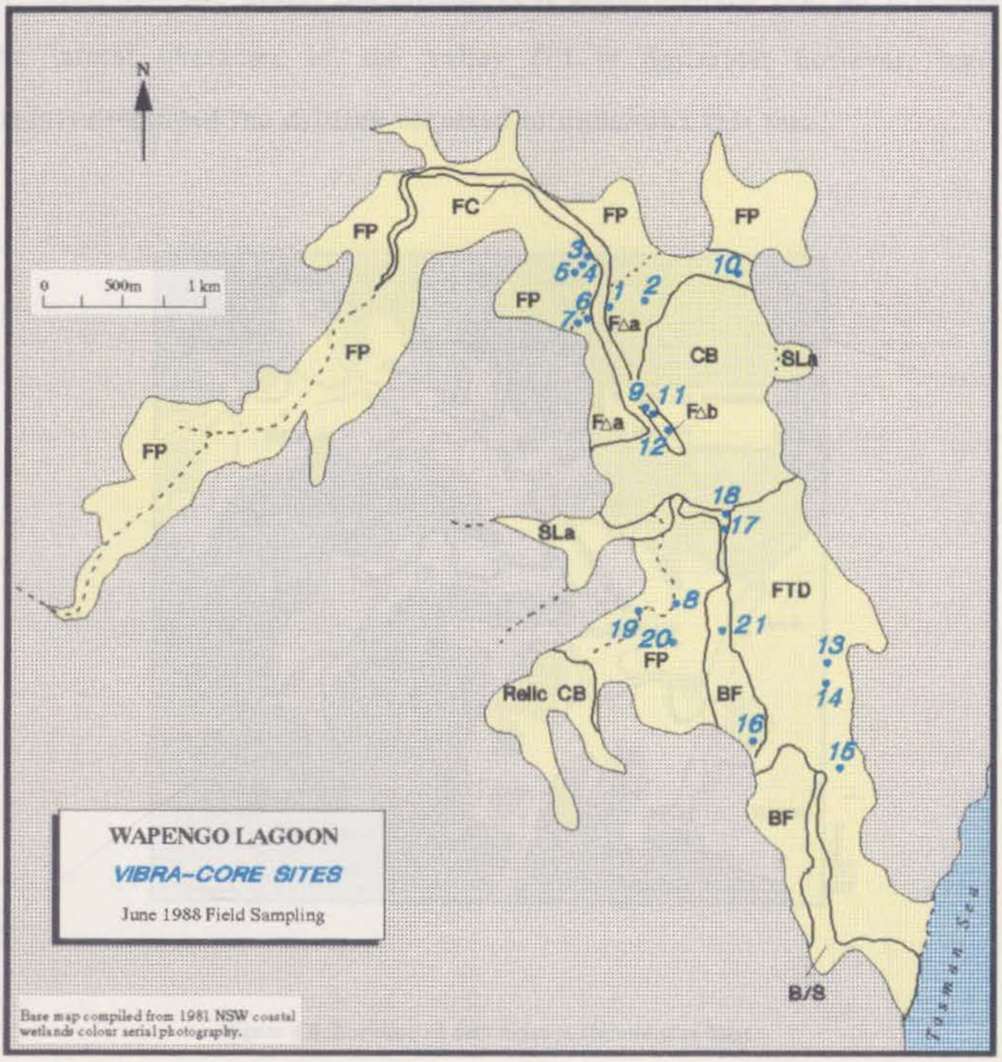
Figure 4.4: Location of short hammer-cores in Wapengo Lagoon.

4.4.3 Vibracoring

A vibracorer consisting of an adapted 'Wacker' cement settler attached to a six metre aluminium core barrel via a six metre coil was used to collect 23 vibracores from Wapengo Lagoon (Fig. 4.5). The method was found to be most suited to finer grained sediments but not well sorted compact sands. The technique was not used in Narrawallee due to the partially consolidated nature of the substrate. Sampling in Wapengo concentrated in the estuarine lagoon and fluvial portions of the system. Several vibracores were also taken from the landward end of the flood tide delta (Fig. 4.5). The sampling strategy was to collect cores along a longitudinal transect from the lower reaches of the Wapengo Creek floodplain along the fluvial delta and into the lagoon basin. A lateral transect across the fluvial delta was also undertaken in order to provide data from channel distal locations. Core compaction was measured and corrected for in the same manner described in section 4.3.2.

4.4.4 Deep drilling

Drilling of deep holes was undertaken in Narrawallee Inlet only, with the intention of sampling the valley fill to basement. Basement is here defined as bedrock. Two truck mounted rigs were used, a Gemco rig and a Jaycro rig. Both have the capacity to auger and core unconsolidated sediments. Augering involves sinking an uncased hole with solid augers and retrieving sections for subsampling every 1.5 metres. Coring involves casing the entire hole and sampling at 1.5 metre or three metre sections. Core recovery in sands was generally poor due to their poor cohesion properties.



Note: Refer to figure 2 for detail on sub-environments.

Figure 4.5: Location of vibra-cores in Wapengo Lagoon.

Figure 4.6 shows the locations of the six holes drilled for this study. The holes were positioned to define a longitudinal valley transect extending from close to the head of the valley to the presumed seaward limit of the barrier basin.

Drilling was not carried out further seaward due to the dominantly sandy nature of the valley fill and access limitations. It is acknowledged that an investigation of the lateral character of the valley fill is desirable; however, logistical constraints precluded the drilling required to undertake this task.

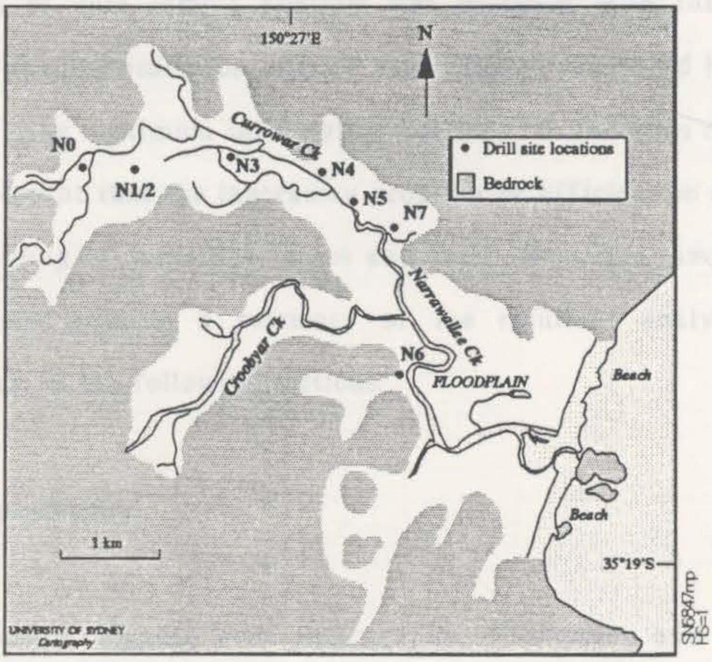


Figure 4.6: Location of drill holes in Narrawallee Inlet.

Holes N1/2, N3, N5 and N6 were cored whilst N7 was augered. Hole N0 was drilled as an auger hole by the N.S.W. Department of Main Roads during bridge construction. Of these, only N0 and N5 encountered the sediment-bedrock contact. The longitudinal valley bedrock profile is thus extrapolated from these two points. The compact nature of the valley fill sediments is such that core compaction is assumed to be negligible, with the exception of the top metre to metre and a half of a drill hole. The amount of compaction was measured for the first core section and corrections to logs made accordingly.

4.5 LABORATORY ANALYTICAL METHODS

A program of core sample analysis was designed with the intention of documenting all the physical properties of the sediment recovered in the field. In addition to providing maximum information pertinent to the aims of the study, it was deemed important that the laboratory program be efficient so as to minimise unnecessary handling of individual cores and their respective samples. The flow chart in Figure 4.7 presents a summary of the resultant analytical program described in detail in the following sections.

4.5.1 Core processing

4.5.1.1 Splitting, logging and photography: Vibracores and hammer-cores were split lengthwise. A power saw was used to cut the core barrel, and a length of wire was employed to separate the two halves of core ensuring minimal disturbance to the sediment. The surface of each half was then cleaned with a trowel and any aluminium/plastic shavings removed. One half was selected for further analyses and the other wrapped in two layers of plastic wrap, labelled and archived.

The working-half of cores were then logged and photographed. All cores were photographed soon after opening, at an approximate scale of 1:1. Core descriptions were directed toward the following properties of the sediment:

(i) the position and boundaries of component sediment units;

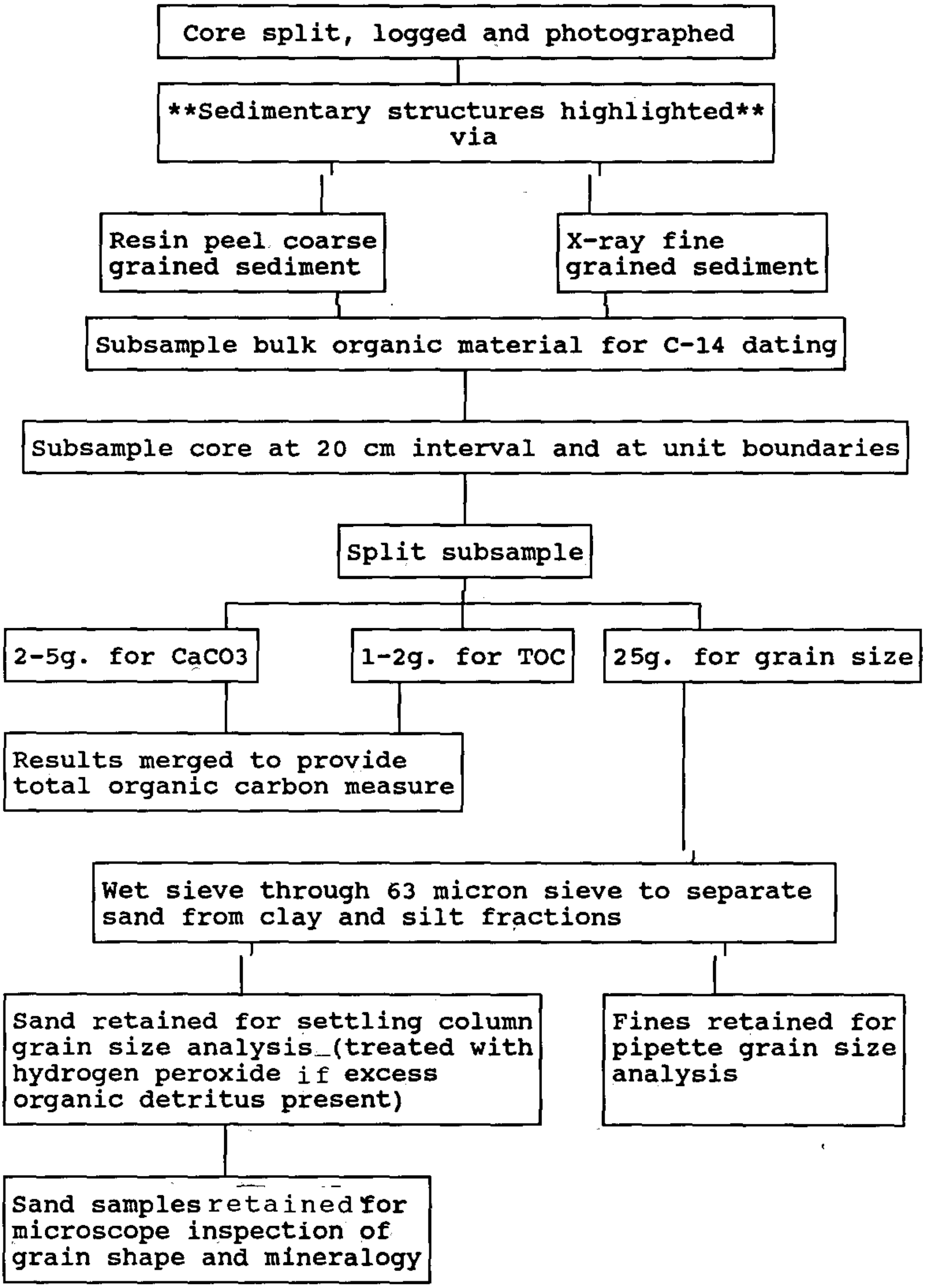


Figure 4.7: Flowchart showing procedure for laboratory analysis of cores.

(ii) the nature of unit boundaries (gradational or abrupt);

(iii) modal sediment texture of each unit;

(iv) degree of hydraulic sorting, evident from the range of particle sizes present;

(v) gross mineralogical content of clastics;

(vi) the character of physical and biogenic sedimentary structures;

(vi) the relative concentration and condition (in situ or disturbed) of organic matter and fossil shell;

(vii) weathering characteristics of each sediment unit, with colour as a primary indicator.

4.5.1.2 X-ray Radiography: Analysis of physical and biogenic sedimentary structures was assisted by means of x-ray radiography of cores. The technique was found to be most suitable for fine to medium grained sediments. Half core sections were x-rayed for 20 milliseconds at 150 milliamps and 62 kilovolts using Dupont Hi plus screen film. Select radiographs were then printed on photographic paper for presentation.

4.5.1.3 Resin relief peels: The unsuitability of coarse grained sediment to x-ray radiography required that resin relief peels be constructed in order to highlight sedimentary structures. Vibracores, hammer cores and box-cores were all peeled. The method involves applying araldite resin (Ciba-Geigy General Purpose Liquid Binder K79) to the face of clean and smoothed cores at a concentration of approximately 0.2 millilitres per square centimetre. A backing board or gauze cloth was placed on the core to provide support for the peel. The resin requires 24 hours to set to maximum hardness, after which the peel is lifted from the core face and washed to remove loose sediment.

4.5.1.4 Subsampling: The interval at which cores were subsampled was determined by the degree of textural heterogeneity within a particular core. Every sedimentary unit recognised in a core was sampled at least once. Thin units (<20cm) were sampled once, whereas units greater than 20 centimetres in thickness were sampled at 20 centimetre intervals. In cases where distinct grading in texture was evident in a particular unit, sampling was such to ensure the trend be recognisable in grain size data. A two centimetre slice of material was extracted to provide sufficient sample for splitting for a variety of analytical procedures. Cores were also sampled for organic material suitable for radiocarbon dating.

4.5.2 Textural Analysis

Quantification of the size of sediment subsamples was achieved using separate analytical procedures for the sand fraction and for the silt and clay fractions. Sample preparation therefore required that the two fractions first be segregated. Samples were first placed in 100 millilitres of a dispersant solution (either 2.23 g/l sodium pyrophosphate or 1.65 g/l potassium pyrophosphate) and allowed to soak for several days to ensure complete disagregation of the sediment. Prior to sieving the sample solution was placed in a ultrasonic bath for 15 minutes to break up any remaining flocs. Samples were then washed with 900 millilitres of dispersant through a 63 micron sieve. The portion of the sample that passed through the sieve was collected and transferred to one litre measuring cylinder. Sediment retained in the sieve, representing the sand fraction, was transferred to a beaker and placed in an oven for drying.

Samples judged to contain less than five per cent silt and clay were washed for 15 minutes through a nest of 150, 63 and 38 micron sieves, on a Fritsch automatic sieve shaker. The clay fraction is discharged by the shaker and lost, while the silt fraction was retained in the bottom sieve to ensure that it was a negligble component. It too was discarded. The sand fraction was dried and stored for size analysis.

When the sand fraction was dry the sample was inspected for organic material. If the amount of organic detritus was sufficient to introduce excess weight to the sand fraction or to interfere with grain settling in a settling tube then the sample was treated with hydrogen peroxide. This involved heating the sample to approximately 60^{o} celsius for several hours to dissolve the organics. The sands were redried, weighed and stored for size analysis.

4.5.2.1 Fine fraction analysis: Size analysis of the silt and clay fraction was carried out via the standard pipette extraction method (Lewis, 1984). The one litre sample solution was allowed stand for at least 24 hours to check for floculation of fines. Samples were stirred thoroughly prior to extractions to ensure complete mixing of the solution. Seven 50 millilitre beakers were labelled and weighed to four decimal places for each sample. The temperature of the solution was measured to determine the extraction depths required. Samples were then stirred for exactly 30 seconds, allowed to settle for 20 seconds after which the first of seven 20 millilitre pipette extractions was made. Each extraction represents a specific particle size interval, including 4 phi, 4.5 phi, 5 phi, 5.5 phi, 6 phi, 7 phi and 8 phi. Beakers are placed in an evaporating oven at 100^{o} celsius. Samples are taken to complete dryness and then weighed. Calculation of the actual weight of each phi fraction in the one litre solution requires correction for the additional weight provided by the dispersant agent. The formula for this calculation is given by:

Weight phi interval = (wt. extraction x 50) - wt. disp.

where wt. dispersant= 1.65 grams for potassium pyrophosphate and 2.23 grams for sodium pyrophosphate

4.5.2.2 Coarse fraction analysis: An automated settling tube was used to measure the particle size of the sand fraction. The tube used is 1.82 metres in length and was calibrated with glass bead standards immediately before analysis. Sand samples were analysed for between 300 and 600 seconds, depending on the size of grains within a sample. Sample size varied between two and ten grams. Data output is in the form of phi units, covering the range -1 phi (2mm) to +4.0 phi (0.063 mm) at tenth phi intervals.

With the exception of large shells, carbonate material was not removed from the sands for the reason that fragmented shells are presumably reworked and therefore are a representative of depositional processes at the sample site. Samples containing gravel were passed through a -1 phi sieve to remove particles too large for the settling tube instrument. The weight of the gravel fraction was recorded and later incorporated into grain size data.

4.5.3 Sediment Geochemistry

Select geochemical properties of estuarine sediments have been analysed with the express purpose of assessing the hydrocarbon source rock potential of component depositional units. To this end, it was necessary to quantify the concentration of total organic carbon (TOC) present within core subsamples. Knowledge of trends in variability of TOC concentrations through a sedimentary profile also provides an interpretative tool for assessing the intensity of biological reworking of sediment and determining relative sedimentation rates. In essence, relatively fast rates of deposition may be linked with low degrees of biological activity resulting in minimal breakdown of organic detritus and high TOC concentrations.

Determination of the concentration of TOC in a sample is achieved indirectly through measurement of total inorganic carbon (TIC) and total carbon (TC). Calculation of the difference between TC and TIC provides a value for TOC. TIC has been determined here via calcium carbonate analysis and TC through sample induction.

4.5.3.1 Calcium carbonate: Measurement of the calcium carbonate content of sediment samples was achieved through acid digestion methods. Dried sample splits were crushed to an homogeneous particle size. The powdered sample was then split through a riffle box, with one split retained for total carbon analysis and the other weighed and set aside for $CaCO_3$ analysis. Dry sample weights were typically of the order of 2 to 8 grams. A complete record of sample details for this procedure is set out in Appendix C.

Samples were treated with approximately 20 ml of 4M hydrochloric acid to dissolve any shell material present. Shell digestion was allowed to continue until no further reaction was observed with the addition of HCl. Sample solutions were then filtered through pre-weighed filters (Whatman No.1) to ensure no loss of fine particulate matter. The entrapped sample and filter were then transferred to an oven for drying overnight at approximately 100^{o}C.

Dried samples and filters were reweighed and the weight difference calculated. The reduction in sample weight following digestion and filtering is attributed to removal of all calcium carbonate present in a sample. It is expected that acid digestion will also leach humic and fulvic acids from the sample. This was observed to occur in association with the adoption of a yellow to brown colour by the acid. It is assumed, however, that the contribution to weight loss by removal of humic and fulvic acids is negligible.

The inorganic carbon content of samples was calculated using the molecular weight of carbon as a correction factor, whereby inorganic carbon constitutes 11.989 per cent of the weight of $CaCO_3$. Thus,

Weight Inorganic Carbon= Weight CaCO3 x 0.11989

4.5.3.2 Total organic carbon: As mentioned previously, measurement of total organic carbon (TOC) is achieved indirectly through a difference calculation between TC and TIC. Total carbon is determined here by sample induction. The method involves sample combustion in a LECO induction furnace and gravimetric detection of total carbon liberated.

A random 0.2-0.4 gram subsample of the dry sample split was placed in ceramic crucible with approximately the same volume of iron and copper chips. The metal chips act as accelerators for the induction coil. Sample weight is recorded accurately to four significant figures. Immediately prior to combustion, the weight of the gravimetric absorption bulb is recorded, also to four decimal places. The sample crucible is then placed in the LECO combustion tube of the induction furnace and burnt for exactly five minutes.

The equipment is designed to trap all carbon produced during combustion (released as CO_2) in an absorbant media consisting of sodium hydroxide on asbestos held within the absorption bulb. Oxygen is allowed to flow through the entire system to ensure complete sample combustion and delivery of liberated gases to the bulb. A valve in the carbon bulb is left open during combustion to allow through flow. Unwanted products, such as sulphur, water vapour and dust, are trapped in separate bulbs positioned ahead of the carbon bulb.

Upon completion of the burn, the valve is quickly closed and the bulb weighed. The gain in bulb weighed is then input to the following formula to provide a value for per cent total carbon,

$\%TC = (B \times 0.2729 \times 100)/W$

where, B= weight gain of bulb,

0.2729= ratio of C/CO_2

W= weight of sample.

The value for total organic carbon was then calculated by subtracting that for total inorganic carbon from total carbon. Tabulated results for all samples analysed on the LECO induction furnace are presented in Appendix D.

Samples with known carbon content were also analysed in order to calibrate the LECO furnace and to compare results obtained from the LECO with those from the 'traditional' loss-on-ignition method. This method involves igniting pre-weighed samples in crucibles at 400°C for 24 hours and measuring the weight loss (Smith and Atkinson, 1975).

Three coal samples were used as standards. These had previously been calibrated against certified standards by the laboratory of the N.S.W. Electricity Commission. Table 4.1 presents a summary of the results of replicate analysis of the three coal samples in the LECO furnace and in the muffle furnace used for loss-on-ignition.

SAMPLE	ELCOM %C	LECO %C	L-O-I %C	n
COAL A	59.50	59.24 ± 0.39	75.24 ± 0.16	3
COAL B	61.40	61.14 ± 0.16	76.77 ± 0.13	3
COAL C	66.70	65.94 ± 0.27	81.97 ± 0.13	3

Table 4.1: Summary of comparative carbon analysis for ELCOM (Electricity Commission Standard), LECO and L-O-I (loss-on-ignition) methods. Error terms denote one standard deviation calculated from three replicate analyses.

The results set out in Table 4.1 indicate internal consistency for both the LECO and L-O-I analytical procedures. Of concern, however, is the significant exaggeration of carbon values in the L-O-I results. These results exceed those determined for the standards by an average of 15.46 per cent among the three samples. This result can be attributed to the fact that the L-O-I method does not distinguish between all products of combustion. Thus, a weight loss calculation will incorporate carbon, sulphur and interstitial water losses from the sample. Despite reproducable L-O-I results the method is not considered appropriate for the aims of this study. Desirable TOC concentrations for potential hydrocarbon source rocks are cited by Bjorlykke (1989) to be between one and three per cent. Thus, the level of accuracy required here for TOC determination in sediments is beyond the L-O-I method.

Replicate sediment samples were analysed using the LECO furnace for select samples in order to assess the representativeness of a 0.2-0.4 gram sub-sample. Five samples from Narrawallee drill core N2 were chosen on the basis that they were perceived to represent a range of total carbon concentrations. A summary of the replicate analyses, set out in Table 4.2, shows close agreement between TC values for the samples analysed, with less than one per cent variation in all cases. On the basis of these results and of those for the coal analyses, it was decided that a single burn per sample would provide a sufficiently representative result.

SAMPLE	%T.C. BURN 1	% T.C. BURN 2
N2.1 0.0m	6.5859	5.8782
N2.1 0.2m	1.9084	1.7770
N2.1 0.4m	0.6838	0.6181
N2.4 5.0m	0.4729	0.4940
N2.6 8.0m	1.1663	1.1834

Table 4.2: Summary of replicate LECO total carbon (TC) analyses on samples from Narrawallee Inlet cores.

4.5.4 Dating

Two techniques for determining both absolute and relative ages of sediments deposited in the estuary study sites have been employed for this study. Absolute age estimates on organic material held within host sediments have been obtained via radiocarbon dating. Relative ages on fossil shells have been determined by means of amino acid racemisation dating. Dating of estuarine sediments is considered necessary in terms of the late Quaternary history of the study sites for two reasons. First, dating is required to assist in the problem of resolving a chronostratigraphic profile via correlation of data from separate cores. In this case both absolute and relative dating tools are applicable. Second, construction of age-depth curves for individual facies provides for calculation of long term sedimentation rates and therefore demands absolute dating.

4.5.4.1 Radiocarbon dating: Carbon-14 dating of organic materials recovered from Wapengo Lagoon and Narrawallee Inlet cores were submitted to two laboratories for assay. Four samples from Wapengo and two from Narrawallee were submitted to the NWG Macintosh Centre for Quaternary Dating at the University of Sydney for standard liquid scintillation counting. Analytical procedures employed by this laboratory are outlined by Gillespie (1986). Two samples retrieved from Narrawallee cores and considered too small (< 1 gram) for conventional C-14 dating methods were sent to the Institute of Nuclear Sciences, Department of Scientific and Industrial Research, New Zealand for accelerator mass spectrometer dating. Details regarding methods for producing graphite from samples and accelerator measurements are set out in Wallace et al. (1987) and Lowe and Judd (1987).

4.5.4.2 Amino acid racemisation dating

Measurement of the extent of amino acid racemisation (epimerisation) within fossil shells has been undertaken for eight samples from Narrawallee Inlet drill cores. The technique was employed to provide a comparatively rapid and inexpensive relative age estimate of the major facies units that comprise the Narrawallee valley fill. The relative age of fossil shell material is derived from an interpretation of the ratio of D-isomer (epimers) to the L-isomer for a suite of amino acids (Murray-Wallace and Kimber, 1990). In general terms, the greater the value of the D/L ratio the greater the age of the shell.

Pretreatment of samples involves cleaning a 0.5-1.0 gram shell fragment followed by a light acid etch with 1M hydrochloric acid. An acid hyrdrolysis step follows in which the sample is dissolved in a minimum volume of 8M HCl. The solution is heated in an oven at 110°C for 16 hours. Upon cooling, the solution is filtered through Whatman No. 2 filter paper and subsequently reduced via evaporation to a volume of 1-2 millilitres. The solution is transferred to a cation-exchange column. The column is rinsed with distilled water and then eluted with 2M ammonia. Only the eluent is collected from the column. The eluent is snap frozen in liquid nitrogen and placed on a freeze drier overnight.

The sample is then treated to derivatise amino acids. After removal from the freeze drier, distilled water is added to the powder residue and the solution filtered (Whatman No. 2). The sample is dried under a stream of nitrogen in an aluminium heating block at 80°C. 250 microlitres of 3.3M propan-2-ol/HCl mixture is added to sample vials which are flushed with nitrogen, capped and heated for one hour at 110°C. Upon cooling, the sample is again dried under nitrogen. 250 microlitres of dichloromethane and 50 microlitres of pentafluoropropionic acid anyhydride are added to the sample. Vials are again flushed with nitrogen, capped and heated at 110°C for 10 minutes. Samples are dried under nitrogen. Finally, samples are transferred to reaction vials using a 100 microlitres of dichloromethane.

The final stage in the procedure is the analysis of the volatile derivative by gas chromatography. A Hewlett Packard (model 5890A) gas chromatograph was used to detect amino acids liberated from 5-10 microlitres of sample solution. The sample is analysed at 60°C for two minutes and then the temperature is raised 4°C per minute until 196°C is attained, whereupon the temperature is held at that level for a final 10 minutes.

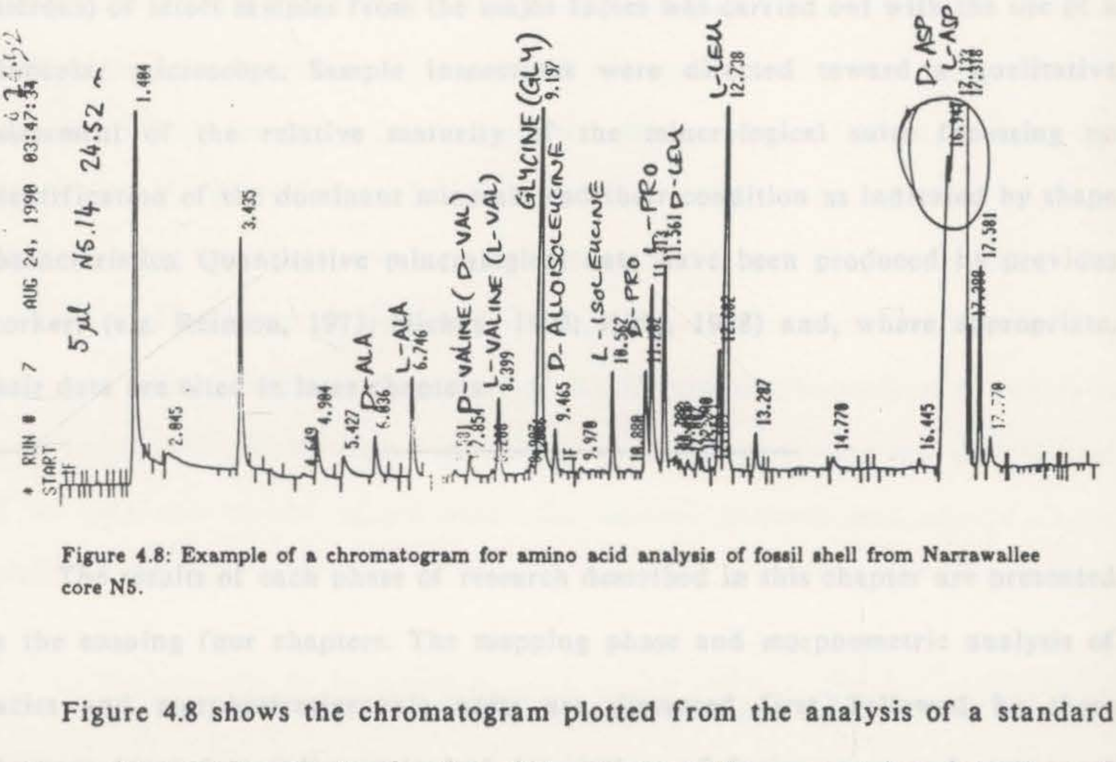


Figure 4.8: Example of a chromatogram for amino acid analysis of fossil shell from Narrawallee core N5.

Figure 4.8 shows the chromatogram plotted from the analysis of a standard amino acid solution. Peaks in the plot represent the progressive detection of individual amino acids. Detection times are printed adjacent to each peak and the integrated area of each peak are tabulated below the graph. The liberation of D-amino and L-amino acid for individual acids occurs at approximately the same time for all analyses, though the D and L peaks are not always adjacent to each other. In some cases (eg. Glycine) it is not possible to separate the two peaks. Identification of D and L peaks and calculation of D/L ratios is, therefore, a relatively straightforward task.

4.5.5 Mineralogical analysis

It was beyond the scope of this study to undertake detailed analysis of the mineralogical properties of the sediments sampled from the two study sites. Rather, an examination of the gross mineralogy of the coarse fraction (>63 microns) of select samples from the major facies was carried out with the use of a binocular microscope. Sample inspections were directed toward a qualitative assessment of the relative maturity of the mineralogical suite focussing on identification of the dominant minerals and their condition as indicated by shape characteristics. Quantitative mineralogical data have been produced by previous workers (e.g. Reinson, 1973; Hickey, 1978; Kidd, 1978) and, where appropriate, their data are cited in later chapters.

The results of each phase of research described in this chapter are presented in the ensuing four chapters. The mapping phase and morphometric analysis of facies and morphostratigraphic units are discussed first, followed by three chapters devoted to sedimentological descriptions of facies zones and component units.

CHAPTER 5: ESTUARINE FACIES MORPHOMETRY

5.1 INTRODUCTION

The evolutionary model for N.S.W. estuaries developed by Roy (1982, 1984a) incorporated a classification scheme that was based upon qualitative assessments of estuary type and the relative degree of filling for individual estuaries. Three types of estuary were recognised: (i) drowned river valley estuaries; (ii) bay-mouth barrier estuaries; (iii) coastal lake (Roy, 1984a). The general characteristics of each type are summarised in chapter three. Within each type four stages of infill were defined in broad qualitative terms, thereby providing for recognition of immature and mature estuaries. The classification provided a useful yardstick for identifying the general character of individual estuarine deposits, yet lacked a firm quantitative component. The results presented in this chapter represents the first attempt to quantify and statistically analyse the depositional style and degree of estuary filling for a sample of N.S.W. estuaries. In essence, the analysis complements existing conceptual models by contributing toward the development of an empirical model of estuarine depositional patterns and spatial facies relationships.

Three complementary statistical grouping techniques (ENTROPY, C.A.R.T., P.C.A.) are employed to produce a classification scheme for 68 south coast estuaries. The sample includes the total population (n=55) of estuaries and lagoons occurring within the Lachlan Fold Belt structural unit of southern N.S.W. and the 14 estuaries that lie within the southern portion of the Sydney Basin. The interpretation of the classification is directed toward distinguishing modes of estuarine sedimentation and highlighting a spectrum of infill stages.

The morphometric analysis presented herein also allows for inter-estuary comparison on a completely objective basis. An additional product, therefore, of the statistical analysis of south coast estuaries has been the development of criteria for selection of field sampling sites. The morphometric properties of the two field sites, Wapengo Lagoon and Narrawallee Inlet, are presented and assessed in the context of their respective statistical classes.

Catchment geology between the Lachlan Fold Belt and southern Sydney Basin units does differ, yet the estuaries exhibit broadly similar palaeovalley configurations and catchment dimensions (see Appendix A). Catchments are characteristically of high relief and are drained by relatively small rivers (Chapman et al., 1982). As noted in chapter two, it is the apparent homogeneity of geological and topographical estuarine settings that prompted the analysis of this particular section of the N.S.W. coast. Despite this homogeneity, the results of the morphometric analysis indicates variation in the relative size of depositional units along the coast. Consideration must, therefore, be given to possible variations in sediment sources when accounting for the existence of different modes and degrees of infill. Both terrestrial and marine sources must be considered. Thus, an analysis of catchment characteristics including, dimensions, lithology and slope gradients is presented. Variations in the supply of sediment from the nearshore and shoreface environments is more difficult to assess. For the purposes of this chapter, existing models for the onshore transport of sediment will be utilised (Roy et al., 1980; Thom and Roy, 1985).

Modelling of facies character in this manner must be supported by and ultimately incorporate detailed sedimentological information. It is therefore intended that the explanation presented in this chapter for the variation in estuary infill character be of a preliminary nature. A complete explanation for varied estuary infill is reserved until the sedimentologic character of study site estuaries is described and analysed (see chapter 9).

5.2 ESTUARINE MORPHOSTRATIGRAPHIC UNITS AND SEDIMENTOLOGICAL ZONES

Analysis of the morphometric characteristics of estuarine facies zones has involved a multi-stage process of data generation and manipulation. The statisitcal classification methodology developed for this study is detailed in chapter four. To briefly reiterate, thirteen morphostratigraphic units have been identified from aerial photographs, each of which has an established definition (see Table 1.1). Clearly, not all estuarine systems feature the entire range of morphostratigraphic units. On a gross morphological scale, however, it is possible to identify in all systems at least two of three facies zones that comprise an assemblage of some or all of the units.

Firstly, Zone A represents morphostratigraphic units that are the product of marine and/or nearshore processes. This zone may, therefore, include the barrier spit complex, flood-tidal delta, tidal entrance channel, barrier flat, and beach ridge plain units.

Secondly, Zone B represents typical estuarine lagoon (i.e. low energy) environments of deposition. Component units are the barrier (or central) basin, supratidal shoreline and intertidal shoreline deposits. This zone is not surficially evident in estuaries that have been almost infilled, it having been buried by material from Zone A and/or Zone C.

Finally, Zone C features a morphostratigraphic unit assemblage that is the product of fluvial and fluvio-estuarine processes. It therefore includes the floodplain, fluvial channel, point bars, and the supratidal and intertidal portions of fluvial deltas.

5.3 DEFINITION OF FACIES MORPHOMETRY

For the purposes of this study, facies morphometry is taken to mean the areal expression of individual facies zones and their component morphostratigraphic units. Measurement of the surface area occupied by units and zones facilitates the quantitative description of the style and stage of estuary deposition for individual estuaries. The degree of estuary, or palaeovalley, infilling is expressed through the relative areal extent of each of the three zones. Thus, in general terms, an estuary that has experienced relatively slow infilling during the Holocene will be areally dominated by Zone B. As palaeovalley infilling proceeds, the areal extent of Zones A and C increases as fluvial deltaic/floodplain and flood-tidal delta deposits prograde over Zone B deposits from opposing directions. The interplay of facies zones allows Zones A and C to be considered as the independent variable assemblage and Zone B as the dependent assemblage. The results of the statistical analysis of these relationships are presented in the following section.

5.4 RESULTS OF STATISTICAL CLASSIFICATION

5.4.1 ENTROPY classification.

(a) Zone Data: Initially, standardised facies zone data (3 variables) for all 68 estuary sites were subjected to the ENTROPY classification procedure. The plot of R_S values versus number of classes is presented in Figure 5.1. The R_S statistic is a measure of between-class variability as a percentage of total variability of the data set. R_S values increase rapidly from 47.5% for a two class solution to 80.05% for a five class classification. Beyond this, the level of return from additional classes, in terms of R_S values, is unsatisfactory. A five class solution appears, therefore, to be most appropriate for the zone data.

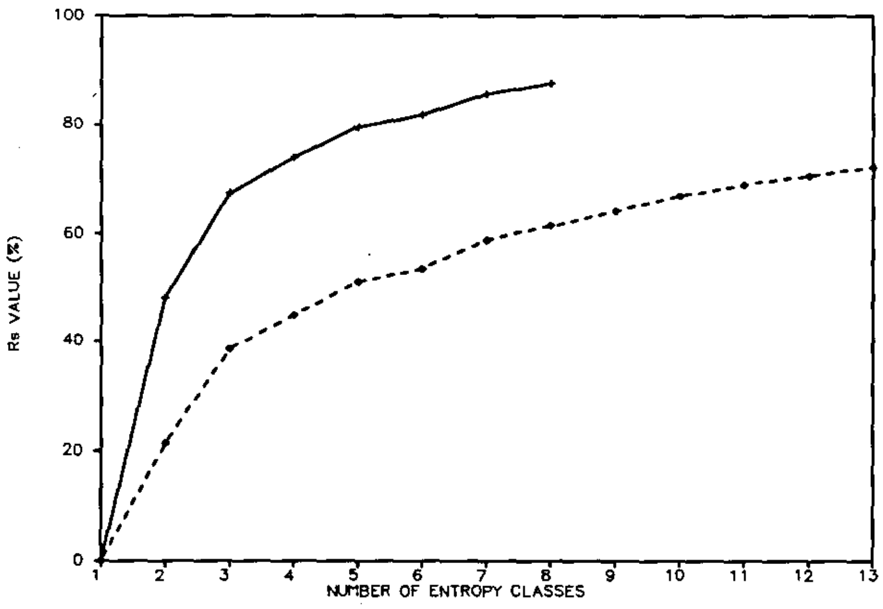


Figure 5.1: Plot of ENTROPY R_s values for 1 to 8 class solutions for three variables (solid line) and 1 to 13 class solutions for 13 variables (dashed line).

As a means for testing for consistency in zone data between the Lachlan Fold Belt and Sydney Basin estuaries, the ENTROPY programme was run on a data set that excluded southern Sydney Basin estuaries. The five class grouping (R_S= 79.26%) produced from the 55 estuaries within the Lachlan Fold Belt correlates strongly with the previous 68 observation result in terms of class characteristics and class membership. Moreover, when the Sydney Basin estuaries are included in the analysis there is no preferred class to which they belong. This result suggests that it is not possible to discriminate on a statistical basis between the facies morphometry of estuaries from the two structural provinces of the N.S.W. south coast.

Although a five class result for facies zone data appears most appropriate in statistical terms, inspection of the plots of summary statistics (mean and standard deviation) for each class suggest the existence of only three *primary* classes, two of which may be divided into sub-classes (Fig. 5.2). The five ENTROPY classes are henceforth referred to as class 1, classes 2A and 2B, and classes 3A and 3B. Morphometric data and the ENTROPY class associated with each estuary are listed in Appendix A.

Class 1 is distinguished by a relative dominance of the estuarine lagoon facies zone (Zone B), with a mean Zone B proportion of 54.0% (σ=8.0%). Twenty estuaries were placed in this class. Valley filling of estuaries within class 1 is only in the early stages, as indicated by the relatively limited extent of Zone A (x=25.4%, σ=8.0%) and Zone C (x=20.6%, σ=10.2%) development (Fig. 5.2). Estuaries in this class are therefore considered to be geologically immature (Roy, 1984).

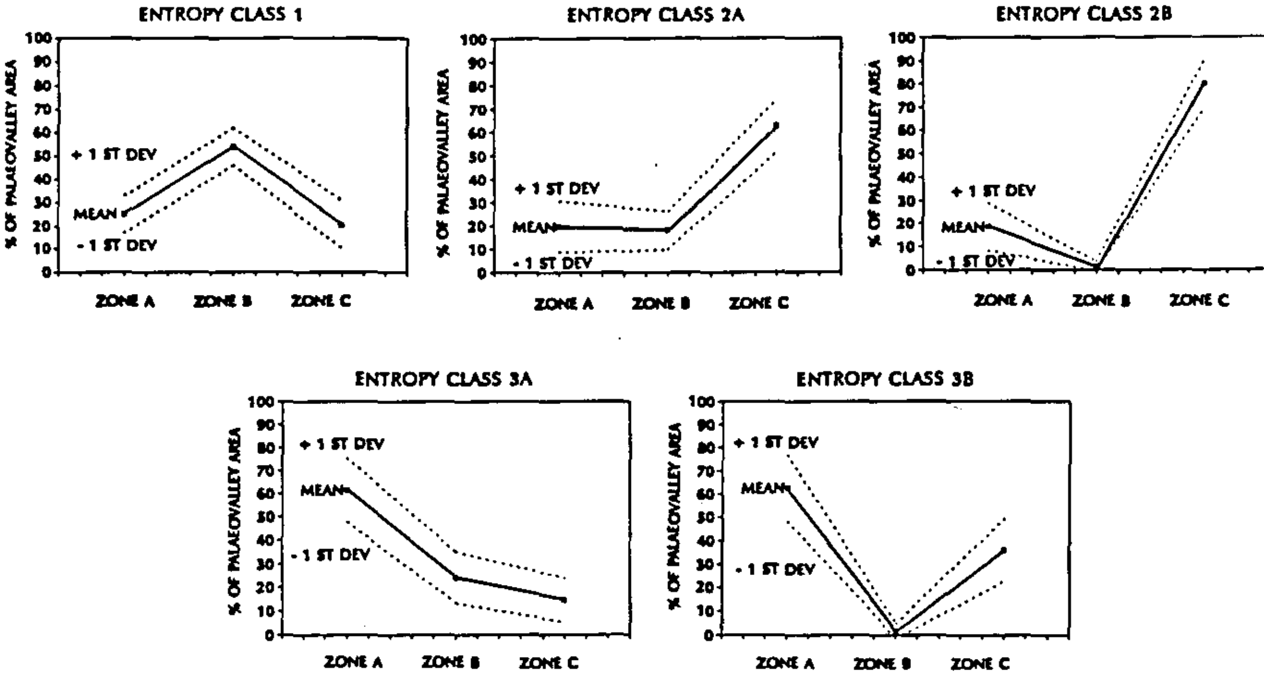


Figure 5.2: Summary statistics plots for five class ENTROPY solution for facies Zones A, B, C.

Classes 2A and 2B incorporate estuaries that surficially exhibit a significant degree of infilling dominated by the fluvial facies assemblage (Zone C) (Fig. 5.2). Class 2A consists of 15 estuaries and 2B of 14 estuaries. The Zone C mean values of 62.5% (σ=11.5%) for 2A and 80.1% (σ=10.1%) for 2B indicate that classes 2A and 2B represent two distinct groups of estuaries that are at the latter stages of valley filling and that much of the sediment is sourced from the catchment. The advanced infill stage is reflected in the low mean Zone B values of 17.9% (σ= 8.1%) for class 2A and 1.4% (σ=2.1%) for class 2B. Indeed, class 2B estuaries are completely full with sediment which, in the terminology of Roy (1984a), indicates maturity. Zone A statistics reveal uniformity in the relative area occupied by marine sourced deposits. Thus, the mean Zone A data are 19.6% (σ=10.9%) and

18.5% (σ=10.2%) for classes 2A and 2B, respectively. Furthermore, these values are akin to the Zone A value of 25.4% for class 1. The significance of the lack of variation of Zone A among classes 1 and 2 will be discussed later.

Classes 3A and 3B are characterised by a proportional dominance of barrier/inlet facies zone (Zone A) (Fig 5.2). Eleven estuaries were classed as type 3A and eight as type 3B. Mean values for Zone A for 3A and 3B are very similar, 61.7% (σ=13.8%) and 62.6% (σ=14.3%) respectively. The distinction between the class 3 sub-classes is in the proportion of fluvial zone facies assemblage. Thus, Zone C means are 14.4% (σ=9.4%) for 3A and 35.9% (σ=13.3%) for 3B. The mean proportion of the estuary valley surface occupied by the Zone B unit asssemblage is 23.9% (σ=10.7%) for class 3A and 1.5% (σ=2.9%) for class 3B. Given the uniformity in relative Zone A area among class 3 estuaries, it appears that Zone B area differences are due to variable Zone C deposition. The apparent greater Zone C variability will be shown to be a major factor in estuary evolution (see section 5.5).

Figure 5.3 presents two scatter plots in which the dependent variable (Zone B) is plotted against the independent variables (Zones A and C) for all 68 estuaries. The five ENTROPY classes are delineated by approximate borders around class members, thereby highlighting sub-populations of south coast estuaries. These cluster plots serve to illustrate the limited extent of variation within each class and the clear differences between the relative significance of facies zones in estuaries at different infill stages. In both plots the clusters are arranged in a manner such that immature estuaries (class 1) occupy the upper sector of the plot and mature estuaries the lower portion. In addition, the two classes of mature estuaries are well separated due to the respective dominance of fluvial (class 2) and marine (class 3) infilling.

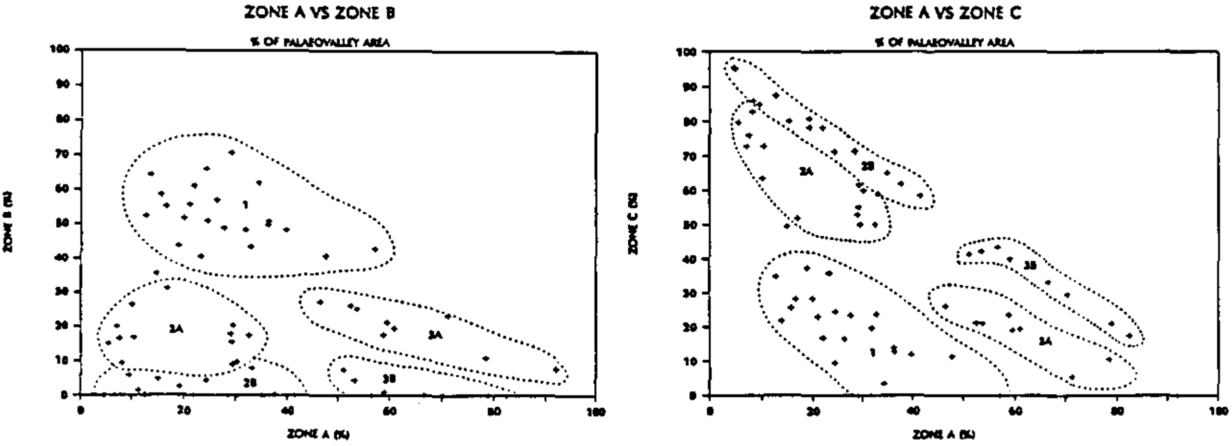


Figure 5.3: Scatter plots of facies zone data showing five ENTROPY class clusters for 68 estuaries.

The ENTROPY Z statistic is a useful measure for highlighting variable behaviour that is peculiar to a particular class. The Z statistic is defined as the difference between the class mean and population mean for a particular variable, measured in standard deviation units. The sign of the Z value indicates whether a particular variable in a class is above (+) or below (-) the population mean. Figure 5.4 graphically depicts the significance of interrelationships between facies zones in each of the ENTROPY classes.

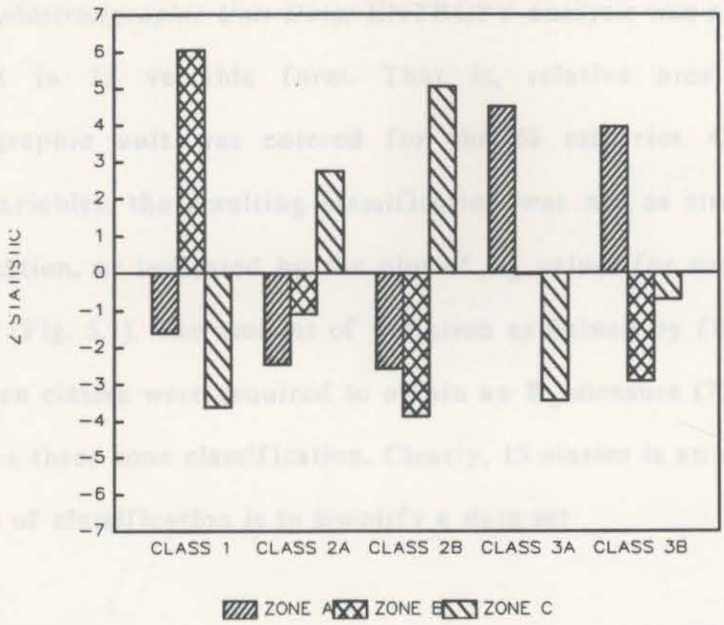


Figure 5.4: Bar graph plot of Z statistics for Zones A,B,C for the five ENTROPY classes.

The dominance of Zone B in class 1 is reflected by the high positive Z statistic value of +6.04. Accordingly, Zone A and Zone C statistics are negative and relatively low, -1.73 and -3.57, respectively. In class 2A the highest Z statisitic of +2.75 is assigned to Zone C and in class 2B it increases to +5.05 in accord with the advanced infill state of 2B estuaries. Zone B in class 2B also produces a relatively high statistic of -3.86, which is due to the consistently low to negligible valley area occupied by Zone B in this class. Finally, the dominance of Zone A in classes 3A and 3B is recorded by respective positive Z statistics of +4.50 and +3.96. Zone B in the mature sub-class (3A) has a relatively high negative Z statistic of -2.91 due to the absence of an estuarine lagoon in many 3A estuaries (Fig. 5.4).

(b) Morphostratigraphic Unit Data: ENTROPY analysis was also performed on the data set in 13 variable form. That is, relative area data for each morphostratigraphic unit was entered for the 68 estuaries. Given the larger number of variables, the resulting classification was not as strong as the three zone classification, as indicated by the plot of R_S values for successive levels of classification (Fig. 5.1). The amount of variation explained by five classes is only 51.3%. Thirteen classes were required to obtain an R_S measure (72.2%) comparable to that for the three zone classification. Clearly, 13 classes is an excessive number since the aim of classification is to simplify a data set.

The distinction between the degree and style of estuary infill identified by the three zone classification remains clear when mean percentage values for each morphostratigraphic unit are plotted as cumulative percentages of palaeovalley area (Fig. 5.5). Moreover, the plot identifies the units that contribute most to the character of each class. Thus, for class 1 estuaries the steepest part of the cumulative plot is associated with the barrier basin (cb) unit, which is consistent with the immature condition of class 1 estuaries.

The cumulative plots for classes 2 and 3 are well removed from one another as testimony to the different infill modes apparent for their respective estuary sub-populations. The steepest sector of the class 2 curves is aligned with the floodplain (fp) morphostratigraphic unit, whereas for class 3 curves the barrier/spit (bs), flood-tidal delta (ftd) and beach ridge plain (srp) units combine to produce the steepest part of the plot. Both class 2 and 3 sub-class plots mimic one another except at the barrier basin unit point in the curve. At this point the plots diverge. The divergence is a function of the negligible surface expression of the barrier basin in mature (2B and 3B) estuaries. It is interesting to note that there is no appreciable difference between the shoreline units (sla, slb) of the subclasses, as might be expected for estuaries at different stages of infill (Fig. 5.5).

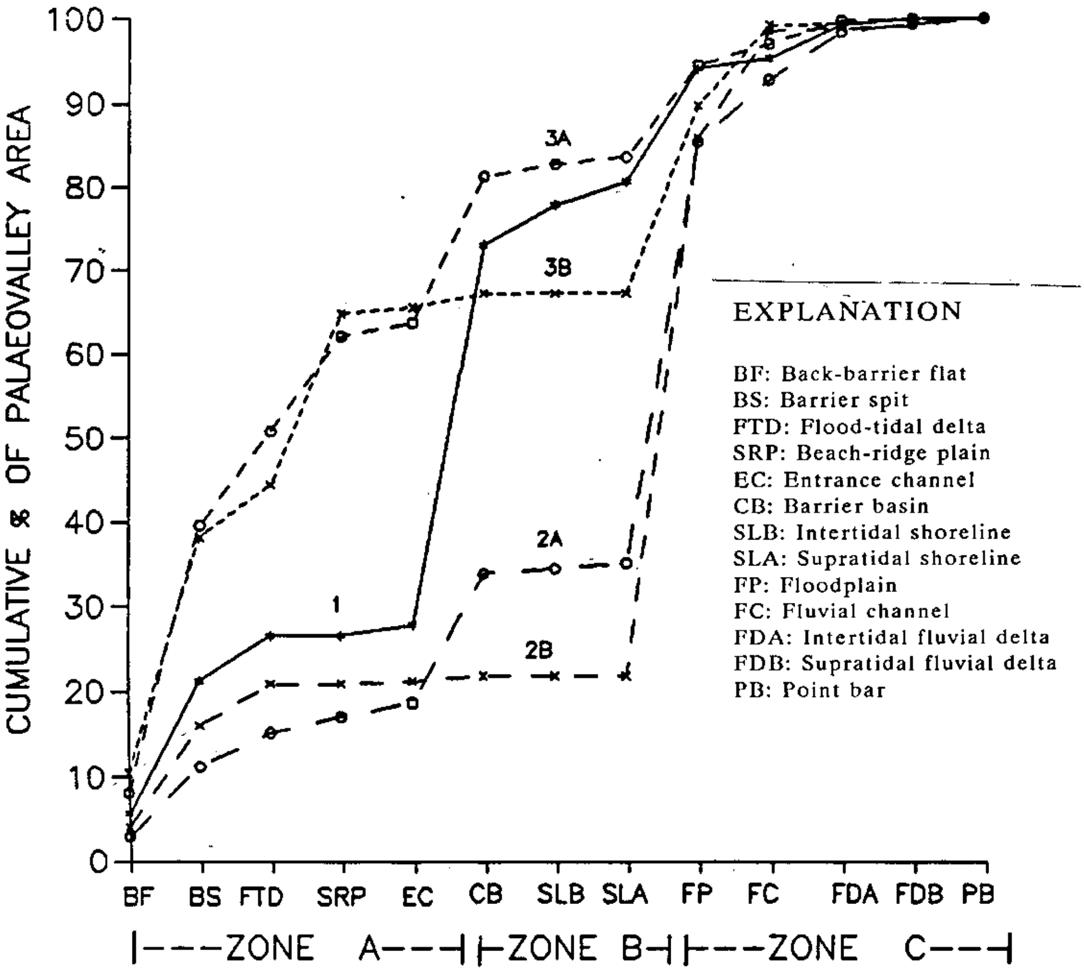


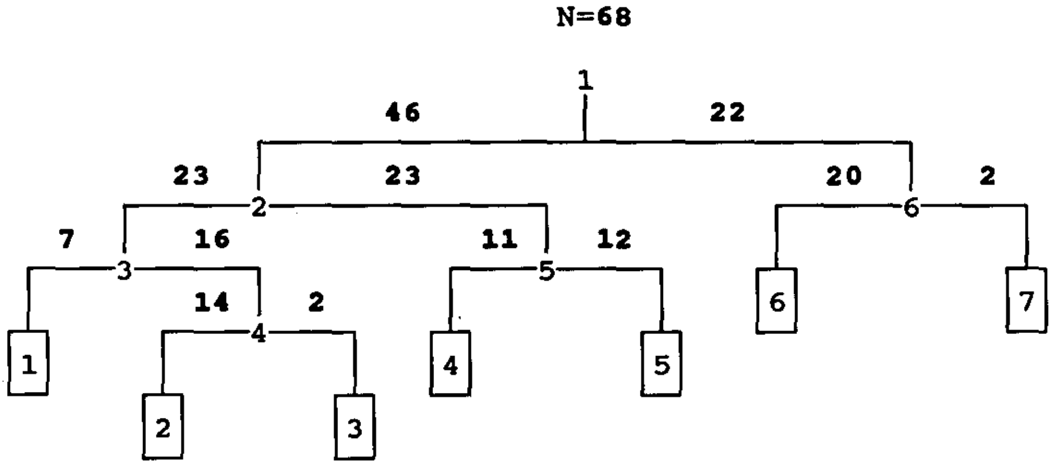
Figure 5.5: Morphostratigraphic units plotted as cumulative percentage of palaeovalley area. Note that units are not arranged in any specific order along the x-axis.

In summary, the ENTROPY classification of estuarine morphometric data appears to have extracted the primary morphological characteristics of a spectrum of valley infill states. The classification identifies a broad range of infill states and points to two modes of infilling, fluvial dominant and marine dominant, each of which are characterised by unique interrelationships of facies zone assemblages. Further analysis of these relationships, especially among morphostratigraphic units, is provided by results of the C.A.R.T. classification presented below.

5.4.2 Classification and Regression Trees classification

The C.A.R.T. procedure is employed here because it provides additional information regarding the properties of ENTROPY classes. Specifically, the method identifies the critical variable(s) that determine membership of each class. A full description of the C.A.R.T. method is presented in chapter four. Standardised areal data for all thirteen estuarine morphostratigraphic units were entered into the C.A.R.T. programme (Briemann, 1984). The five classes produced by the ENTROPY procedure were used as the pre-determined class identifier for each of the 68 estuaries. C.A.R.T. attempts to replicate the input classification and in doing so constructs a tree which shows successive splits of the data. Figure 5.6 shows the classification tree diagram designed by C.A.R.T. Six decision levels (stages of splitting) were made to produce seven terminal nodes (classes).

The initial split resulted in 46 estuaries going to the left branch of the tree, and 22 going to the right. This decision was made on the basis of the proportion of palaeovalley area occupied by the barrier basin morphostratigraphic unit, with 28% being the split value. Thus, the estuaries of the left branch have a barrier basin area of less than 28% and those to the right a basin area greater than 28%. The second split identified a further break in barrier basin values. The 46 estuaries of the left branch were split into two groups of 23, based on a barrier basin value of 7.5% (Fig. 5.6).



* *Non-bolded numbers are decision levels, 1 to 6.*

**Bolded numbers represent the number of estuaries that meet the requirements of a particular decision.*

**Numbers enclosed in boxes are terminal nodes, taken here to represent ENTROPY classes of estuary (see Table 5.1).*

Figure 5.6: C.A.R.T. classification tree diagram.

The floodplain morphostratigraphic unit was used as the critical variable for the third and fifth decision levels. It is important to point out that the criteria set at each decision level are carried to latter levels and ultimately to the terminal nodes. For example, at the third decision level, the 23 estuaries grouped by decision two according to a barrier basin values of less than 7.5% were split further into one group of seven with a floodplain unit less than 38.8% of the valley area and a second group of 16 with a floodplain area exceeding 38.8%. The group of seven estuaries occupy terminal node one. Terminal nodes are the most important part of the classification tree because they represent the closest replication of the input classification. Terminal nodes are associated by C.A.R.T. with the original ENTROPY classes and the strength of correlation between nodes and classes is calculated as a measure termed rule accuracy. Thus, terminal node one is associated with class 3B and has a rule accuracy of 66.7% (Table 5.1).

The fourth decision level is to be disregarded here since it involves creating a terminal node (three) containing only two estuaries extracted from a group of 16 estuaries. This decision was made using the barrier flat morphostratigraphic unit cutoff value of 8.2%. This is questionable since the majority (11) of the estuaries concerned have barrier flat values of 0.0%. Moreover, terminal node three has a level of accuracy of only 22.2%, while node two has an accuracy of 92.3% (Table 5.1). Terminal nodes two and three are therefore manually merged to represent ENTROPY class 2B.

At the fifth decision level, a floodplain value of 26.2% was identified as the point for dividing 23 estuaries into one group of 11 and another of 12. This split produced terminal nodes four and five, representing classes 3A and 2A respectively. Both nodes have high accuracy values, 81.8% for node four and 80.0% for node five.

The final decision level, number six, involves splitting the 22 estuaries, initially assigned to the right branch of the tree, into one group of 20 estuaries with barrier flat values less than 12.3% and another group of two estuaries with barrier flat exceeding 12.3%. These two groups represent terminal nodes six and seven, respectively (Fig. 5.6). Although the use of the barrier flat unit appears valid in this decision, (it is present in the majority of estuaries), the split is to be ignored. This entails manually regrouping the two estuaries of node seven into node six which correlates perfectly with ENTROPY class 1. The two node seven estuaries previously belonged to ENTROPY class 3A but referral to the zone scatter plots in Figure 5.3 show these would be outliers if included in class 3A. Moreover, inclusion in class 1 allows for neater definition of class boundaries.

TERMINAL NODE	RULES	ESTUARY CLASS	RULE ACCURACY
1	Floodplain < 38.80% Barrier Basin < 7.55%	3B	66.7%
2	Barrier Flat < 8.28% Floodplain > 38.80% Barrier Basin < 7.55%	2B	92.3%
3	Barrier Flat > 8.28% Floodplain > 38.8% Barrier Basin < 7.55%	3B	22.2%
4	Floodplain < 26.20% Barrier Basin > 7.55% Barrier Basin < 28.00%	3A	81.8%
5	Floodplain > 26.20% Barrier Basin > 7.55% Barrier Basin < 28.00%	2A	80.0%
6	Barrier Flat < 12.30% Barrier Basin > 28.00%	1	95.0%
7	Barrier Flat > 12.30% Barrier Basin >28.00%	3A	18.2%

Table 5.1: Decision rules and rule accuracy for C.A.R.T. classification tree.

The C.A.R.T. output is summarised via a set of decision rules for each terminal node and these are set out in Table 5.1. Note that rule accuracy for terminal node seven of 18.18% is considerably less than for the other five nodes. This low accuracy vindicates the manual rejection of this node, along with node three. Given the exclusion of nodes three and seven, the similarities between the ENTROPY derived classes and C.A.R.T. classes are significant and are reinforced by a 91% agreement between the output of the two classification methods.

As outlined in the preceding methods chapter, C.A.R.T. also produces a classification tree that is the best alternative to the original using surrogate variables. The surrogate being the variable that best reproduces the split and terminal nodes produced using primary variables. Surrogate variables are used because it is possibile that the primary variable at a particular decision level may mask the significance of other variables. The surrogate classification may, therefore, be used to further assess the validity of the primary classification.

Use of the surrogate variable creates two new nodes (t_{Left}~,t_{Right}~) from node t that are less accurate alternatives to the originals (t_{Left}^* and t_{Right}^*), having higher node impurity and containing different proportions of estuaries. Table 5.2 presents the surrogate variables and associated rules and accuracy levels for the same number of decision levels used in the primary classification tree. Surrogate accuracy is similar to rule accuracy in that it is a measure of the strength of correlation between the input classification (ENTROPY) and the output classification (C.A.R.T. surrogate).

At the first decision level, the floodplain unit is substituted for the barrier basin unit. A split value of 23.6% is used and the accuracy of the surrogate is 68.4%. The remaining five decision levels employ a variety of morphostratigraphic units, including the flood-tidal delta, barrier spit, supratidal fluvial delta and supratidal shoreline. The level of accuracy in using these units as criteria for dividing the estuaries into classes is not particularly high, ranging from 33.3% to 66.7% (Table 5.2). More importantly, the surrogate accuracy does not exceed the accuracy of the rules generated for the primary classification (Table 5.1). The masking effect of the primary variables is, therefore, considered not to be significant for this data set and the decision rules incorporating the primary variables may be accepted with confidence.

DECISION LEVEL	SURROGATE VARIABLE	DECISION RULE	SURROGATE ACCURACY
1	Floodplain	To t_L if > 23.6%	68.4%
2	Supratidal Fluvial Delta	To t_L if < 1.07%	33.3%
3	Flood-Tidal Delta	To t_L if > 4.01%	50.0%
4	Supratidal Shoreline	To t_L if < 0.72%	56.1%
5	Barrier Spit	To t_L if > 25.6%	66.7%
6	Flood-Tidal Delta	To t_L if > 0.24%	60.8%

Table 5.2: Decision rules and accuracy of surrogate variables for alternative C.A.R.T. classification. t_L denotes left branch of split in classification tree.

The final output from C.A.R.T. to be considered here is the relative rating score assigned to all variables. The performance of each morphostratigraphic unit, with respect to the decrease in node impurity it yields as a surrogate variable, is used to assign a rank score to each unit. Table 5.3 presents the relative importance ratings for the 13 units. These values are in the range 0 to 100, with the most important variable having a value of 100.

The floodplain and barrier basin units are assigned the highest ratings of 100 and 85, respectively. The high ratings reflect the identification of the floodplain and basin units as critical variables in the design of the classification tree and associated decision rules. Apart from the barrier flat unit, all remaining units were assigned low importance scores of less than 40 (Table 5.3). The high floodplain and basin ratings are consistent with the use of these units as critical variables for determining class membership in the C.A.R.T. classification tree. The result is also in agreement with the ENTROPY output in that a major factor in determining the current state of estuary infill appears to be the degree of floodplain (Zone C) development and, by association, the degree of barrier basin infill. The low rating given to Zone A morphostratigraphic units is interpreted to reflect the lack of variability among south coast estuaries in the proportion of the valley area they occupy. That these trends in the data were identified by both ENTROPY and C.A.R.T. classification procedures suggests that the existence of a spectrum of estuary infill states is primarily due to fluvial (Zone C) variabilty.

MORPHOSTRATIGRAPHIC UNIT	SCORE (0-100)
Floodplain	100
Barrier Basin	85
Barrier Flat	52
Fluvial Channel	38
Barrier Spit	37
Fluvial Delta: Supratidal	36
Shoreline: Intertidal	33
Flood-Tidal Delta	29
Shoreline: Supratidal	26
Beach Ridge Plain	24
Fluvial Delta: Intertidal	15
Fluvial Point Bar	12
Entrance Channel	6

Table 5.3: C.A.R.T. relative variable importance ratings.

5.4.3 Principal Components Analysis classification

The final set of results pertaining to statistical treatment of estuary morphometric data to be considered here is the output from Principal Components Analysis. PCA also provides for identification of critical variables and is used here to enhance the ENTROPY and C.A.R.T. outputs. The 13 standardised estuarine morphostratigraphic unit variables were transformed to three principal components using the covariance option of Wright's (1985) P.C.A. BASIC programme described in chapter four. Figure 5.7 presents a scatter plot of object (estuary) scores for the first and second principal components and Table 5.4 lists variable scores for all three principal components. Each estuary is given a symbol identifying it with one of the five estuary classes derived through ENTROPY and C.A.R.T. The first and second components together account for 83.3% of the total variance, with the majority (61.7%) taken up by the first component. The scatter plot shows a strong association between each estuary class and a particular quadrant of the plot.

The quadrant of the plot defined by negative estuary scores for both the first and second principal components (-/- quadrant) is almost solely occupied by ENTROPY class 1. This clustering is interpreted as a function of the negative correlation between the barrier basin unit and both the first and second principal components. Correlation values, or variable scores, are -0.48 and -0.73 for the first and second components, respectively. This result is consistent with the aforementioned evolutionary status and facies character of class 1 estuaries. That is, they are immature and areally dominated by Zone B facies assemblage, notably the barrier basin unit.

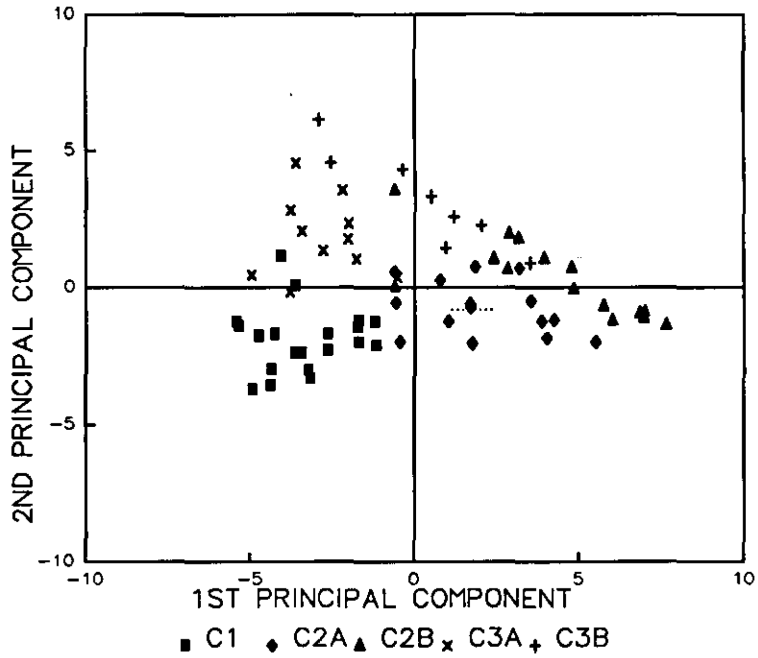


Figure 5.7: Scatter plot of first and second principal component scores for 68 south coast estuaries. Symbols correspond to the five ENTROPY classes: 1, 2A, 2B, 3A, 3B.

MORPHOSTRATIGRAPHIC UNIT	VARIABLE SCORES 1ST P.C.	2ND P.C	3RD P.C.
Floodplain	0.8473	-0.3276	-0.1803
Fluvial Channel	0.0495	0.2482	0.1671
Fluvial Point Bar	0.0082	-0.0024	0.0080
Supratidal Fluvial Delta	-0.0428	-0.0689	0.0080
Intertidal Fluvial Delta	-0.0006	-0.0121	0.0041
Barrier Basin	-0.4830	-0.7309	-0.0372
Supratidal Shoreline	-0.0157	-0.0319	0.0127
Intertidal Shoreline	-0.0476	-0.0073	-0.0114
Flood-Tidal Delta	-0.0646	0.0685	0.1865
Barrier Flat	-0.0691	0.1561	-0.1031
Beach Ridge Plain	0.0053	0.2785	0.6261
Barrier Spit	-0.1813	0.4291	-0.7068
Entrance Channel	-0.0054	0.0007	0.0264

Table 5.4: P.C.A. variable scores for the first, second and third principal components.

ENTROPY class 2A occupies the +/- quadrant of the plot, though some estuaries overlap into the lower margins of the other three quadrants (Fig. 5.7). Positive first principal component scores are associated with a strong positive floodplain variable score of +0.85. Negative second component scores are possibly the combined effect of moderate to strong negative variable scores for the floodplain and barrier basin units of -0.33 and -0.73, respectively. These scores reflect the significance of the floodplain morphostratigraphic unit in the valley fill but also emphasise the incomplete infill state of the barrier basin among class 2A estuaries.

ENTROPY class 2B estuaries generally lie in a sector of the scatter plot defined by medium to high positive first component scores and low positive and negative second component scores (Fig 5.7). The positive relationship with the first principal component is attributed to the high floodplain variable score of +0.85. As noted, estuary scores for the second component range from strongly positive to negative. This is due to the absence of a morphostratigraphic unit in this class that behaves in a sufficiently consistent manner to produce a significant association with the second principal component. The emergence of the floodplain morphostratigraphic unit as the only significant variable in the P.C.A. analysis highlights the advanced infill state of class 2B estuaries.

ENTROPY classes 3A and 3B both possess positive estuary scores for the second principal component (Fig. 5.7). These positive scores are associated with a relatively strong positive barrier spit variable score of +0.43 for the second component. The first principal component does not have a strong correlation with any of the Zone A morphostratigraphic units, although class 3A has a less variable set of estuary scores for the first component than 3B (Fig 5.7). That is, 3A scores are all negative due to the influence of the barrier basin unit which has a variable score of -0.48. This relatively complex result is interpreted to be a function of the relative dominance of Zone A facies in class 3A estuaries, while also identifying that infill is incomplete. Class 3B estuaries, which are largely infilled, have a range of estuary scores for the first component reflecting the lack of a dominant morphostratigraphic unit for that component.

Figures 5.8 and 5.9 present scatter plots of the first and third principal components, and the second and third components, respectively. These two sets of results offer little in terms of extracting clear associations between estuary scores and ENTROPY classes of estuaries, nor between estuary class and morphostratigraphic units. The lack of significant patterns in the covariance plots is reflected by the small amount of total variance accounted for by each component. The second component accounts for 21.6% and the third component for only 16.7%.

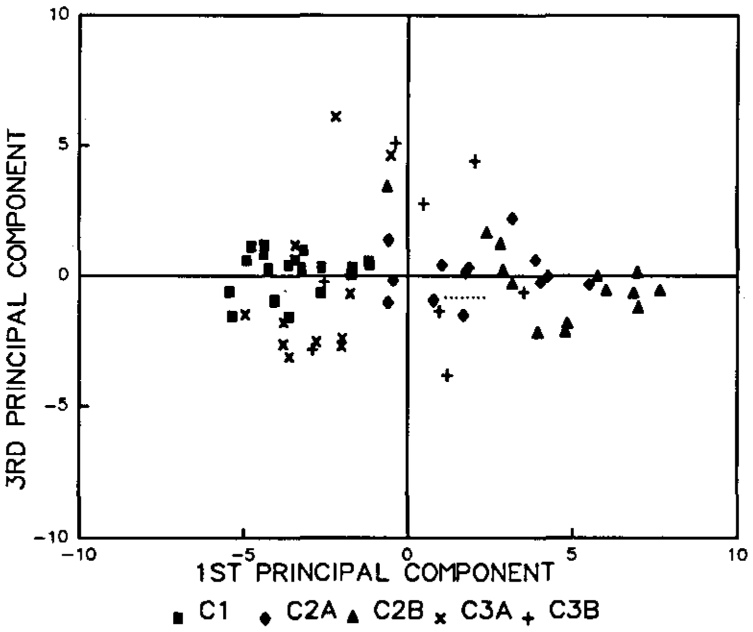


Figure 5.8: Scatter plot of first and third principal component scores for 68 south coast estuaries.

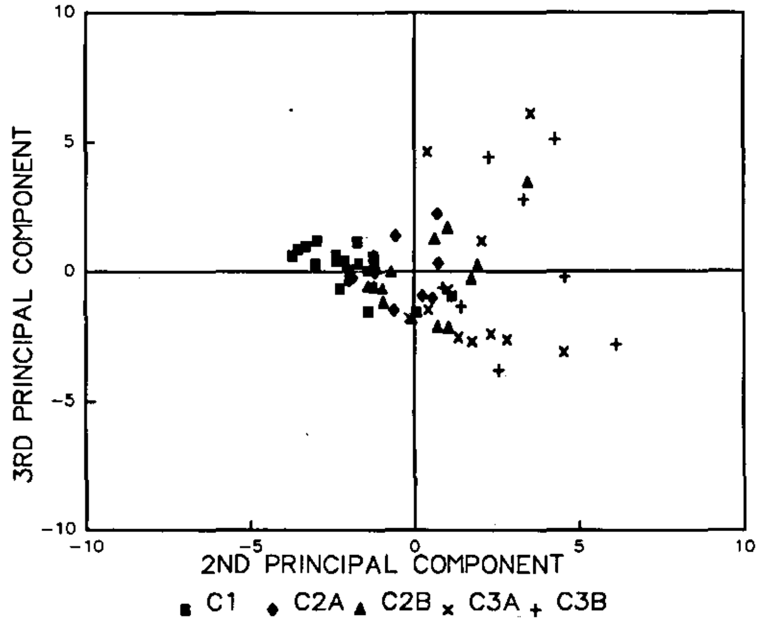


Figure 5.9: Scatter plot of second and third principal component scores for 68 south coast estuaries.

Figure 5.9 shows a tighter cluster of points around the origin for second and third component scores than the plots involving the first component, thereby illustrating the progressively smaller contribution made by each estuary to successive principal components. Furthermore, variable scores associated with the third component are consistently low (Table 5.4). The only exception being scores of +0.62 and -0.71 assigned to the beach ridge plain and barrier spit units. These values are interpreted to be due to large barrier spit and beach ridge deposits in several class 3A and 3B estuaries which plot outside the cluster in the +/+ quadrant in Figure 5.9.

Using variable scores calculated by P.C.A. it is possible to design a ranking of estuarine morphostratigraphic units in terms of the strength of association between each unit and a principal component. Table 5.5 presents ranked morphostratigraphic unit according to their correlation with the first principal component. The highest rank is given to the variable with a score furthest from zero since the strongest correlations are expressed by scores closest to unity. The ranking proposed by the C.A.R.T. program is reproduced in Table 5.5 for comparison. There is a high level of agreement between the two ranking systems as demonstrated by the Spearman Rank Correlation Coefficient value of 0.90. Moreover, the importance of the floodplain and barrier basin variables in the data set, is again emphasised.

MORPHOSTRATIGRAPHIC UNIT	VARIABLE SCORE	RANK	C.A.R.T. RANK
Floodplain	0.8472	1	1
Barrier Basin	-0.4830	2	2
Barrier Spit	-0.1813	3	5
Barrier Flat	-0.0691	4	3
Flood-Tidal Delta	-0.0646	5	8
Fluvial Channel	0.0495	6	4
Shoreline: Intertidal	-0.0476	7	7
Fluvial Delta: Supratidal	-0.0428	8	6
Shoreline: Supratidal	-0.0157	9	9
Point Bar	0.0082	10	12
Entrance Channel	0.0054	11	13
Beach Ridge Plain	-0.0053	12	10
Fluvial Delta: Intertidal	-0.0006	13	11

Table 5.5: P.C.A. derived ranking of morphostratigraphic units.

P.C.A. was also performed on standardised estuary zone data (3 variables), generating two principal components. The first component accounts for 67.4% of total variance in the data and the second component for 32.6%. Estuary scores for the principal components are plotted by class in Figure 5.10. The association between ENTROPY classes with quadrants of the scatter plot is again evident.

Class 1 solely occupies the +/+ quadrant. Positive estuary scores for both first and second components are reflected by the moderate to strong positive respective component scores of +0.45 and +0.68 for the Zone B unit assemblage (Table 5.6).

Classes 2A and 2B both have consistent negative first component scores, which is interpreted as a function of the very strong negative first component score of -0.81 for the Zone C assemblage. This result is consistent with the dominance of fluvial facies in Class 2 estuaries. The second principal component for classes 2A and 2B plots as a mixture of low positive and negative scores (Fig. 5.10). The low second component score of +0.04 for the Zone C variable is interpreted to derive from this combination of low positive and negative estuary values. The lack of an identifiably strong association between class 2 estuaries and a second component variable score emphasises the importance of facies Zone C among those estuaries.

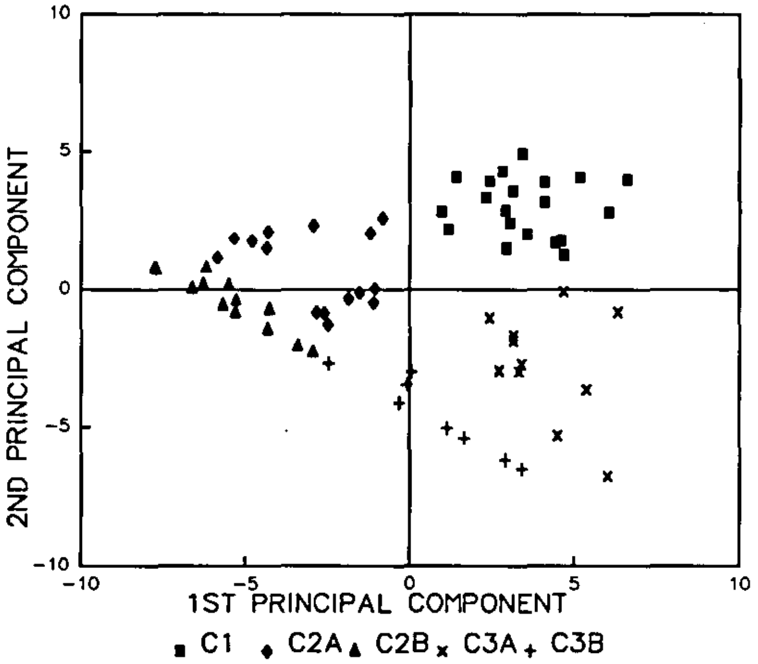


Figure 5.10: Scatter plot of first and second principal component scores for 68 south coast estuaries. Symbols correspond to the five ENTROPY classes: 1, 2A, 2B, 3A, 3B.

Finally, with three exceptions all members of classes 3A and 3B plot entirely within the +/- quadrant of the plot (Fig. 5.10). All estuaries possess a negative second component score, which is interpreted as a function of the strong negative Zone A score of -0.73. The predominantly positive scores for the first component are correlated with both the Zone B positive score of +0.45 for the less mature 3A class, and the Zone A score of +0.37 for the largely infilled 3B estuaries.

FACIES ZONE	1ST COMPONENT SCORE	2ND COMPONENT SCORE
Zone A: Barrier/Inlet unit assemblage	0.37	-0.73
Zone B: Estuarine unit assemblage	0.45	0.68
Zone C: Fluvial unit assemblage	-0.81	0.04

Table 5.6: P.C.A. derived scores for estuarine facies Zones A, B, C.

When variable scores are ranked according to proximity to zero, Zones A and C behave in an opposing manner for each principal component (Table 5.6). That is, the Zone A variable ranks lowest (0.37) for the first component and highest (-0.73) for the second component. Conversely, the Zone C assemblage ranks highest (-0.81) for the first component and lowest (0.04) for the second. The Zone B assemblage has a mid-rank for both components. These rankings are interpreted to identify Zones A and C as the primary independent variable assemblages and highlight the existence of two distinct modes of valley filling along the N.S.W. south coast.

5.5 SUMMARY OF RESULTS OF MORPHOMETRIC ANALYSIS

The output of the ENTROPY, C.A.R.T. and P.C.A. analyses suggest that consistent relationships exist within the estuarine morphometric data set employed here. Utilisation of three complementary statistical techniques has enabled the design of a comprehensive classification system. Each procedure offered a product that could be merged with the others to enhance the overall interpretation of the data. Thus, the ENTROPY classes were used as input for the creation of a classification tree and definition of class rules via C.A.R.T. The ENTROPY classes were also applied to the interpretation of P.C.A. data transformation, allowing the association of each class of estuary with the dominance of certain morphostratigraphic units and facies zones.

The ENTROPY classification is interpreted to identify the existence of three primary groups of estuary among the estuaries of the N.S.W. south coast. Collectively, these groups define a range of points along the estuarine evolutionary spectrum that are manifest by varying valley infill states. Moreover, they indicate the existence of two modes of infilling:

(i) The first mode, represented by class 2, is characterised by a dominant development of fluvial morphostratigraphic units (Zone C);

(ii) the second mode, incorporating class 3, is dominated by barrier/inlet morphostratigraphic units (Zone A).

Classes 2 and 3 have sub-groups which identify significant variations in infill states. The distinction between the sub-groups of both classes is in the degree of development fluvial morphostratigraphic units. The percentage of barrier/inlet morphostratigraphic units, however, remains constant between the sub-groups of both classes. The transition to complete infilling appears to be due solely to increased floodplain development and not Zone A deposition. Class 1 estuaries are immature, featuring relatively extensive estuarine morphostratigraphic units (Zone B) and minimal Zone A and Zone C development.

That the floodplain morphostratigraphic unit is the primary variable for determining the degree of palaeovalley infilling is demonstrated further by the C.A.R.T. and P.C.A. results. These results suggest that the floodplain is the most significant unit of the Zone C assemblage. Decision rules designed by C.A.R.T. for ENTROPY derived classes, employed the floodplain as a critical variable in defining class membership. Consequently, it ranks as the most important variable. The barrier basin variable was also used in decision rules and was ranked the second most important variable. The high rank assigned to the barrier basin is interpreted as due to the direct influence the fluvial zone has upon the areal extent of the basin. Thus, the proportion of palaeovalley occupied by the barrier basin is important for the proposed classification.

The lack of variability of marine morphostratigraphic unit proportions between sub-groups is considered an important result because it is consistent with the theory of rapid onshore emplacement of barrier and tidal delta sands during early to mid-Holocene times (Roy et al., 1980, Thom and Roy, 1985). Sedimentological evidence and geochronologic data will be presented in the following chapter that supports the proposition that Zone A deposits are indeed relict features. In contrast, the variable development along the coast leads one to presume that the Zone C assemblage has been active throughout the Holocene and continues to be so. Supporting sedimentologic and dating data are presented in chapters seven and eight.

5.6 CLASSIFICATION OF FIELD STUDY SITES:

As stated earlier, the morphometric analysis of estuarine morphostratigraphic units must ultimately be extended to incorporate sedimentological data. Two approaches to the sedimentological characterisation of the proposed classification scheme are possible. The first approach involves exploring within class sedimentological homogeneity and the second, between class heterogeneity. The importance of considering variablility both within and between classes has been emphasised in other areas of geographical enquiry and it is generally argued that demonstration of within class homogeneity should be come before between class comparisons (Mather, 1972; Forrest 1981). An analysis of sedimentological contrasts between classes may be premature here because one would lack the confidence that a single sample site is sedimentologically representative of a particular class. Furthermore, an appreciation of within class variability is necessary for proper assessment of between class contrasts. The demonstration of sedimentological homogeneity would appear to present itself as the more important immediate research problem and is therefore adopted for this study. If within class homogeneity is proven on sedimentological grounds then one may proceed with confidence with an investigation of between class analysis.

Given that the variable ranking designed by C.A.R.T. and P.C.A. established the floodplain and barrier basin morphostratigraphic unit as the two most significant variables in the data set it is appropriate that field sampling focus upon the class most representative of this dominance. Sub-classes 2A and 2B meet these criteria because they include estuaries that possess a significant floodplain and barrier basin component. In addition to featuring the significant variables, these sub-classes each represent distinct stages of palaeovalley infill.

Wapengo Lagoon and Narrawallee River have been selected as sample sites for classes 2A and 2B, respectively. Wapengo is appealing from the field sampling perspective because it features a diverse array of morphostratigraphic units that are readily observable at the surface and which provide for detailed and controlled field sampling. The morphometric characteristics of Wapengo Lagoon's morphostratigraphic units and facies zones are detailed in Table 5.7. The area available for estuarine sedimentation in Wapengo at present sea-level is 7.86 km^2. The morphometric data show Wapengo Lagoon to be an estuary filled with predominantly terrestrially sourced sediment, with Zone C constituting 53% of palaeovalley area and 48% of volume. Zone B occupies 18% of the area and approximately 12% of the volume of the estuary. Zone A, however, is not insignificant in contributing to valley fill, occupying 29% of estuary area and 39% of volume. The comparatively small Zone B volume is a function of the incomplete infill state of the basin.

Narrawallee, being in a more advanced stage of filling lacks surface expression of many of the units found in Wapengo. Eighty-seven per cent of the valley surface area ($10.81km^2$) is occupied by fluvial floodplain deposits. Volumetrically, Zone C deposits comprise 43% of the valley fill (Table 5.7). The floodplain interfingers seaward with an assemblage of Zone A units, including flood tide delta, barrier flats and barrier spit. The Zone A assemblage occupies only 13% of valley area but makes up 48% of the fill volume. Zone B facies are not surficially evident, however, subsurface investigations to be discussed in chapter seven, show Zone B sediments to be incorporated in the valley fill.

MORPHOSTRATIGRAPHIC UNIT	WAPENGO		NARRAWALLEE	
	AREA (%)	2A MEAN $\pm 1\sigma$	AREA (%)	2B MEAN $\pm 1\sigma$
Barrier Spit	2.9	8.9± 8.1	7.2	11.1±10.4
Barrier Flat	6.5	3.2± 5.9	3.9	1.5± 3.1
Beach Ridge Plain	0.0	2.1± 6.0	0.0	0.0± 0.0
Flood-Tidal Delta	19.6	4.4± 6.2	1.2	4.6± 9.6
Entrance Channel	0.02	0.9± 1.9	0.3	1.3± 3.6
Barrier Basin	14.9	16.5± 8.3	0.0	1.4± 2.1
Supratidal Shoreline	3.1	0.8± 1.3	0.0	0.0± 0.0
Intertidal Shoreline	0.0	0.7± 1.3	0.0	0.0± 0.0
Supratidal Fluv Delta	5.6	6.3± 8.8	0.0	0.2± 0.9
Intertidal Fluv Delta	0.4	1.1± 1.9	0.0	0.3± 1.2
Fluvial Channel	2.5	5.6± 5.6	2.5	14.5±17.5
Fluvial Point Bar	0.0	0.5± 1.2	0.0	0.8± 1.6
Floodplain	44.5	48.9±14.9	84.9	64.1±23.0
Zone A Volume (m^3x10^6)	13.7	A:39.5%	64.7	A:48.7%
Zone B Volume (m^3x10^6)	4.2	B:12.2%	10.9	B: 8.2%
Zone C Volume $(m^3x10^6$	16.7	C:48.2%	57.2	C:43.1%

Table 5.7: Morphometric data for Wapengo Lagoon and Narrawallee Inlet morphostratigraphic units. ENTROPY class 2A and 2B summary statistics are also listed. Volume data was calculated by multiplying the surface area of each zone by the mean facies thickness taken from vibracore and drill information.

In statistical terms, both Wapengo and Narrawallee are highly representative of their respective estuary classes (Table 5.7). Of the 15 estuaries within ENTROPY class 2A, Wapengo has the greatest number of morphostratigraphic units that, in terms of percentage of valley surface area, are within one standard deviation of the mean area for the class. Only two units, the supratidal shoreline and flood-tidal delta are outside the limits set by the standard deviation. The shoreline unit is only slightly larger in proportional area (3.1%) than the mean (0.8 +/- 3.0%) for the class. The flood-tidal delta, however, is considerably larger (19.6%) than the class mean (4.4 +/- 6.2%) and is partly a function of the unusual orientation of the inlet with respect to ocean swells. A more detailed explanation is provided in chapter six. All six morphostratigraphic units that receive surface exposure in Narrawallee are within the range of one standard deviation from the class 2B mean (Table 5.7).

Figure 5.11 presents a series of plots of zone data for each class 2A estuary showing the mean and single standard deviation statistics. Wapengo Lagoon (estuary no.8 in Fig. 5.11) plots consistently within the bounds set by the standard deviation lines. In the Zone B plot, Wapengo actually equates with the class mean value. Moreover, Wapengo is one of only four 2A estuaries that features all three zones within the standard deviation limits. The other estuaries are Pambula Lake (no. 2), Nelson Lagoon (no. 6) and Lake Meroo (no.15).

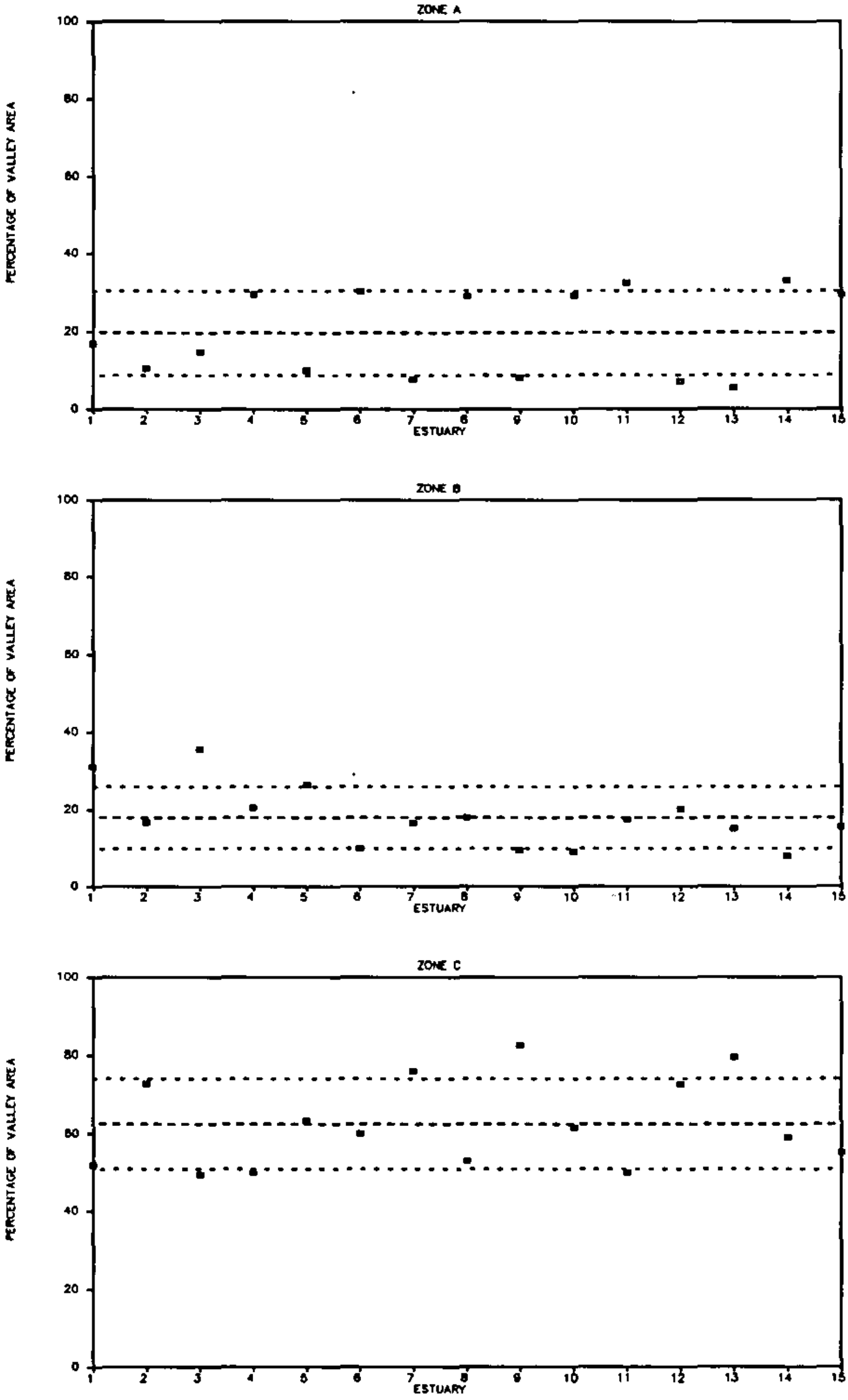


Figure 5.11: Plots of Zone A, Zone B and Zone C values for the 15 class 2A estuaries. Dashed line represents mean value and dotted lines represent one standard deviation either side of the mean. Wapengo Lagoon is estuary no.8.

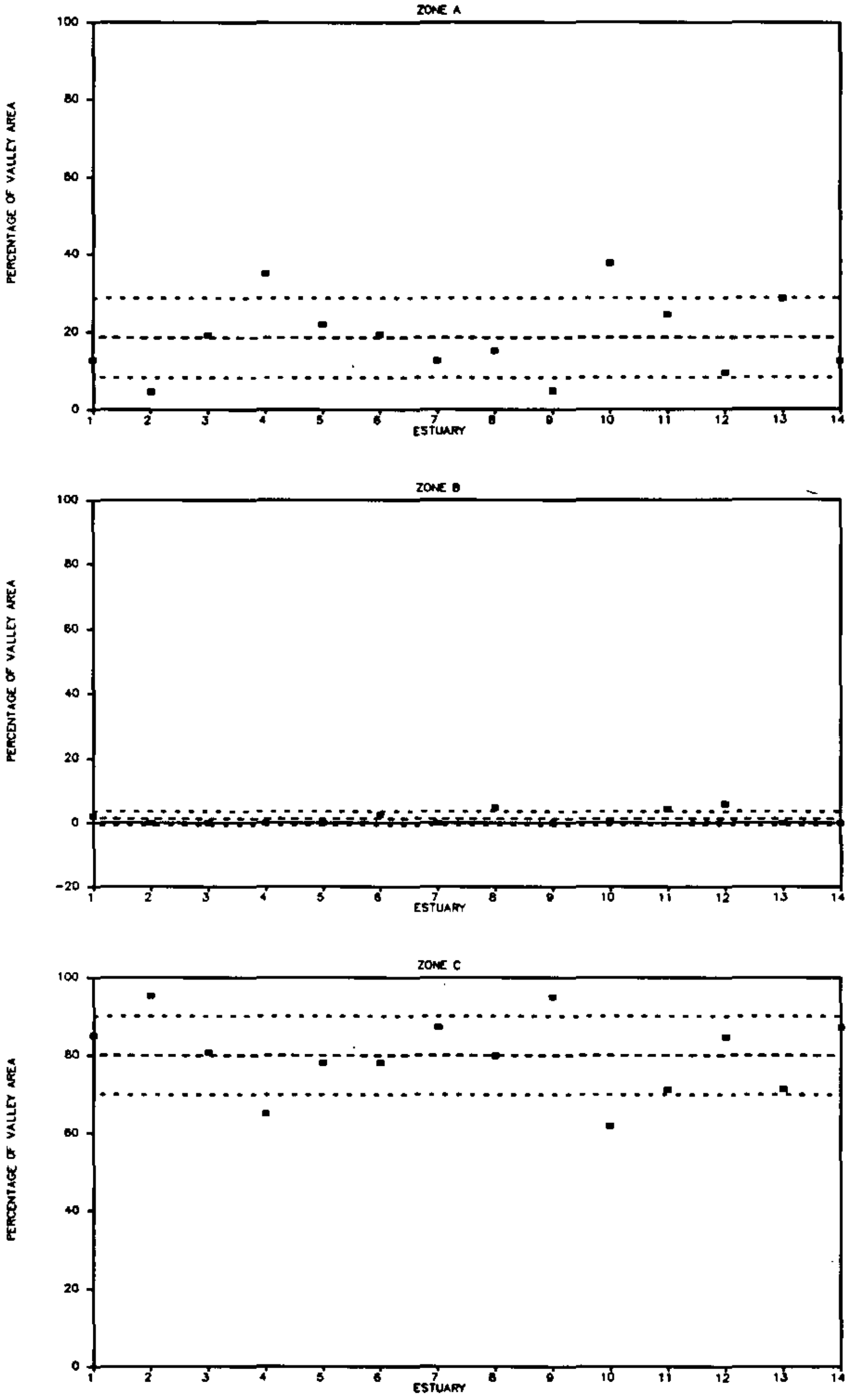


Figure 5.12: Plots of Zone A, Zone B and Zone C values for the 14 class 2B estuaries. Dashed line represents mean value and dotted lines represent one standard deviation either side of the mean. Narrawallee Inlet is estuary no.14.

With regard to class 2B estuaries, there is less scatter among the zone data than for class 2A. Narrawallee Inlet (no. 14) is one of seven estuaries with the proportional area of all three zones less than one standard deviation from the class mean (Fig. 5.12). The other estuaries are: Tomaga River (no. 1); Little Creek (no. 3); Woodburn Creek (no. 5); Towamba River (no. 6); Bobundara Swamp (no. 7), and; Mollymook Creek (no. 13). Whilst these estuaries are statistically representative of their class, Narrawallee is the most appealing for field analysis because it has the largest palaeovalley area (10.8 km^2) of all class 2B estuaries (Appendix B).

5.7 INFLUENCE OF ESTUARY CATCHMENT DIMENSIONS UPON PALAEOVALLEY INFILL.

An examination of relationships between estuaries and their respective catchments is a logical extension to the morphometric analysis of estuarine morphostratigraphic units, especially since that analysis demonstrated the significance of Zone C deposits in the estuary infill process. This section is presented in the form of a progressive analysis of catchment-estuary relationships.

Initially, raw estuary catchment area is plotted against Zone C area which is expressed as a proportion of palaeovalley area for the five ENTROPY classes (Fig. 5.13). It is apparent from this plot that catchment area alone does not significantly influence the degree of Zone C development. The members of ENTROPY classes are arranged in a fashion that merely reflects larger Zone C percentages for the mature classes, notably 2A and 2B.

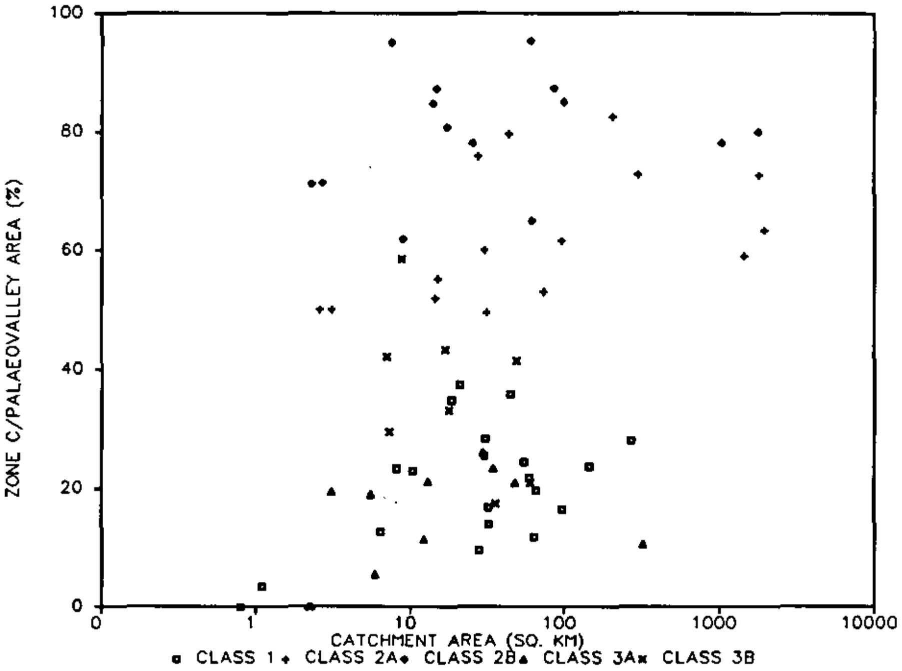


Figure 5.13: Log-linear plot of estuary catchment area and Zone C area as a percentage of palaeovalley area, showing the five ENTROPY classes.

To facilitate further analysis of estuary-catchment associations, consideration must also be given to the nature of the relationship between size of the catchment delivering sediment and the size of the palaeovalley in receipt of that sediment. Figure 5.14 shows these two variables to be relatively well correlated when plotted along log scales. The correlation coefficient (r^2) for the data set is +0.70, which simply indicates that larger catchments feed larger palaeovalleys, yet the absolute size of each increases logarithmically. Palaeovalley and catchment areas were therefore combined to produce a dimensionless measure, whereby the former is expressed as a percentage of the latter. This value may then be compared with the relative degree of Zone C deposition within an estuary. Theoretically, estuaries with a small delivery area relative to the receiving area (i.e. high palaeovalley/catchment percentage value) should be associated with a relative lack of development of the fluvial morphostratigraphic unit assemblage.

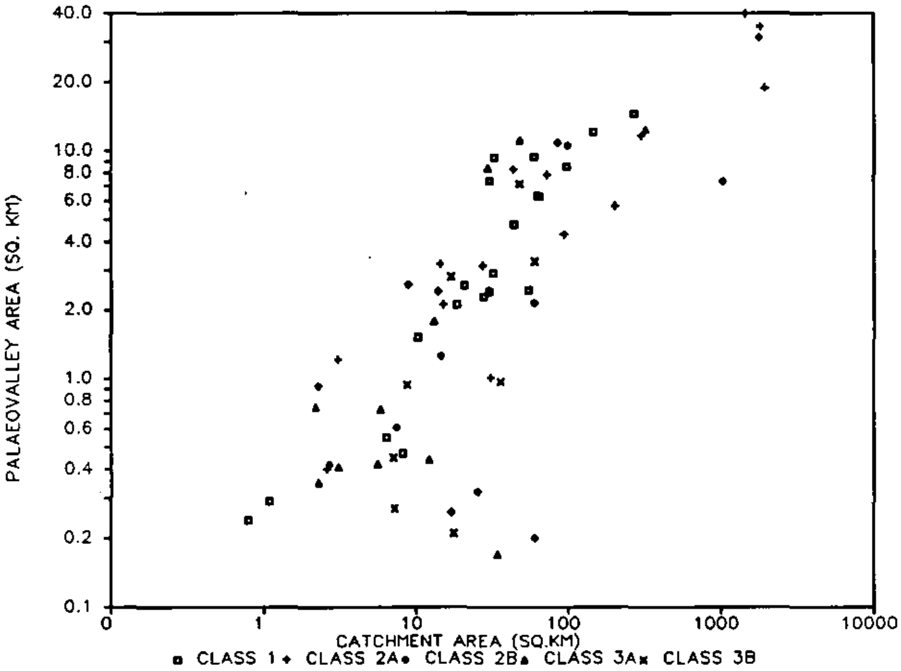


Figure 5.14: Log-log plot of estuary catchment area against palaeovalley area for all 68 south coast estuaries. The r^2 value is +0.7.

Figure 5.15 presents a scatter plot of palaeovalley to catchment ratios versus proportional Zone C areas for the five ENTROPY classes of estuary. There is no indication in the plot of a significant relationship between the extent of Zone C development and palaeovalley/catchment ratios. The members of the ENTROPY classes are loosely clustered and again arranged in a manner that is in accord with greater Zone C values for the mature classes. Most importantly, there is no differentiation between immature and mature estuary classes with respect to the x-axis of the plot. The expectation that immature estuaries are those with large palaeovalleys relative to catchment area and vice versa for mature estuaries appears to be too simplistic. It is therefore necessary to extend the analysis to incorporate a volumetric component.

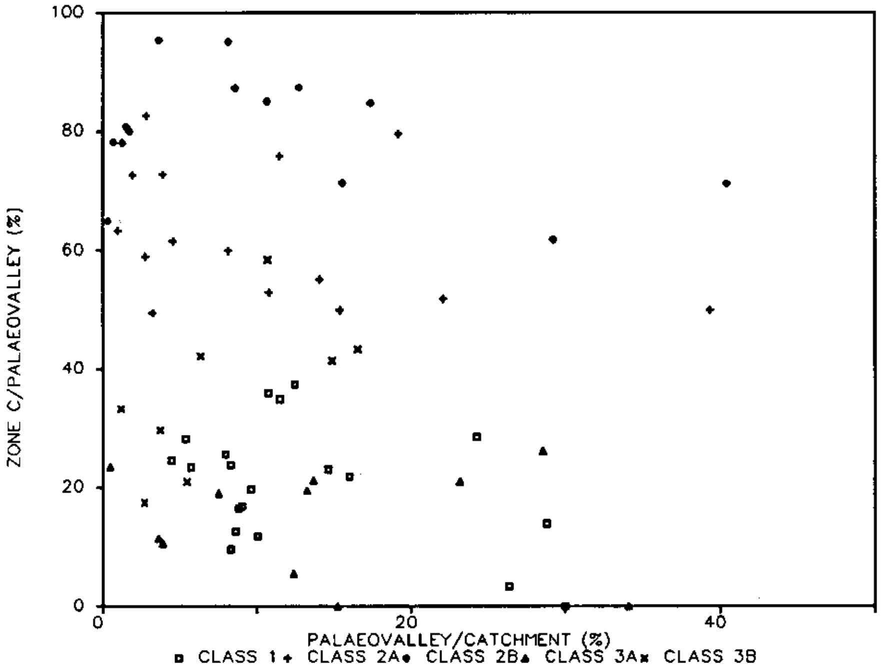


Figure 5.15: Plot of palaeovalley/catchment ratios versus percentage of palaeovalley area occupied by Zone C, showing the five ENTROPY classes.

Roy (pers. comm., 1990) calculated approximate volumes of terrestrially derived sediment for 14 south coast estuaries. These data are supplemented here by Zone C volumes for an additional 16 estuaries that are members of those ENTROPY classes characterised by a dominance of floodplain, fluvial channel and fluvial delta deposition over barrier/inlet infilling (i.e classes 1, 2A and 2B). Sediment volumes were calculated by multiplying the known Zone C area for each estuary by the estimated mean thickness of the deposit. Thickness estimations are based upon coring data from Wapengo Lagoon and subsurface extrapolations of valley sides. Figure 5.16 presents a log-log plot of the catchment area versus Zone C volume for 30 south coast estuaries.

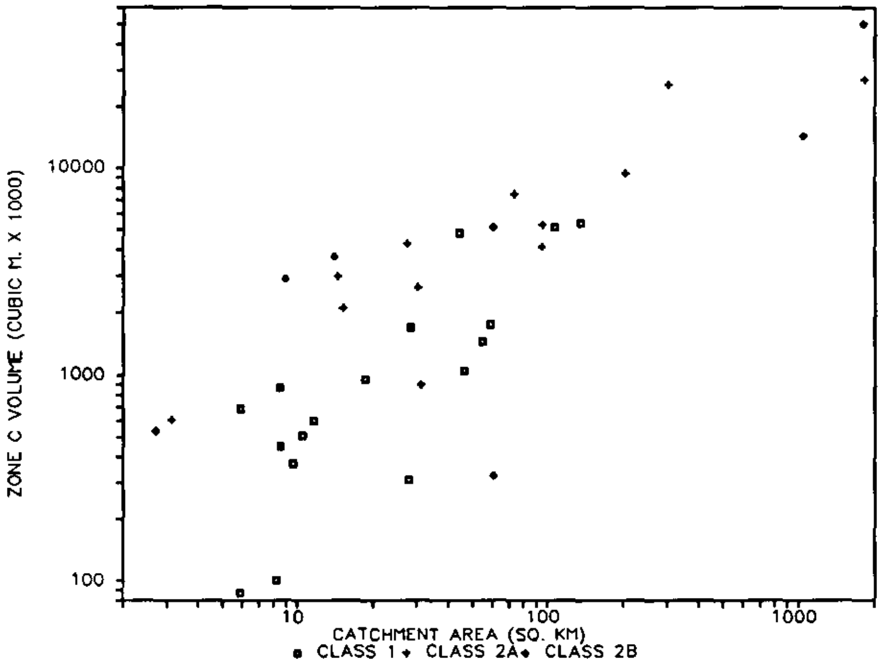


Figure 5.16: Log-log plot of estuary catchment area versus approximate Zone C volume for 30 select estuaries from ENTROPY classes 1, 2A and 2B. The r^2 value is +0.77.

A relatively strong linear relationship is apparent between the two variables, with a correlation coefficient (r^2) of +0.77. This result indicates, not unexpectedly, that since the end of the Postglacial Marine Transgression the larger catchments have yielded greater volumes of sediment for deposition in their respective estuaries than small catchments. Figure 5.16 also shows the ENTROPY class to which each estuary belongs. There is no suggestion of an association between class and volume of Zone C sediment and/or catchment size. For example, immature estuaries (class 1) are spread along the length of the spectrum of points in the plot, with mature estuaries (classes 2A and 2B) interspersed throughout. In other words, not all large catchments, with correspondingly large sediment yields, have been able to infill their estuaries.

Furthermore, estuaries with comparable catchment size and Zone C volume are, paradoxically, at very different infill stages.

Presumably, additional factors including catchment shape, topography and erodability of component lithologies are also influencing the delivery of sediment from catchments to estuaries. It was considered beyond the scope of this study to quantify all these variables for the 68 south coast estuaries. However, data presented by Kidd (1978) for 14 south coast estuaries allows for a preliminary analysis of the strength of the relationship between catchment topography, general lithology and the extent of Zone C deposition in those estuaries.

Kidd (1978) measured the catchment area occupied by each of four categories of slope gradients: less than 3^o; 3^o-8^o; 8^o-15^o; and greater than 15^o. Of the four categories, the steeper two were the most variable among the 14 catchments (Kidd, 1978). For simplicity, the two sets of data have been merged. Figure 5.17 shows a plot of the percentage of catchment area occupied by slopes greater than 8^o versus percentage of estuary area occupied by Zone C deposits. The plot also identifies the general bedrock type in each catchment. The catchments of Barragoot, Cuttagee, Wapengo, Middle, Nelson, Nullica and Curalo estuaries are composed of Ordovician metasediments. Devonian sedimentary and volcanic rocks characterise the catchments of Merimbula, Back, Wallagoot and Pambula estuaries, and the Murrah, Bega and Towamba estuaries are fed by granitic catchments. Of the three lithological groups, the granites are considered the least resistant to weathering and the most abundant in sand sized particles (Gunn, 1978; Kidd, 1978).

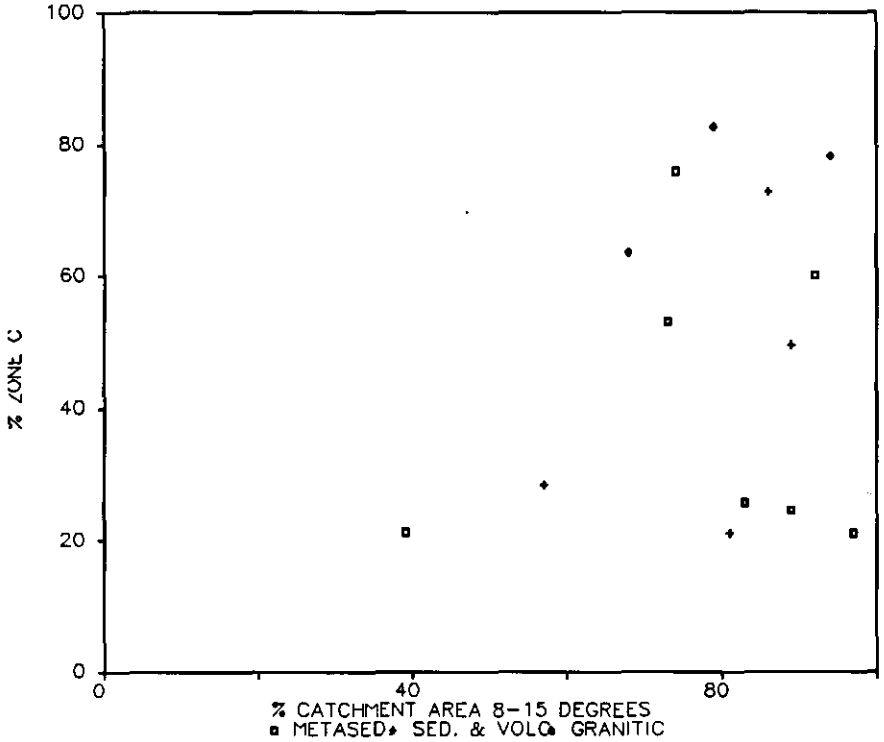


Figure 5.17: Plot of percentage of catchment slopes steeper than 8° and percentage Zone C area for 14 estuaries, showing also general catchment lithology. (Slope data from Kidd (1978)).

Several points are evident from the data in Figure 5.17. First, that there is no major difference between the three lithologies in the proportion of respective catchments occupied by steep slopes. Second, the granitic catchments are associated with comparatively large areas of estuarine Zone C deposits, yet the association is not exclusive to those catchments. Thirdly, not all catchments dominated by steep slopes necessarily drain into large Zone C areas.

The significance of catchment lithology with respect to the extent of Zone C deposition is further illustrated when the slope data from Kidd (1978) are plotted against approximate Zone C volume (Fig. 5.18). The three catchments with greatest Zone C volume in their estuaries also have a granitic lithology and a large proportion (>70%) of their surface steeper than 8^{0}. Those catchments with relatively erosion resistant rocks (metasediments, volcanics) and a proportion of their surface steeper than 8^{o} comparable to the granitic catchments, have a Zone C volume that is an order of magnitude less than the granite catchments. There appears, therefore, to be a relatively clear and logical correlation between steep catchments that feature rocks less resistant to erosion and estuaries with significant volumes of Zone C sediment. Yet the degree of scatter among the small sample of estuaries considered here suggests that that the interplay of variables associated with the flux of sediment from hinterland to receiving basin is by no means simple and most certainly is not linear.

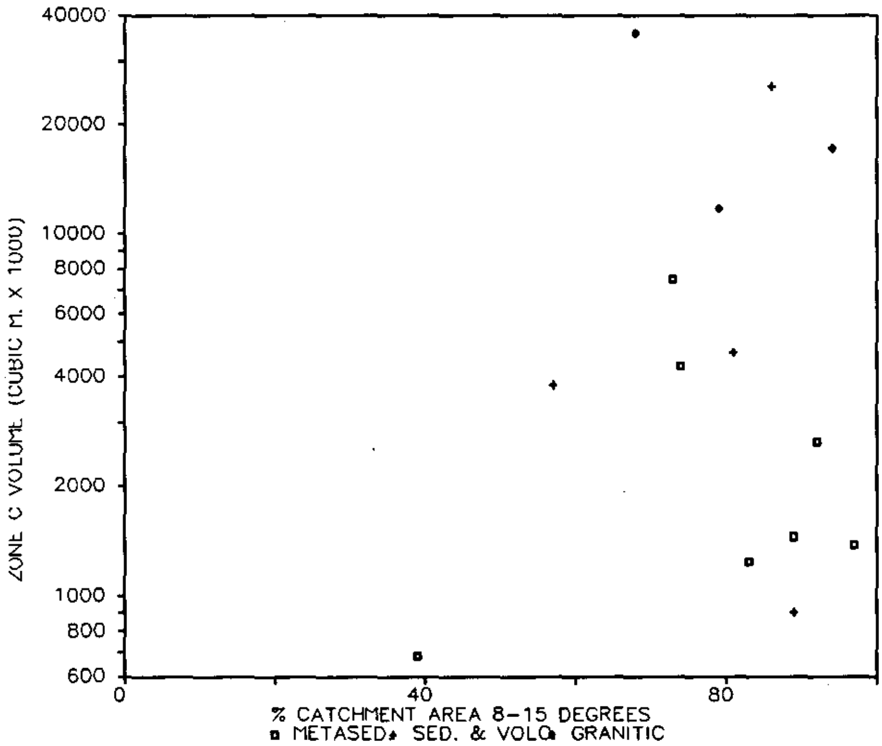


Figure 5.18: Log-linear plot of percentage of catchment slopes steeper than 8^{o} and volume of Zone C for 14 estuaries, showing also general catchment lithology. (Slope data from Kidd (1978)).

While the data presented here is by no means comprehensive, it does provide an indication of the influence catchment topography and lithology have upon the degree of terrigeneous sedimentation in estuaries. To adequately understand the problem requires analysis of factors not considered here and include, catchment shape, soil type, vegetation cover, drainage density and micro-climate.

One conclusion to be drawn from the results presented in this chapter is that the degree of palaeovalley infilling with terrestrially derived sediment is only partially determined by the volume delivered from the catchment. Clearly, the volume of the receiving basin is also an important variable. It is, therefore, assumed that the bedrock topography of incised valleys along the south coast is not sufficiently variable to produce the degree of estuary fill variation that exists. This assumption is supported by calculations made by Hunter (1989) who estimated from seismic and drilling data that the depth of bedrock incision in Lake Conjola, an immature estuary, and in Narrawallee Inlet, a mature estuary, is 30-35m in both valleys.

It is postulated that the volume of the receiving basin for estuaries at present sea-level is not controlled by the bedrock topography alone. A secondary pre-Holocene depositional surface must also exist. Specifically, that surface is presumed to be defined by remnant Pleistocene deposits. Implicit to this argument is that Pleistocene deposits are not preserved in all estuaries. Indeed, they are most likely to be most fully preserved in mature estuaries only, hence the variable infill states among south coast estuaries. Sedimentological evidence supporting this hypothesis will be presented in later chapters.

CHAPTER 6: SEDIMENTOLOGY OF THE SEAWARD FACIES ZONE (ZONE A)

6.1 INTRODUCTION

A systematic description of the sedimentological characteristics of morphostratigraphic units occurring within Zone A, which extends landward from the estuary mouth, is presented in this chapter (Fig. 1.5). Initially, the nature of depositional processes acting within Zone A are detailed. Particular emphasis is given to the landward attenuation of tidal range and attendant weakening of tidal current energy. Each morphostratigraphic unit is then described in terms of their general morphology, bed topography, textural characteristics, physical and biogenic sedimentary structures, carbonate and organic content, and gross mineralogical composition. These traits are considered in the context of their surface expression and in the subsurface as revealed in core section. Sedimentological information is placed in the context of the general character of inlet processes, notably the landward gradient in tidal flow velocity. Thus, spatial patterns in mean sediment texture, bed topography, bedform and suburface structures, and the relative intensity of biological activity, are explained in terms of the transition from relatively high energy to low energy depositional conditions. Changes in depositional conditions are also assessed from the record yielded by vertical sequences.

Zone A morphostratigraphic units are separated here into 'dynamic' and 'static' units. Dynamic units are defined as those under the influence of modern estuarine tidal processes. Therefore, they lie within the intertidal and subtidal portions of Zone A and include the flood tidal delta, inlet channel and barrier flat units. The bulk of data pertaining to the dynamic units will derive from Wapengo Lagoon samples. Narrawallee Inlet is less suited to a comprehensive examination of dynamic Zone A units due to an advanced stage of infill. However, drill hole data from the seaward end of the Narrawallee valley, provides important information relevant to the preservation style of Zone A sediments. Narrawallee data are reviewed in the context of the preservation potential of Zone A deposits in chapter ten.

Static morphostratigraphic units are defined as those Zone A units that are not subject to regular tidal inundation. Aeolian activity and shoreface wave processes are the dominant processes influencing these units, which include the barrier/spit and beach-ridge plain. The term 'static' is not meant to imply that the units are completely inactive nor unaffected by depositional and/or erosional processes. Rather, the implication is that supratidal deposits are in a more stable condition than the intertidal deposits. Such relative inactivity is partly due to and promoted by the well vegetated surface of the barrier and beach-ridge units. Consequently, apart from foredune blowouts, dune bedforms are immobile and often poorly preserved. Therefore, static units do not lend themselves to detailed sedimentological investigation in the manner carried out for the dynamic intertidal units and are not discussed in this chapter. A review of the general sedimentologic properties of static units is included in chapter three.

The sedimentological characteristics described in this chapter provide the basis for interpreting the age and evolution of Zone A deposits in the context of existing evolutionary models for coastal deposits along the N.S.W. coast (see chapter nine). Furthermore, these characteristics can be examined in terms of their preservation potential in the geological record (see chapter ten).

6.2 PROCESS FRAMEWORK

6.2.1 Tidal range

The open coast of New South Wales experiences a microtidal tidal regime. The mean spring tidal range is 1.6 metres (Chapman et al., 1982). Within the protected waters of embayments, estuaries and coastal lakes, however, the tidal range is reduced considerably. Attenuation of the tidal prism is effected by the presence of sand shoals in the mouths of estuaries. These shoals, or flood tidal deltas, reduce the accommodation space for tidal waters within the confines of the estuary and, depending upon the dimensions of the estuary valley and the area occupied by the tidal delta, can reduce tidal range within the estuarine basin to less than 0.10m (Williams, 1983). This phenomenon equates with that observed by Stauble et al. (1988) in microtidal inlets along the eastern coast of Florida, where tidal range is reduced from 0.64m to 0.12m. Stauble et al. (1988) propose that inlet and lagoon tides are uncoupled from ocean tides on the basis that a progressive tidal wave does not flow through to the inner portion of the inlet and lagoon. Instead, tidal flow is explained in terms of the response to differences in water levels between the ocean and lagoon and that almost 98% of the energy resulting from these height differences is dissipated through frictional effects within the restricted inlet (Stauble et al., 1988).

Accurate tidal data do not exist for either Wapengo Lagoon nor Narrawallee Inlet study sites, but process data collected by other workers in several south coast inlets of similar form and dimensions to Wapengo and Narrawallee provide a guide to the general nature of tidal conditions within the two estuaries. Tidal stage and current velocity have been monitored by the N.S.W. Public Works

Department within the entrances to Lake Illawarra, Wagonga Inlet, Lake Merimbula and Pambula Lake and by the C.S.I.R.O. in Burrill Lake and the Tomaga River (see Fig. 1.2 for estuary locations). Wapengo Lagoon possesses an entrance that is of comparable length (3.15km) and shape to Illawarra (2.77km), Wagonga (2.70km), Merimbula (3.53km) and Burill (2.0km) entrances (Fig. 6.1). All inlets have extensive flood tidal delta shoals and all were in an unaltered state (i.e. neither dredged nor artificially trained) when tidal data was collected.* In addition, all estuaries feature broad estuarine basins open to tidal exchange landward of the entrance channel. In contrast, the Tomaga River estuary is extensively infilled, existing as a single confined channel without an estuarine basin (Fig. 6.1). Therefore, Tomaga is a useful analogy to Narrawallee Inlet. Pambula Lake is somewhat of an anomaly among south coast estuaries. That is, the entrance channel leading to the central lake basin is narrow and confined by bedrock and lacks the extensive tidal delta shoals of the other estuaries. Tidal data from Pambula is included because the inlet is considered to behave in a similar fashion to mature infilled estuaries, such as Narrawallee.

It should be noted that data cited represent discrete measurement periods which may not represent the full spectrum of tidal conditions within the respective inlets. However, measurements cited below represent both spring and neap tidal conditions and therefore represent maximum and minimum fairweather tidal range. Extreme tidal conditions, such as during conditions of storm surge and ocean setup are not described because necessary data are not available. Nevertheless, the potential impact of extreme conditions must be considered when interpreting the properties of estuarine deposits.

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* Breakwaters were constructed at the entrance to Wagonga Inlet after tidal data cited here was collected (1977).

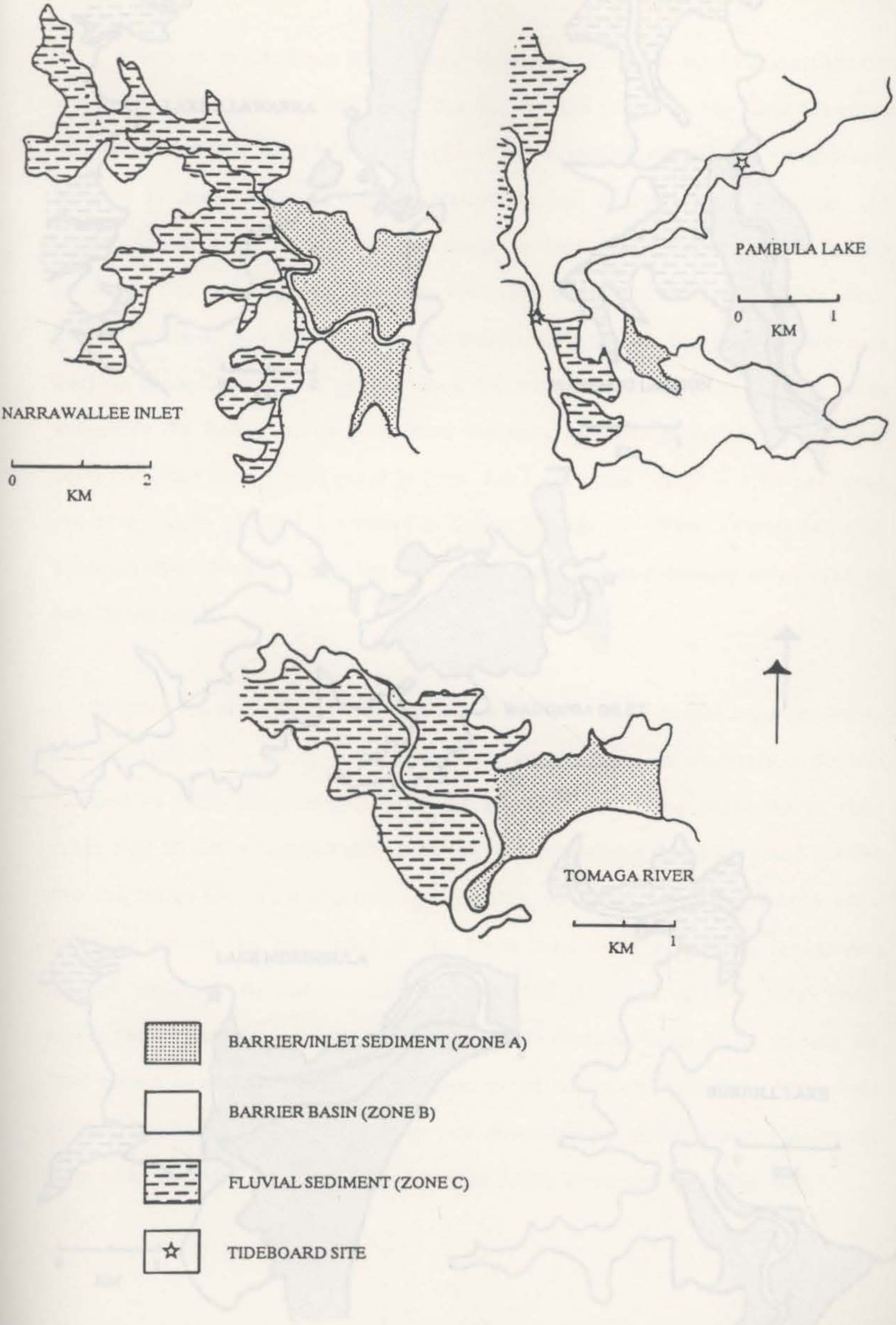
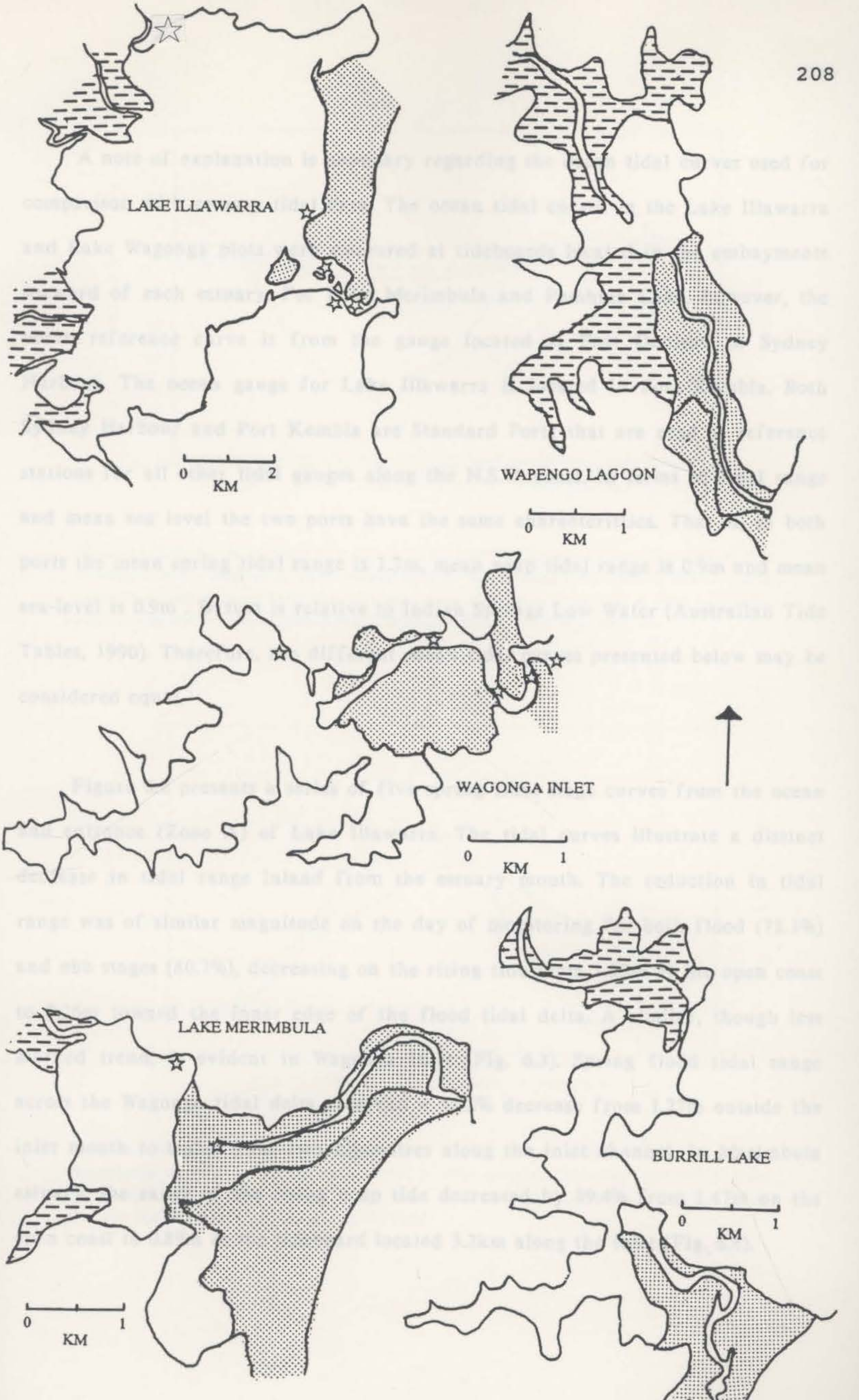


Figure 6.1: Maps of south coast estuaries for which tidal data are presented, showing common form of inlets.


LAKE ILLAWARRA
0
2
KM
WAPENGO LAGOON
0
KM
1
WAGONGA INLET
0
KM
1
LAKE MERIMBULA
0
KM
1
BURRILL LAKE
0
KM
1

A note of explanation is necessary regarding the ocean tidal curves used for comparison with estuary tidal data. The ocean tidal curves in the Lake Illawarra and Lake Wagonga plots were measured at tideboards located in the embayments seaward of each estuary. For Lake Merimbula and Pambula Lake, however, the ocean reference curve is from the gauge located at Fort Denison in Sydney Harbour. The ocean gauge for Lake Illawarra is located in Port Kembla. Both Sydney Harbour and Port Kembla are Standard Ports that are used as reference stations for all other tidal gauges along the N.S.W. coast. In terms of tidal range and mean sea level the two ports have the same characteristics. That is, in both ports the mean spring tidal range is 1.3m, mean neap tidal range is 0.9m and mean sea-level is 0.9m . Datum is relative to Indian Springs Low Water (Australian Tide Tables, 1990). Therefore, the different ocean tidal curves presented below may be considered equal.

Figure 6.2 presents a series of five spring tidal stage curves from the ocean and entrance (Zone A) of Lake Illawarra. The tidal curves illustrate a distinct decrease in tidal range inland from the estuary mouth. The reduction in tidal range was of similar magnitude on the day of monitoring for both flood (78.3%) and ebb stages (80.7%), decreasing on the rising tide from 1.20m at the open coast to 0.26m toward the inner edge of the flood tidal delta. A similar, though less marked trend, is evident in Wagonga Inlet (Fig. 6.3). Spring flood tidal range across the Wagonga tidal delta recorded a 51.2% decrease from 1.27m outside the inlet mouth to 0.62m some two kilometres along the inlet channel. In Merimbula estuary, the range of the rising neap tide decreased by 39.4% from 1.47m on the open coast to 0.89m at the tideboard located 3.2km along the inlet (Fig. 6.4).

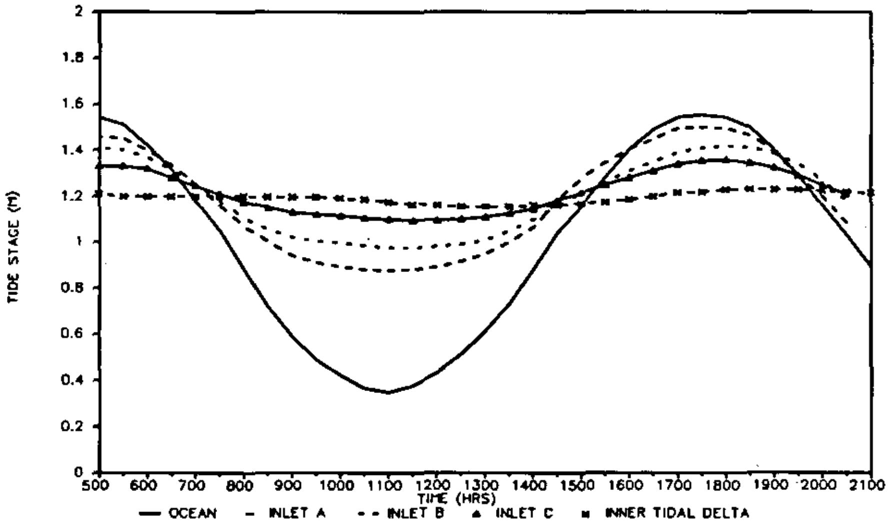


Figure 6.2: Lake Illawarra spring tidal curves, 2 May 1974. Tidal gauge locations are: Ocean- Port Kembla; Inlet A- 600m along inlet channel; Inlet B- 1000m along inlet channel; Inlet C 1820m along inlet channel; Inner Tidal Delta- on lake shore adjacent to inner edge of flood tidal delta, 3200m along inlet channel. (Source: Public Works Department, N.S.W., 1982).

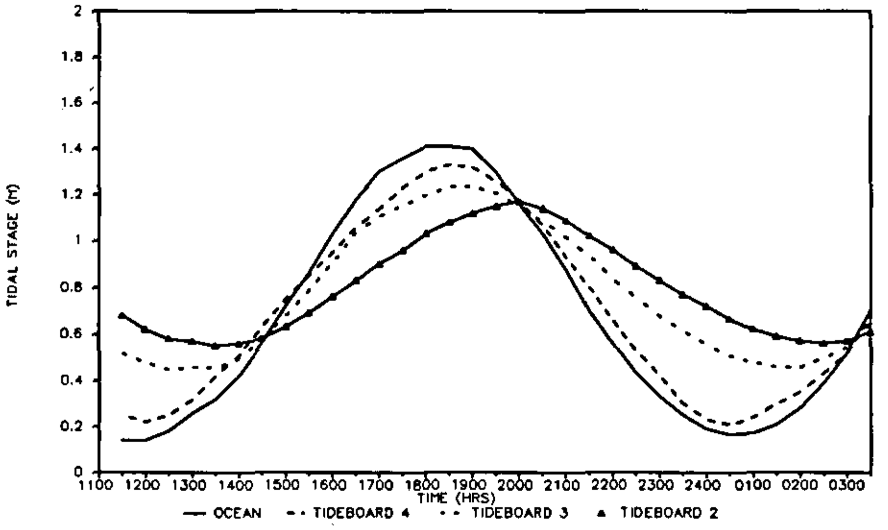


Figure 6.3: Wagonga Inlet spring tidal curves, 11 May 1976. Tidal gauge locations are: Ocean- immediately seaward of inlet mouth; Tideboard 4- 190m along inlet channel; Tideboard 3- 735m along inlet channel; Tideboard 2- 2060m along inlet channel. Inlet channel length- 2770m (Source: Public Works Department, N.S.W., 1978)

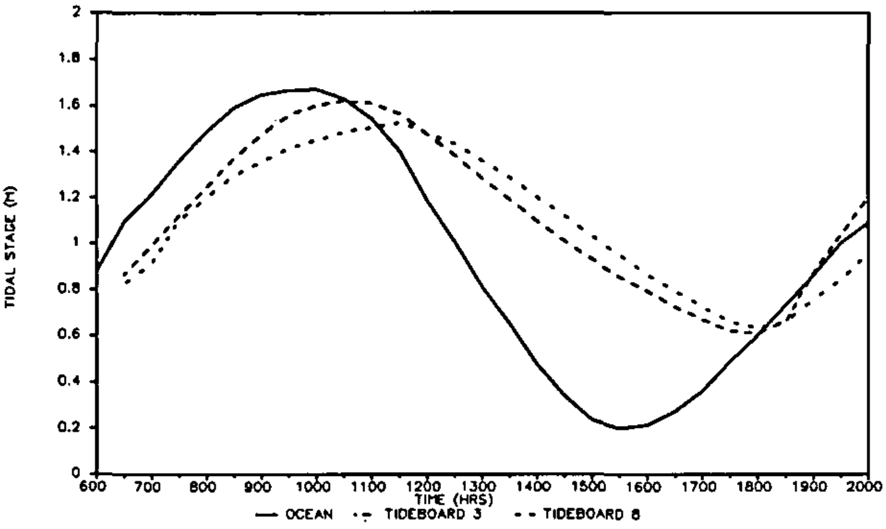


Figure 6.4: Lake Merimbula neap tidal curves, 8 October 1979. Tidal gauge locations are: Ocean- Fort Denison; Tideboard 3- 1260m along inlet channel; Tideboard 8- 3160m along inlet channel. Inlet channel length- 3530m (Source: Public Works Department, N.S.W., 1983).

The pattern of a significant attenuation of spring and neap tidal range common to the entrance channels of Illawarra, Wagonga and Merimbula is assumed to be universal to microtidal, wave-dominated estuaries with similar entrance configurations. It is, therefore, likely that the tidal characteristics described for the aforementioned three inlets also prevail in Wapengo Lagoon. Thus, tidal range along the entrance to Wapengo should be reduced by between 40% and 80% of ocean tidal range. Field observations in Wapengo Lagoon during spring and neap conditions confirm the predicted variation in tidal range. For example, on 30/6/88 the spring ocean tidal range was 1.6 metres. At the landward end of the Wapengo flood tidal delta, tidal flats that are exposed at low water were covered by approximately one metre of water. During neap conditions, ocean tidal range was 0.8m and the same landward site was less than 50 centimetres under water.

Attenuation of the flood tide was less significant within the entrance to Pambula Lake (Fig 6.5). Pambula neap tidal data describe a loss of only 27.5% between the ocean (1.60m) and tideboard 2 (1.16m) situated approximately 1.4km landward of the estuary mouth. The comparative lack of reduction in tidal range within the Pambula entrance may be largely attributed to the narrow, bedrock confined shape of the entrance channel. Restriction of tidal waters to a single confined channel is likely to result in non-depositional and erosional conditions on the channel bed. As a result, flood tidal delta shoals within the Pambula entrance are not as well developed as within the other estuaries and tidal range is only slightly reduced along the inlet.

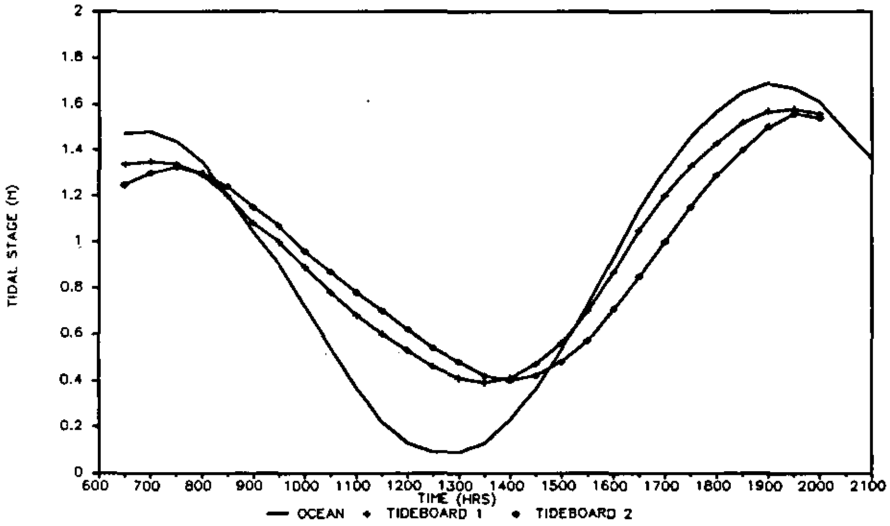


Figure 6.5: Pambula Lake tidal curves, 4 October 1979. Tidal gauge locations are: Ocean- Fort Denison; Tideboard 1- 670m along inlet; Tideboard 2- 1300m along inlet. (Source: Public Works Department, N.S.W., in prep).

Tidal conditions within Pambula are of significance beyond being an exception to the tidal characteristics of the other estuaries. The inlet configuration of Pambula provides an analogy for estuaries which have attained an advanced stage of valley filling and feature a single narrow, albeit meandering, tidal channel. Narrawallee Inlet is a case in point. The decrease in degree of tidal attenuation with increased estuary maturity was postulated for barrier estuaries (Type 2) by Roy (1984, Fig. 4). This relationship is graphically illustrated in Figure 6.6 which plots tidal range profiles in Tomaga River estuary and Burrill Lake as a percentage estimate of ocean tidal range. Tidal range in the Tomaga River near the river mouth is 25% less than ocean range and 9.2km upstream it is reduced by 70%*. For comparison, Burrill Lake is plotted as an example of an immature estuary. Within the outer kilometre tidal range is 62% less than the ocean range and is reduced to 4% of ocean range some 9.6km landward. Therefore, it is predicted that tidal range within Narrawallee is reduced by the same margin as measured in Pambula and Tomaga, that being approximately one third less than ocean tidal range. Confirmation is provided by field observations of fluctuations in creek levels at drill site N5, located 5.3 kilometres upstream from the estuary mouth. Tidal range at the site was 1-1.25 metres on a day when ocean tidal range was 1.6 metres, representing a reduction of 22-38%.

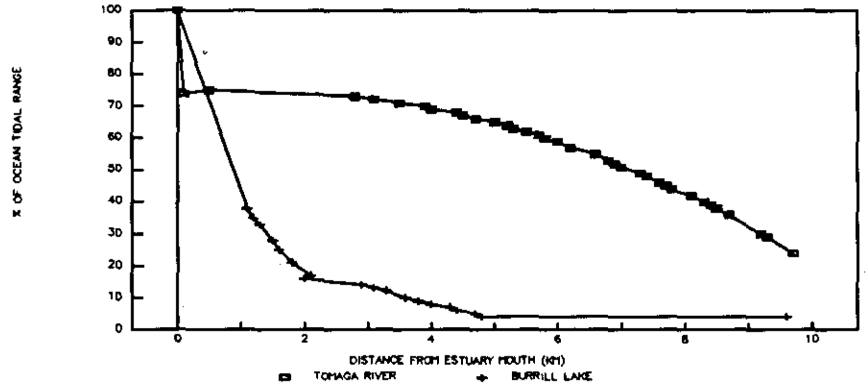


Figure 6.6: Tomaga River and Burrill Lake profiles of tidal range as percentage of ocean tidal range, calculated from nine episodes of tidal monitoring between 1974 and 1978. (Source: Anderson and Storey, 1981).

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* C.S.I.R.O. tidal data is published as percentage of ocean tidal range only. Absolute tidal range data is not available.

6.2.2 Tidal current velocity and tidal discharge

In conjunction with the landward decrease in tidal range, the flood tidal delta also acts to weaken tidal currents within the inlet. As flow velocity decreases along an inlet so does the capacity of tidal currents to transport sediment. However, the rate at which flow velocities weaken is not uniform. In the absence of tidal data specific to Wapengo, it is again necessary to draw analogies with other inlets. Tidal flow velocity data measured at several points along an estuary entrance channel is only available for Lake Illawarra. Figure 6.7 illustrates the form of the longitudinal velocity profile for Lake Illawarra. These data record a distinct landward reduction in mean flood flow velocity from 0.54m/sec to 0.28m/sec along a 2.5km transect. Conversely, ebb currents increase in strength toward the estuary mouth, from a mean velocity of 0.21m/sec to 0.68m/sec.

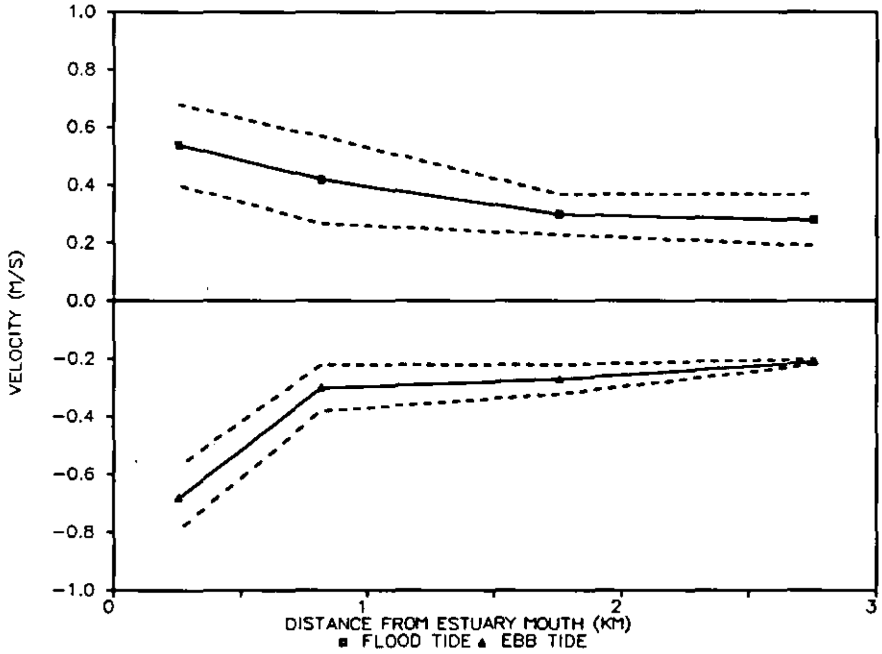

Figure 6.7: Lake Illawarra longitudinal velocity profile, 25 October 1977. Solid line represents mean flow velocity for four measurements taken at hourly intervals before and after high and low water. Dashed lines represent one standard deviation either side of the mean. (Source: Public Works Department, N.S.W., 1982).

A characteristic of the Lake Illawarra velocity profile is that much of the loss of tidal energy is affected along the outer (seaward) 800m of the inlet transect. Thus, the gradient of the flood tide velocity profile decreases from 0.0123^{o}, along the outer interval of the transect, to 0.0011^{o} along the inner interval. Likewise, the ebb flow velocity profile increases from 0.0034^{o} along the inner interval to 0.0225^{o} along the outer interval of the profile. Tidal energy loss across the outer shoals of the flood tidal delta is also evident from the plot of tidal head loss and discharge rates for Lake Illawarra (Fig. 6.7).

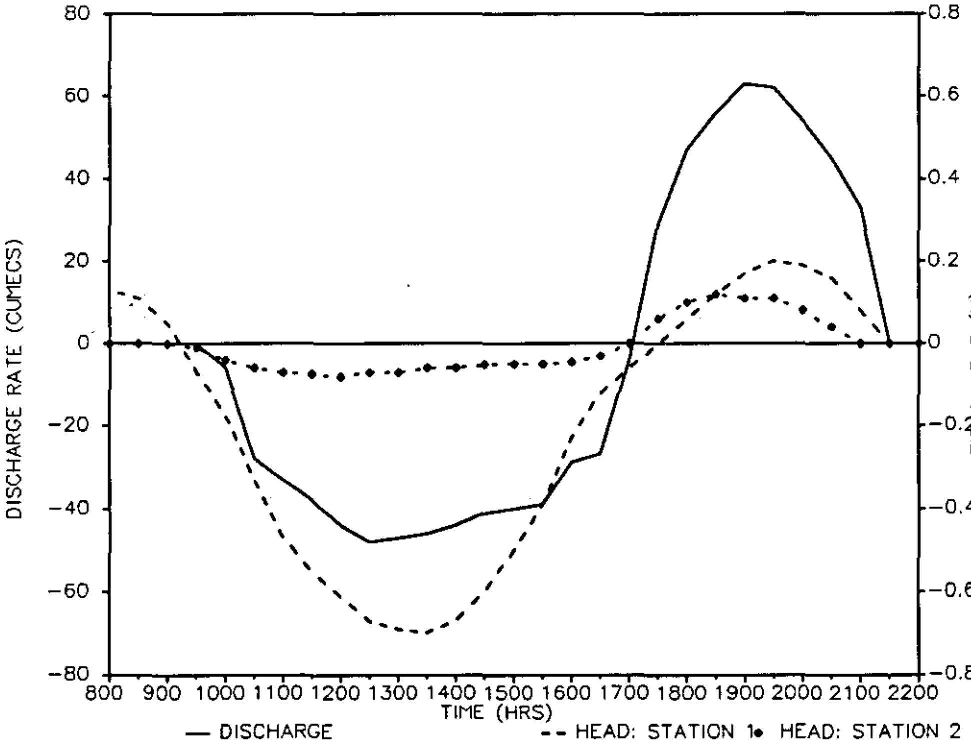

Figure 6.8: Lake Illawarra spring tidal discharge rates and tidal head loss, 25 October 1977. The station 1 tidal head curve describes head loss across the outer 600m of the inlet, and the station 2 curve across the inner 2340m of the inlet. Head loss is calculated as the difference in instantaneous tidal levels between adjacent tidal gauges. Positive values correspond to flood flow and negative values to ebb flow. (Source: Public Works Department, N.S.W., 1982).

In Figure 6.8, the majority of spring tidal head is shown to be dissipated across the shoals in the inlet mouth, particularly during ebb flow when 0.70m of tidal head was lost across the outer 600m of the inlet, whereas only 0.08m was lost across the remaining 2340m of the inlet. Peak discharge rates are shown to be greater during flood flow (63 cumecs) than ebb flow (48 cumecs) due to the smaller tidal head within the inner portion of the inlet during the ebb stage (station 2 curve) (Williams, 1983). The salient point of these relationships is that the velocity and sediment transport capacity of tidal currents within Lake Illawarra and, by analogy Wapengo Lagoon, decreases markedly within the outer third of the inlet. The energy loss continues with increasing distance from the estuary mouth, but at a reduced rate.

6.2.3 Wind waves

Two types of wind generated waves may influence the sedimentological character of intertidal and subtidal estuarine deposits. The first and most powerful type are swell waves. As noted in chapter two, swell waves along the N.S.W. coast originate predominantly from the southeast and south, which is in alignment with the direction of the strongest winds. The mean power contained within southerly swell waves arriving at Wapengo beach is 42200 watts per metre. Southeast swell waves are slightly weaker, with 29100 watts per metre (Kidd, 1978). Furthermore, the amount of wave power lost due to bed friction as the wave approaches the shore, is minimal (<5%) (Wright, 1976). During fairweather conditions much of the energy in swell waves is absorbed by the beach/barrier complex and the outer portion of the flood tidal delta. However, during storm conditions swell waves can penetrate further into an estuary, especially if part or all of the barrier has been destroyed during the storm. Indeed, total barrier destruction and storm wave penetration did occur at the Tuross River estuary during the 1974 storms (B.G. Thom, 1991, pers. comm.). Therefore, swell waves have the potential to be a very important mechanism for transporting sediment into estuary mouths and for reworking existing deposits.

The second type of wind wave are small waves that form within the confines of the estuary. Wave activity of this nature is fetch-limited (Bishop and Donelan, 1989). That is, wind direction must match the maximum possible fetch within an estuary inlet for waves to fully develop. Bishop and Donelan (1989) consider that wind waves in semi-enclosed water bodies rarely become fully developed. Observations made in Wapengo Lagoon during a strong southeast wind noted small wind waves up to 50 centimetres in height at high water. These waves have the potential to impact in two ways. The first potential influence is upon bed topography, by forming small scale bedforms (e.g. ripples) and initiating localised sediment movement. The second potential impact is upon the textural composition of surface sediments, by winnowing out silt and clay sized particles.

Both swell waves and small wind waves are ephemeral in their occurrence and, in the context of the character of Zone A sediments, could be considered to be of secondary importance to tidal processes which are continual. However, the impact of extreme events, though relatively infrequent, must not be discounted when interpreting the sedimentary record.

6.3 SEDIMENTOLOGY OF THE FLOOD-TIDAL DELTA UNIT

6.3.1 Morphology

The flood tidal delta in Wapengo Lagoon comprises three distinct shoals, termed here, seaward shoal, medial shoal and landward shoal (Fig. 6.9). The shoals are separated from one another by flood and ebb tidal channels. Both the seaward and medial shoals have developed morphological features of the model flood tidal delta, defined by Hayes (1980). One important difference between the Hayes (1980) model and the flood tidal delta at Wapengo is the absence of an ebb tidal delta at Wapengo. Indeed, ebb tidal deltas are conspicuously absent along the whole south coast. The lack of ebb delta deposition is attributed to the high energy wave conditions at the shoreface. The tidal delta morphological features of Hayes (1980) were first ascribed to mesotidal flood tidal deltas but they also appear relevant to the microtidal setting considered here. That delta morphology in a microtidal setting is similar to that of a mesotidal coast is likely to be a result of the influence of high energy swell wave action that typifies the N.S.W. coast. That is, the energy lacking in tidal currents is compensated for by that embodied within swell waves.

The formation of the various delta morphological elements results from and promotes the separation of flood currents from ebb currents (Hayes, 1980). Thus, the seaward and medial shoals are subdivided into:

(i) a flood ramp and flood channel, defined as a gently seaward sloping surface upon which the flood tide encroaches. The flood channel is incised into the ramp and is typically broad and shallow (<2m).

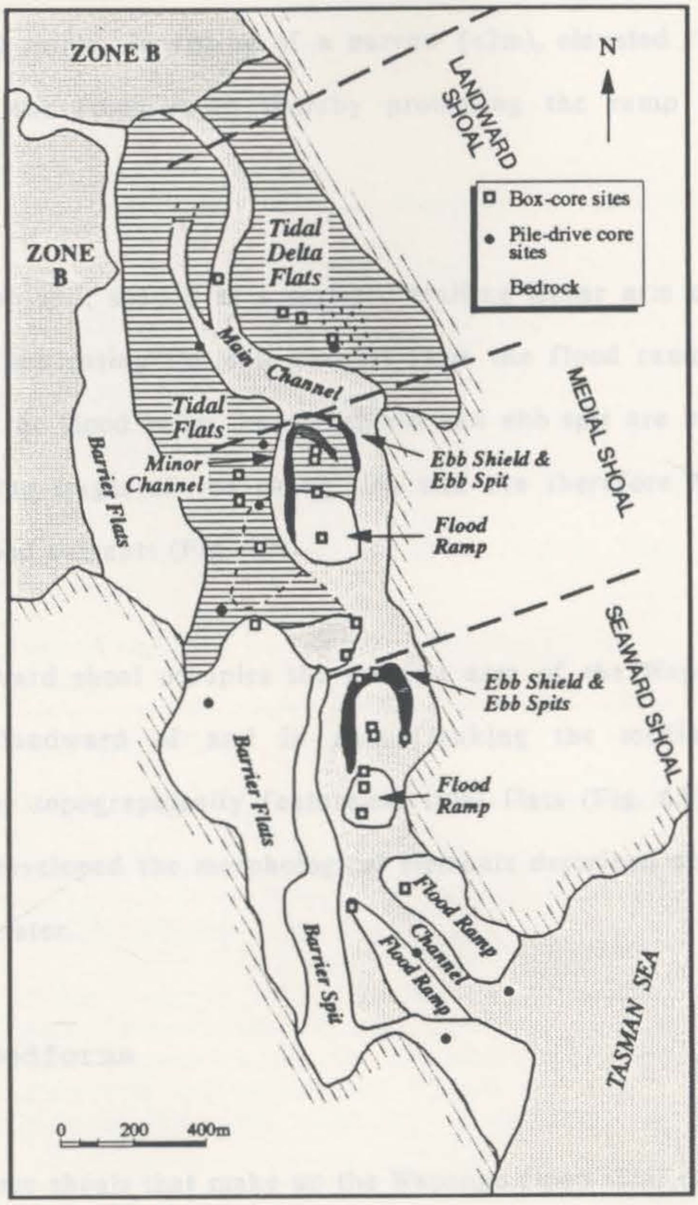

Figure 6.9: Location and plan form of the three shoals and respective morphologic elements comprising the Wapengo Lagoon flood tidal delta. Box-core and hammer-core sites are also shown.

(ii) an ebb shield, consisting of a narrow (<2m), elevated rim flanking the inner edge of the flood ramp thereby protecting the ramp from ebb flow modification.

(iii) an ebb spit, shaped as a seaward trailing linear arm connected to the ebb shield and separating the ebb channel from the flood ramp. Being slightly elevated above the flood ramp the ebb shield and ebb spit are inundated during the latter waning stages of the rising tide and are therefore not significantly modified by flood currents (Fig. 6.9).

The landward shoal occupies the greatest area of the Wapengo flood tidal delta. It lies landward of and in part flanking the medial shoal and is characterised by topographically featureless tidal flats (Fig. 6.9). The landward shoal has not developed the morphological elements described above, for reasons to be discussed later.

6.3.2 Bedforms

Of the three shoals that make up the Wapengo flood tidal delta, the seaward shoal possesses the greater variety of bedforms. Moreover, the entire surface of the seaward shoal is covered by dunes of some form. Bedforms range in size from small to medium two-dimensional (2-D) and three-dimensional (3-D) dunes.* 2-D dunes have straight crestlines, whereas 3-D dunes have wavy crests and scour pits.

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* Bedform nomenclature and descriptors used here conform to the revised subaqueous bedform classification recommended by Ashley (1990). The classification requires use of the term *dune* for all subaqueous bedforms. No association with aeolian dunes is implied.

Table 6.1 presents the bedform classification scheme proposed by Ashley and definitions of descriptive terms used here.

Table 6.1: Subaqueous dune bedform classification scheme and nomenclature. (reproduced from Ashley, 1990).

Subaqueous dune

FIRST ORDER DESCRIPTORS (necessary):

Size: Spacing= small 0.6-5m; medium 5-10m; large 10-100m; very large >100m
Height= small 0.07-0.4m; medium 0.4-0.75m; large 0.75-5m; very large >5m

Shape: 2-Dimensional
3-Dimensional

SECOND ORDER DESCRIPTORS (important):

-Superposition: simple or compound (sizes and relative orientations)
-Sediment characteristics (size, sorting)

THIRD ORDER DESCRIPTORS (useful):

-Bedform profile (stoss and lee slope lengths and angles)
-Fullbeddedness (fraction of bed covered by bedforms)
-Flow structure (time-velocity characteristics)
-Relative strengths of opposing flows
-Dune behaviour-migration history (vertical and horizontal accretion)

Three-dimensionality appears more prevalent, though not restricted to, smaller scale dunes. The small and medium sized bedforms are predominantly ebb-oriented (partly a function of field observations during low water) and are superimposed upon the stoss side of large scale dunes (Fig. 6.10). Bedform crestlines of 3-D dunes exhibit a greater tendency to be in phase for small dunes than for medium sized dunes, though there does not appear to be a consistent relationship between dune size and crestline behaviour.

Figure 6.10: Photograph of small and medium sized 2-D and ripples on the surface of the flood ramp, seaward shoal, Wapengo Lagoon flood tidal delta.

Figure 6.11: Photograph of large 2-D dune that constitutes the flood ramp morphological element of the seaward shoal, Wapengo Lagoon flood tidal delta. Ripples are superimposed on the stoss side of 2-D dunes.

Large dunes equate with elements of the seaward shoal morphology. Thus, the flood ramp element of the shoal is a composite of several large flood-oriented 2-D dunes (Fig. 6.11). Due to their narrow form and higher elevation, the ebb shield and ebb spit elements are characterised by small scale dunes only. The dunes are generally 2-D in form due to the limited tidal inundation period, a period of flow reversal and relatively weak tidal currents. Bioturbation on all elements of the seaward shoal is negligible.

Figure 6.12: Photograph of 2-D dune with small superimposed dune bedforms on the surface of the medial shoal of the Wapengo flood tidal delta. Note the change from non-bioturbated to bioturbated dunes in a landward direction (left to right). Graduations on scale marker are 10cm.

Bedforms on the medial shoal of the Wapengo flood tidal delta are dominated by medium sized flood-oriented 2-D dunes. Like the seaward shoal, the 2-D dunes of the medial shoal define the flood ramp element of the delta. Superimposed on the stoss side of the 2-D dunes are small ebb and flood oriented

2-D and 3-D dunes. However, unlike the seaward shoal, the surface of the medial shoal is not fullbedded. Dunes are fewer in number on the medial shoal, covering approximately 60% of the shoal. In addition, bioturbation is more prevalent, particularly toward the landward end of the shoal (Fig. 6.12).

Figure 6.13: Photograph of bioturbated, topographically featureless tidal flats that characterise the landward shoal of the Wapengo flood tidal delta. Graduations on scale marker are 10cm.

Dune bedforms on the landward shoal of the Wapengo delta are poorly developed, present only in incipient form. The shoal surface topography consists of shallow (<5cm) discontinuous straight scour pits, separated by small low energy 2-D dunes. These bedforms exist only in locations proximal (within 25m) to tidal channels. In distal locations the sediment surface lacks any systematic topographic variation and is intensely bioturbated (Fig. 6.13).

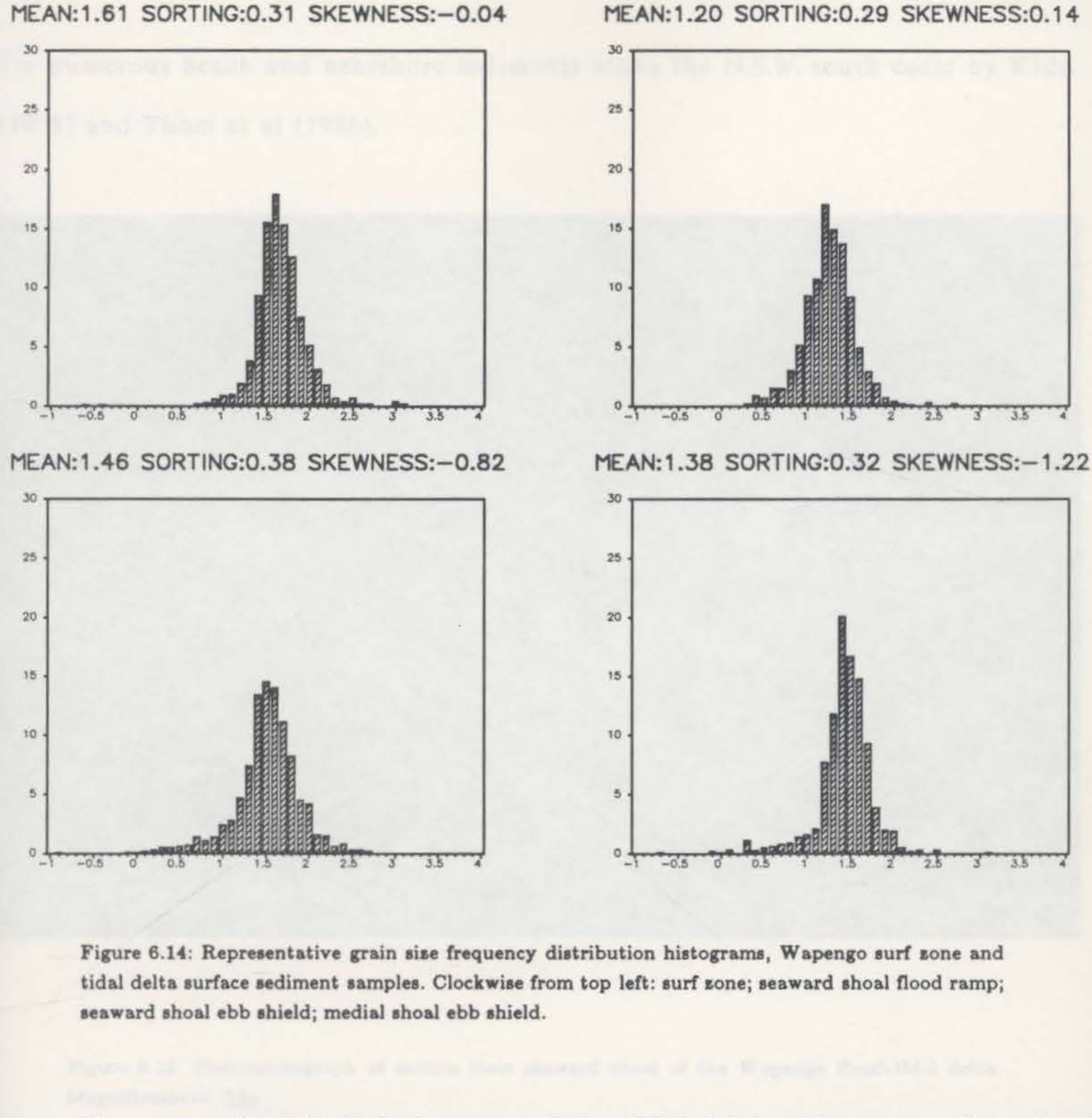
6.3.3 Surface sediment texture and mineralogy

Surface sediments analysed from the Wapengo flood tidal delta range from well to very well sorted medium sub-rounded sands. The silt and clay fraction is negligible to absent, their combined weights never exceed two percent of sample weight (Table 6.2). The presence of silt and clay in tidal delta sediments is considered to be due largely to in-situ production of fines by biological agents rather than weathered clastic minerals and is presumed to be predominantly faecal material. Support for this assumption is provided by total organic carbon results which consistently yielded TOC concentrations of less than two percent.

SHOAL	n	MEAN SIZE (PHI) ± 1σ	MEAN SORTING (PHI) ± 1σ	% SILT	% CLAY
Seaward	22	1.46±0.15	0.34±0.05	0.00±0.00	0.00±0.00
Medial	14	1.44±0.10	0.40±0.06	0.19±0.45	0.42±0.72
Landward	18	1.52±0.1	0.44±0.09	0.38±0.44	0.62±0.50

Table 6.2: Summary statistics for mean grain size and sorting of surface sediment samples from the seaward, medial and landward shoals of the Wapengo flood tidal delta.

Sediment deposited within the flood tidal delta environment displays a close textural and mineralogical affinity to that occurring within the nearshore and surfzone, seaward of the delta. Representative grain size frequency distribution histograms serve to illustrate the similarity between surf zone and inlet sediment and support the premise that tidal delta sediments derive from the shallow nearshore environment seaward of the estuary (Fig 6.14) (Roy et al, 1980).



MEAN:1.61 SORTING:0.31 SKEWNESS:-0.04

MEAN:1.20 SORTING:0.29 SKEWNESS:0.14

MEAN:1.46 SORTING:0.38 SKEWNESS:-0.82

MEAN:1.38 SORTING:0.32 SKEWNESS:-1.22

Figure 6.14: Representative grain size frequency distribution histograms, Wapengo surf zone and tidal delta surface sediment samples. Clockwise from top left: surf zone; seaward shoal flood ramp; seaward shoal ebb shield; medial shoal ebb shield.

The gross mineralogical character of the tidal delta sediments consists of a mature suite of clastic material, dominated by stable minerals. Quartz is by far the dominant mineral, comprising up to 98% of the sediment (Kidd, 1978). Other minor constituents include, feldspars (1%) and heavy minerals (1%). Lithic fragments and micas are not present in the Wapengo tidal delta sediments (Kidd, 1978). The mature mineralogical character of tidal delta sands is illustrated by the photomicrograph in Figure 6.15. A similarly mature suite has been documented for numerous beach and nearshore sediments along the N.S.W. south coast by Kidd (1978) and Thom et al (1986).

Figure 6.15: Photomicrograph of sample from seaward shoal of the Wapengo flood-tidal delta. Magnification= 22x

Detailed grain size analysis of the sand fraction provides data necessary to test for the existence of spatial variation in granulometric properties of the sediment across the surface of the Wapengo flood tidal delta. Mean grain size and sorting for 36 samples are plotted against distance of sample site from the inlet mouth in Figure 6.16. The plot fails to suggest the existence of any distinct longitudinal trend in either statistical parameter. This is further emphasised if summary statistics are plotted according to morphological elements of the flood tidal delta, whereby the flood ramp, ebb shield, ebb spit and tidal flat elements do not plot as distinct clusters (Fig. 6.17).

These results highlight two important properties of the sediments and depositional conditions of the flood tidal delta. First, the uniform textural characteristics of tidal delta sediments is an expression of the strength of inheritance of textural character from the shoreface source environment. Second, that wave and wind reworking of sediment on the continental shelf during multiple eustatic cycles has imparted a degree of sorting and mineralogical maturity that cannot be improved upon by inlet processes, hence surficial spatial grain size trends are lacking.

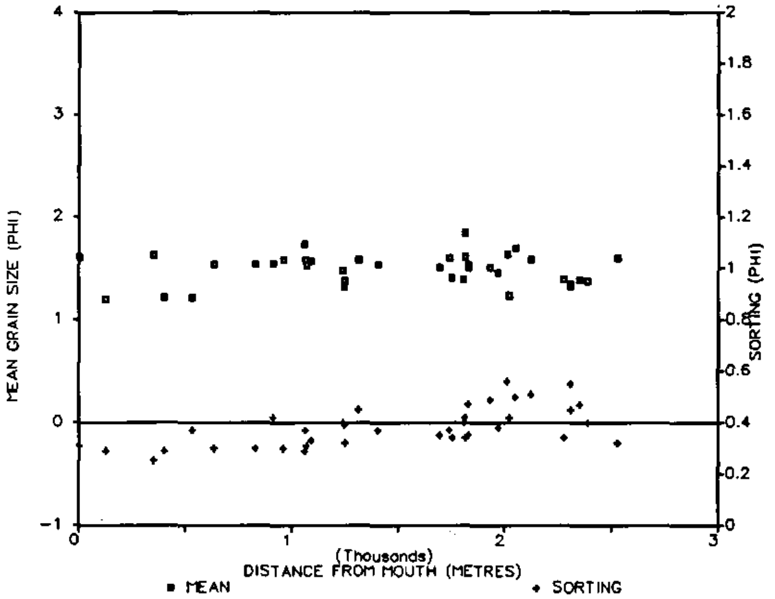


Figure 6.16: Mean grain size and sorting for 36 surface samples plotted against distance from inlet mouth for the seaward, medial and landward shoals of the Wapengo Lagoon flood tidal delta.

It is acknowledged that grain size data from the floors of tidal channels has not been included in this analysis and that gravel lag deposits in channels would disrupt the pattern of textural homogeneity discussed herein. It is argued, however, that the gravel component does not constitute the modal sediment size of the tidal delta shoals. Subsurface data, which incorporate a channel gravel component, will be presented in the following section to support this assertion.

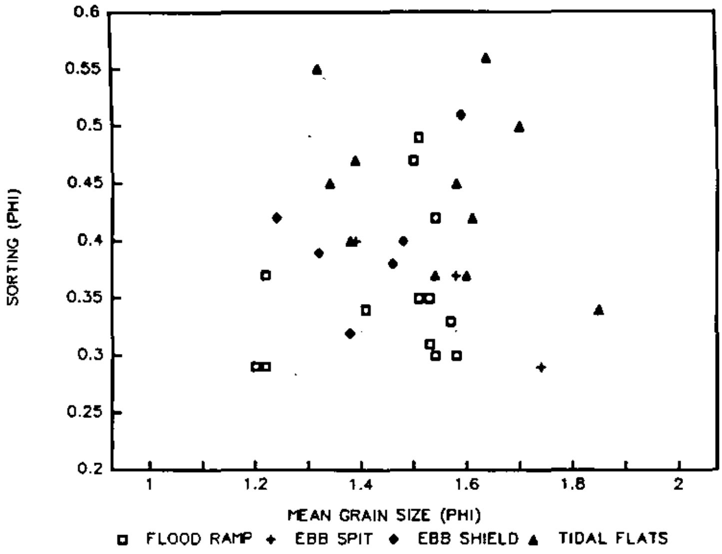


Figure 6.17: Plot of mean grain size and sorting according to tidal delta morphological element, Wapengo Lagoon.

6.3.4 Subsurface sediment texture

In vertical section, flood tidal delta sediments display a slightly greater degree of textural variability than on the delta surface. Even though variation occurs within the restricted size range of 1-2 phi, it exists in a form that may be related to inferred changes in depositional conditions. In the subsurface, tidal delta sediments continue to reflect their marine source by being well to very well sorted medium sands (Table 6.3). Silt and clay content in the subsurface also remains low (<2%) and is primarily of biological origin, as shown by TOC data discussed in section 6.3.6(ii). Textural variations in vertical sections are manifest as upward-coarsening sequences, upward-fining sequences and beds of homogeneous texture that differ only slightly from the texture of overlying beds. The thickness of coarsening and fining sequences varies between five and 20 centimetres, whereas massive beds can be 1-1.5 metres thick. Grain size frequency histograms of samples analysed from hammer-cores taken from the Wapengo flood tidal delta illustrate the subtle nature of textural variation in vertical sections. Typical variation in mean grain size is only of the order of 0.4 phi unit. Variations of less than 0.2 phi are considered to represent massive beds. Table 6.3 presents a summary of the textural properties of each morphological element for the three shoals in Wapengo. Core locations are shown in Figure 4.4

The flood ramp and ebb shield elements of the seaward shoal both exhibit an overall trend of upward coarsening sediment texture. Mean grain size increases uniformly in cores PC18 and PC3 from a medium-fine sand to a medium sand (Table 6.3). Coarsening beds in the flood ramp are 5-20cm thick and in the ebb shield a single 1.2m thick gradational bed exists. The sands are well sorted throughout the deposit, as illustrated by the uni-modal form of the size frequency histograms (Figs. 6.18, 6.19). Frequency histograms record the coarsening trend by a gradual leftward shift in the position of the distribution.

The ebb spit element of the seaward shoal possesses two massive beds with contrasting texture. The basal bed in core PC2 is 30cm thick and comprises a moderately sorted medium sand with a minor gravel component (14%) (Table 6.3). The gravel consists of clastic material and minor shell. The relatively large coarse tail in the frequency histogram reflects the presence of the gravel fraction (Fig. 6.19). Overlying the gravelly sands is a 1.4m thick bed of well sorted medium-fine sands, void of gravel. There is no appreciable variation in grain size within the bed. In contrast to the basal unit, the grain size frequency plots lack a coarse tail and are essentially the same uni-modal shape as the histograms for samples from the flood ramp and ebb shield (Fig. 6.19).

Moving landward, all three elements of the medial shoal yielded a vertical sequence characterised by an upward fining bed, capped by a slightly coarser massive surface unit. The fining unit in cores PC4 and PC5 exists as 50-90cm thick beds of well sorted medium sands grading into medium-fine sands (Table 6.3). Frequency histograms are uni-modal and slightly negatively skewed (Fig. 6.20). The fining trend is rather subtle and is manifest by a slight up-sequence increase in the frequency of grains within phi intervals in the fine tail of the distribution. The coarse capping unit is 25-30cm thick and consists of well sorted medium sands. The coarseness of the unit is recorded by the absence of a fine tail in frequency histograms (Fig. 6.20).

Textural variation in cores taken from the landward shoal do not suggest any consistent trends. Both upward-fining and massive beds can be observed. However, there appears to be a greater grain size variation at sites adjacent to the main tidal channel than at sites more than 50m from the channel. The sequence from cores PC7 and PC14, both channel proximal sites, recorded a fining trend from a well sorted 20-50cm thick basal bed of medium sands with minor gravels (<10%) grading into a 1.1m thick bed of medium-fine sands (Table 6.3). The fining trend is recorded in the frequency histograms by a rightward shift in position of the modal phi interval, an improvement in sorting and an increase in size of the fine tail (Figs. 6.21, 6.22). The upper 10-15cm of the sequence is occupied by a massive coarser bed of well sorted medium sands.

SHOAL	MORPH. ELEMENT	CORE	VERTICAL GRAIN SIZE TREND (PHI)	MEAN SIZE (PHI) +/- 1sd	MEAN SORTING (PHI) +/- 1sd	N
Seaward	Flood ramp	PC18	Coarsening: 1.66-1.22	1.43 +/- 0.17	0.31 +/- 0.02	6
	Ebb shield	PC3	Coarsening: 1.79-1.38	1.61 +/- 0.16	0.30 +/- 0.05	6
	Ebb spit	PC2	Massive: 1.74-1.87	1.72 +/- 0.20	0.40 +/- 0.16	7
Medial	Flood ramp	PC5	Fining : 1.53-1.82	1.61 +/- 0.11	0.47 +/- 0.07	7
	Ebb shield		(coarse cap: 1.53)			
Landward	n/a	PC4	Fining: 1.58-1.89	1.66 +/- 0.18	0.46 +/- 0.07	7
			(coarse cap: 1.46)			
		PC7	Fining: 1.34-1.97	1.74 +/- 0.23	0.43 +/- 0.06	6
		PC14	(coarse cap: 1.85)			
			Fining: 1.22-1.76	1.46 +/- 0.21	0.50 +/- 0.09	5
		PC6	(coarse cap: 1.32)			
		PC15	Fining: 1.46-1.70	1.64 +/- 0.10	0.52 +/- 0.02	5
			Massive: 1.38-1.55	1.45 +/- 0.06	0.45 +/- 0.04	8

Table 6.3: Summary of textural properties of the Wapengo Lagoon flood-tidal delta. SD denotes standard deviation.

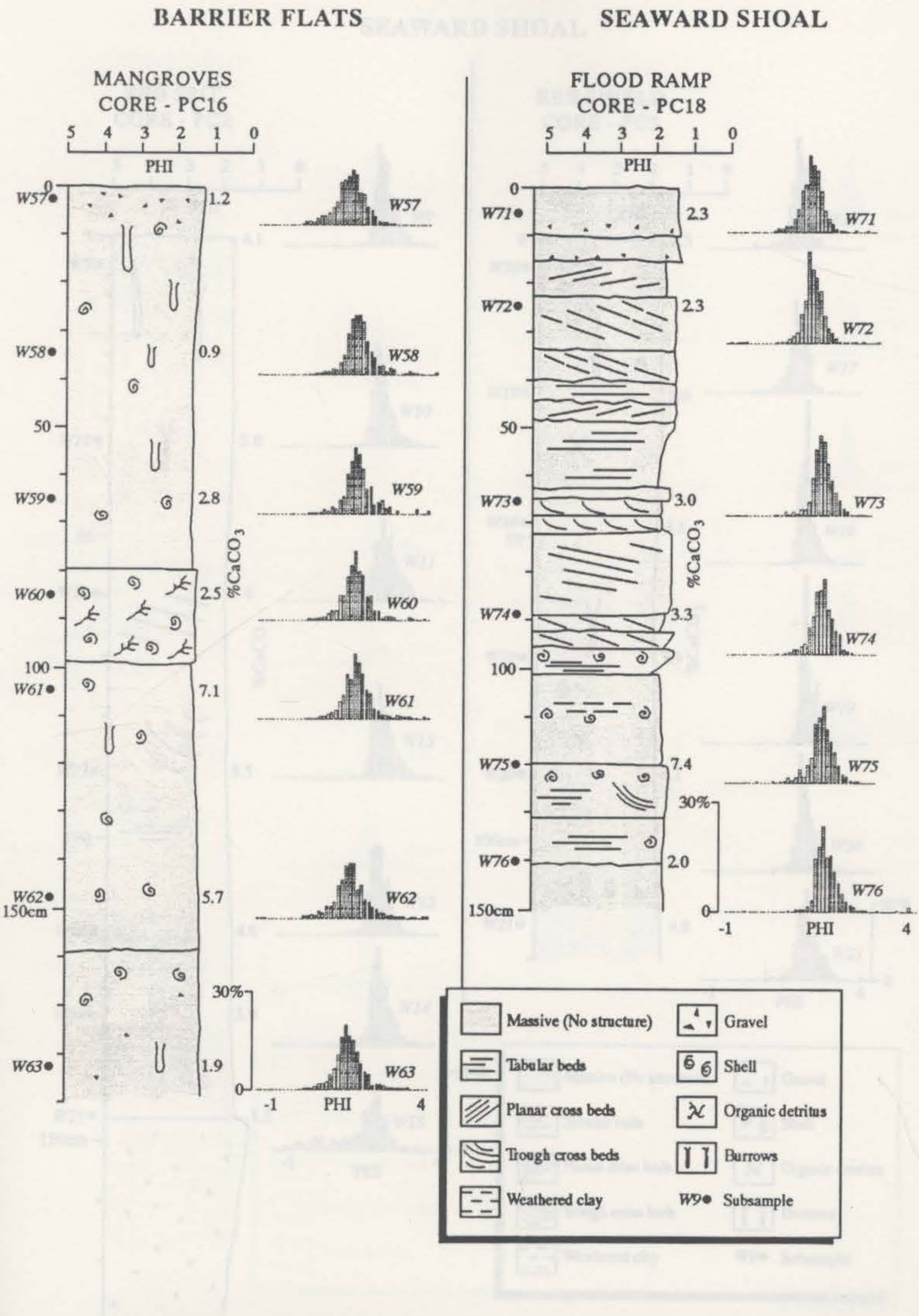


Figure 6.18: Wapengo cores PC16 and PC18 showing: graphic logs plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

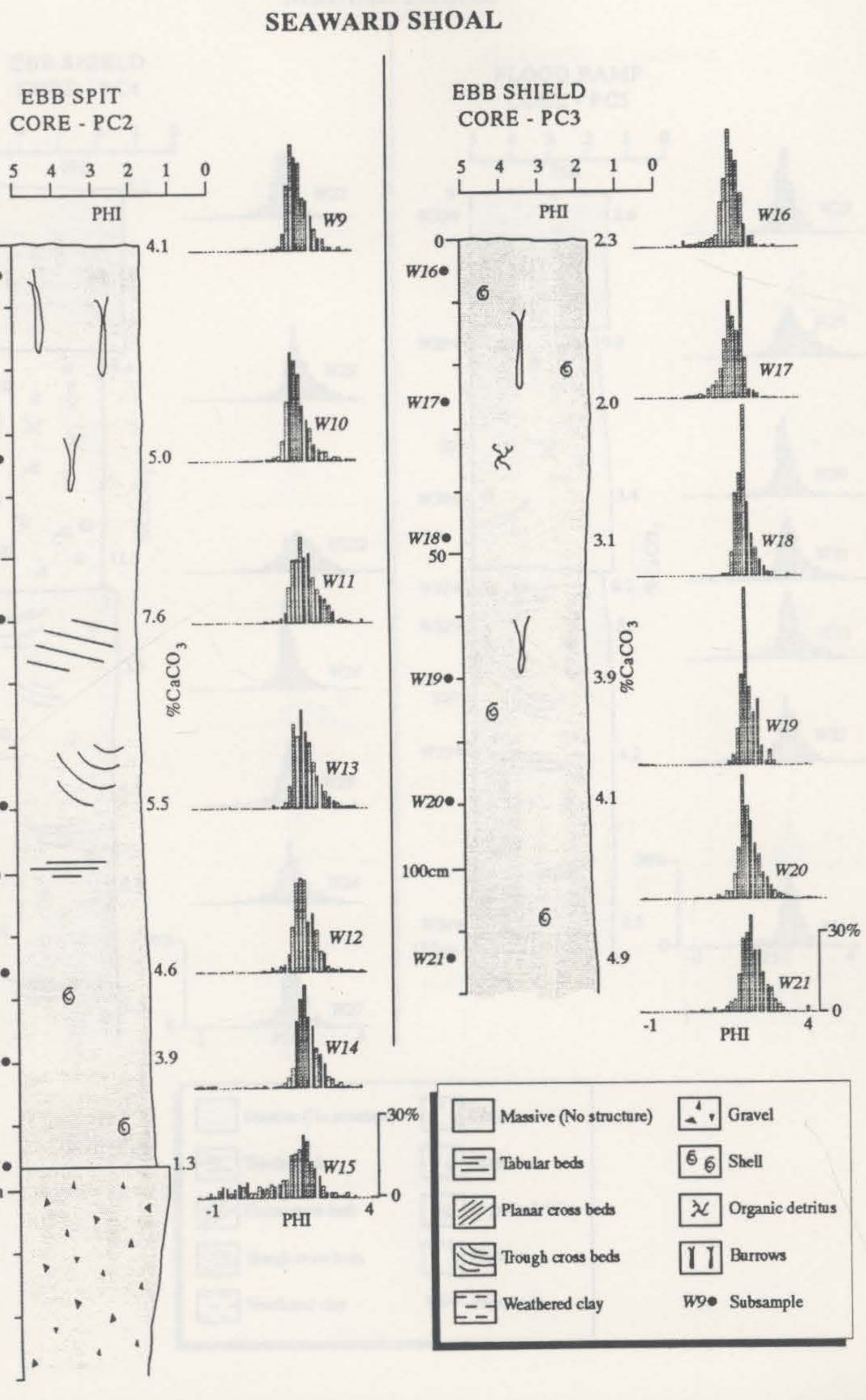


Figure 6.19: Wapengo cores PC2 and PC3 showing: graphic logs plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

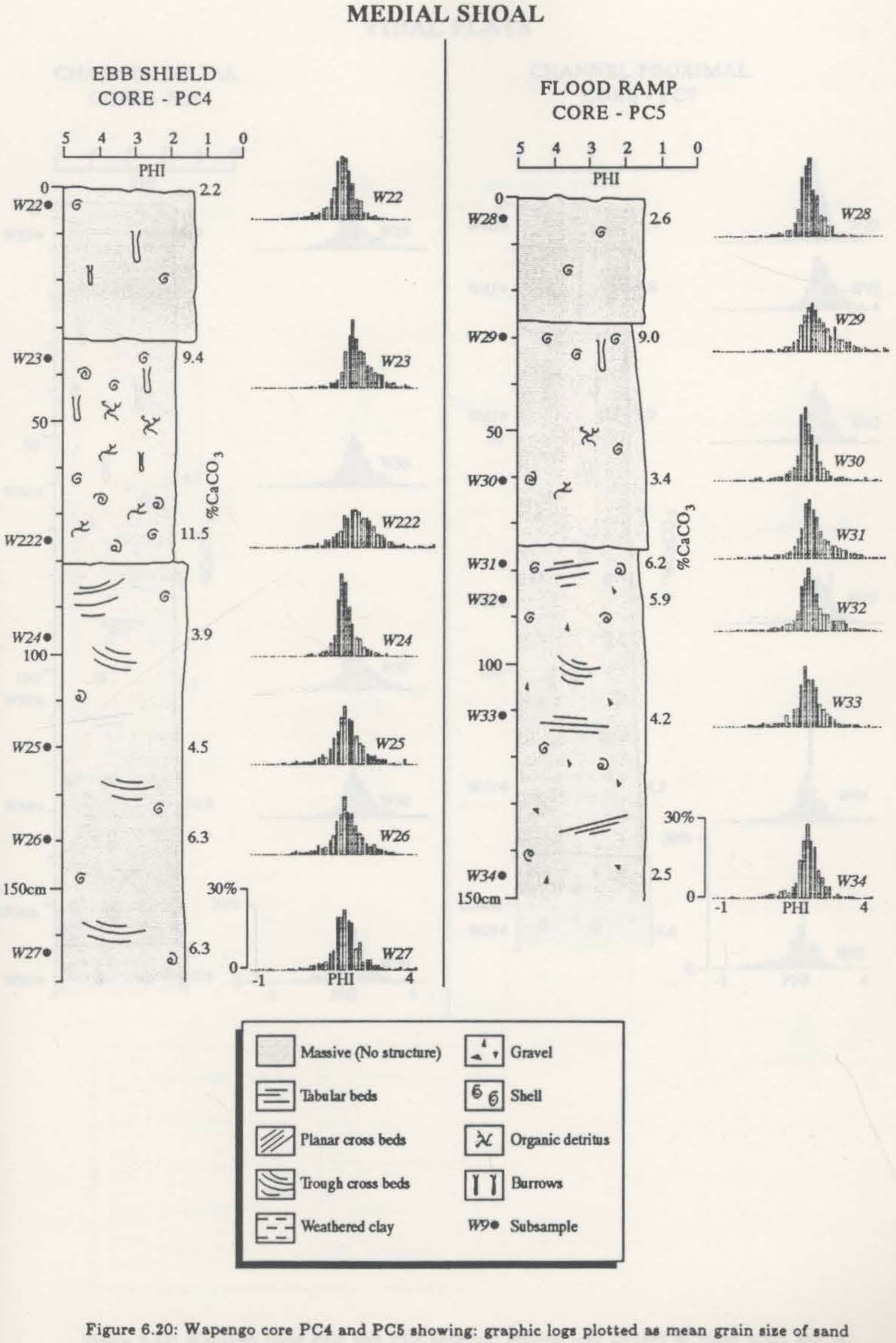


Figure 6.20: Wapengo core PC4 and PC5 showing: graphic logs plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

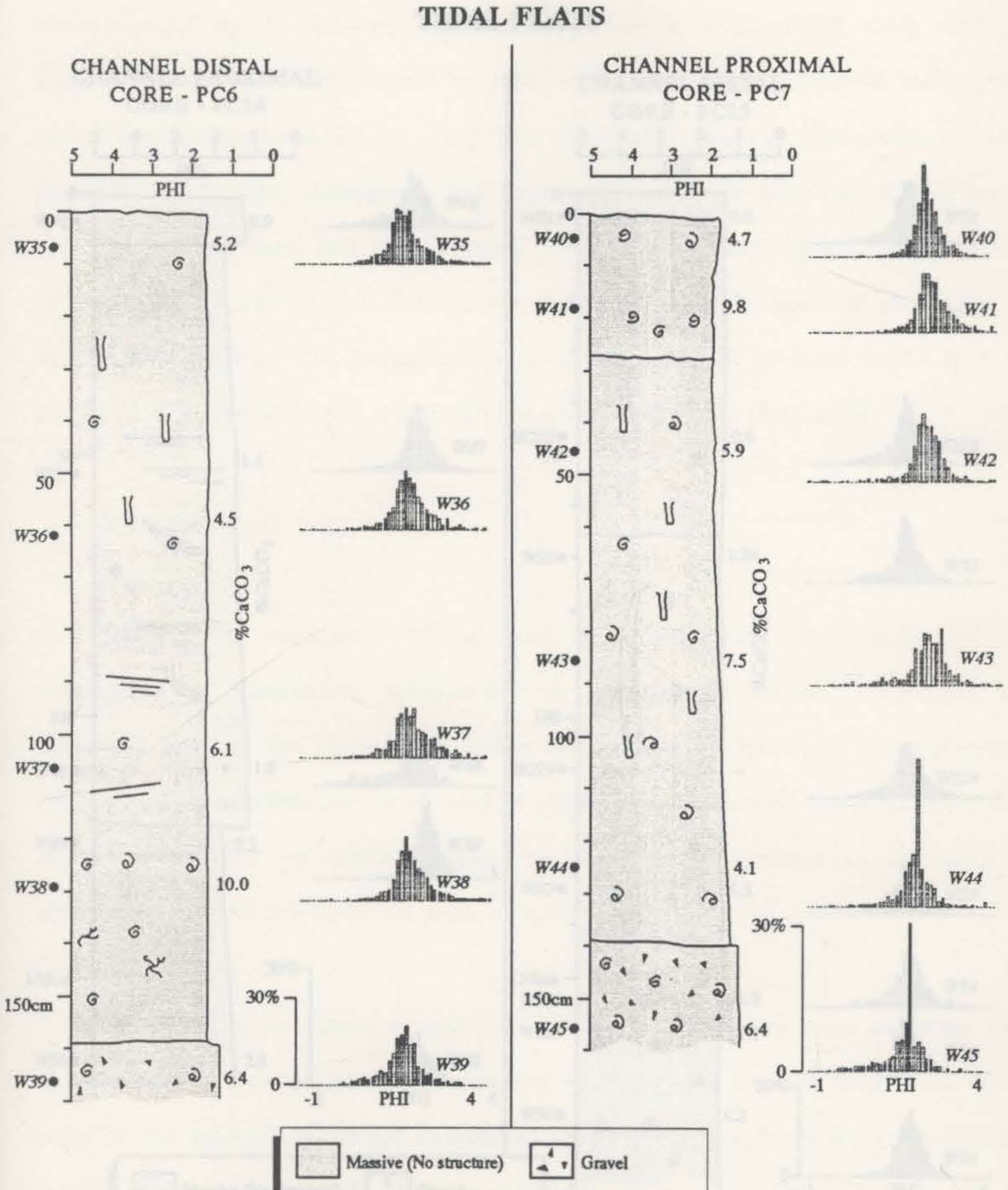


Figure 6.21: Wapengo cores PC6 and PC7 showing: graphic logs plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

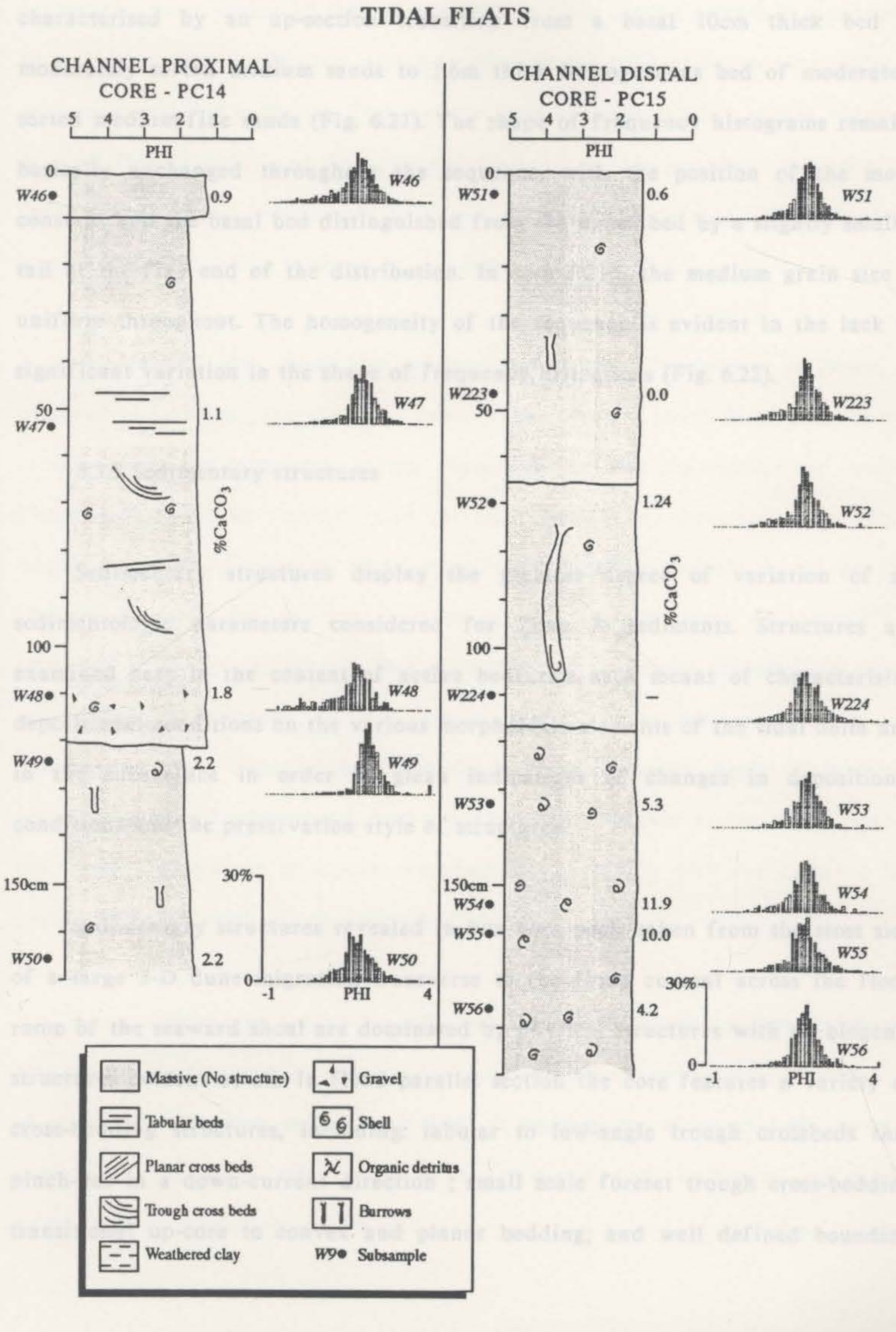


Figure 6.22: Wapengo cores PC14 and PC15 showing: graphic logs plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

Finally, the vertical sequence in cores PC6 and PC15 located away from the tidal channel exhibit only minor variations in sediment texture (Table 6.3). PC6 is characterised by an up-section transition from a basal 10cm thick bed of moderately sorted medium sands to 1.6m thick homogeneous bed of moderately sorted medium-fine sands (Fig. 6.21). The shape of frequency histograms remains basically unchanged throughout the sequence, with the position of the mode constant and the basal bed distinguished from the upper bed by a slightly smaller tail at the fine end of the distribution. In core PC15, the medium grain size is uniform throughout. The homogeneity of the sequence is evident in the lack of significant variation in the shape of frequency histograms (Fig. 6.22).

6.3.5 Sedimentary structures

Sedimentary structures display the greatest degree of variation of all sedimentologic parameters considered for Zone A sediments. Structures are examined here in the context of active bedforms as a means of characterising depositional conditions on the various morphologic elements of the tidal delta and in the subsurface in order to glean indications of changes in depositional conditions and the preservation style of structures.

Sedimentary structures revealed in box core peels taken from the stoss side of a large 3-D dune migrating transverse to the flood current across the flood ramp of the seaward shoal are dominated by physical structures with no biogenic structures evident at all. In flood parallel section the core features a variety of cross-bedding structures, including: tabular to low-angle trough crossbeds that pinch-out in a down-current direction ; small scale foreset trough cross-bedding transitional up-core to convex and planar bedding; and well defined bounding surfaces that are irregular in dip pattern due to the reversing flow conditions (Fig. 6.23a). Similar structures are observed in a section normal to flow (Fig. 6.23b). The preservation of foreset crossbeds in flow normal section is interpreted to represent variation in flow direction through the tidal cycle, causing shifts in migration paths of bedforms. The concave form of some bedding planes, observed in both flow parallel and flow normal sections, is interpreted to have derived from scour pits and convex bedding planes reflect the advancing sinuous bedform crest, all characteristics inherent to 3-D dunes (Rubin, 1987).

Figure 6.23 also shows the primary structures of a vertical sequence, as revealed in core peel, for the flood ramp of the seaward shoal. Small-scale trough cross-bedding and large-scale planar cross-beds are seen throughout the section. The dominant dip of foresets is in the flood (landward) direction, with only a minor indication of reversing flows. Planar foreset beds constitute the thicker (50-100mm) beds of the sequence, whilst trough foresets occur occasionally as relatively thin beds (10-40mm). This assemblage of structures suggests that larger scale dunes, represented by the thicker sets of cross-beds, possessed a 2-D morphology. Three-dimensionality appears to be confined to smaller scale dunes, which is in accord with overall bedform character discussed earlier. Furthermore, the limited occurrence of trough cross-bedding is in line with the expected low preservation potential of small-scale bedforms.

Large numbers of soldier crabs (*Mictyris longicarpus)* were observed actively burrowing into the seaward shoal at low tide, yet burrow traces are rare to absent in all cores taken from the seaward shoal. It appears, therefore, that the seaward portion of the flood tidal delta is too dynamic with bedforms continually migrating and reworking surface

(continued p.241.)

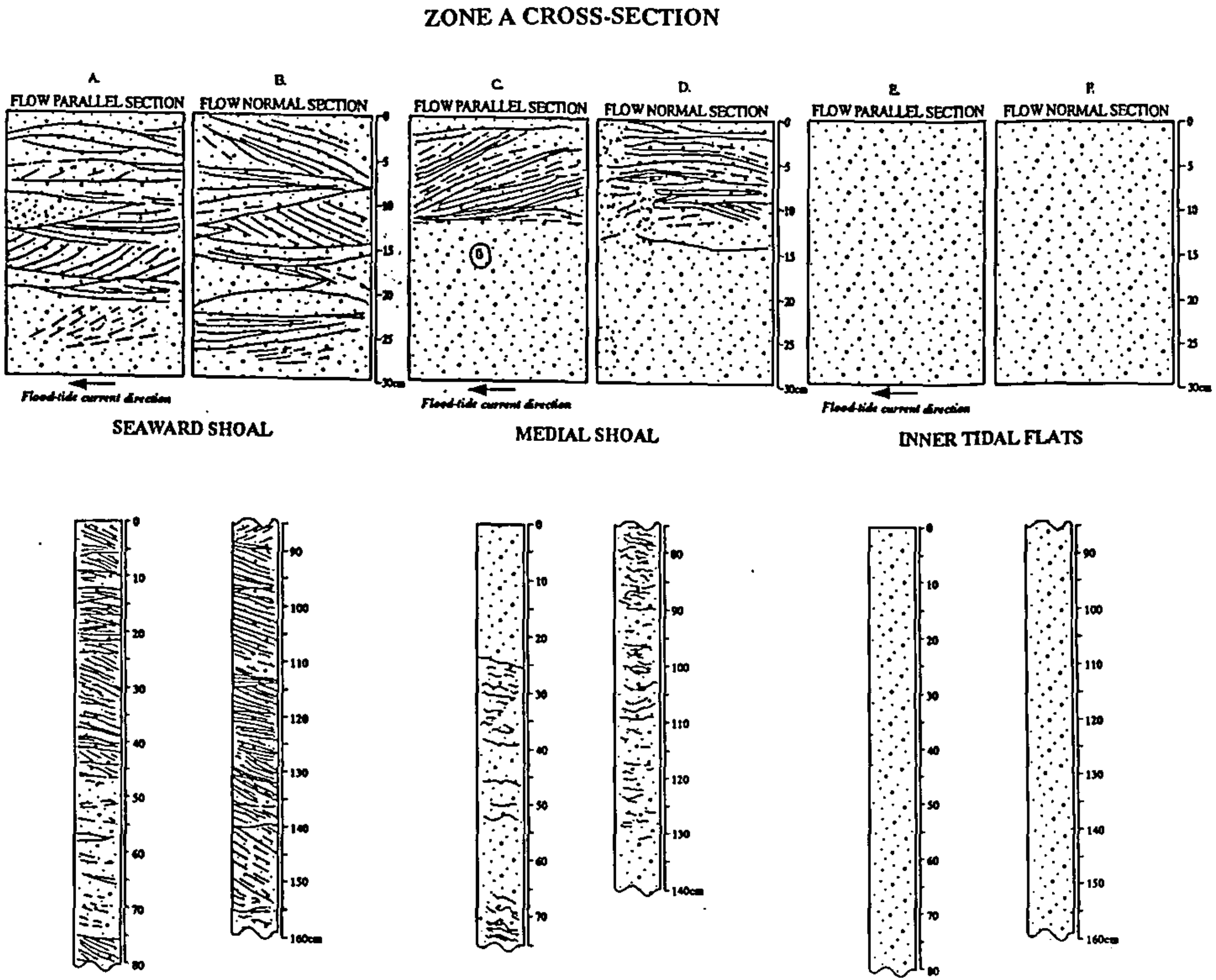


Figure 6.23: Wapengo box-core and pile-drive core diagrams showing sedimentary structures logged from resin peels. Cores represent the seaward shoal, medial shoal and landward tidal flat shoal. Flood current direction is shown.

sediments thereby removing evidence of biological activity from the sedimentary record.

The internal structure of box-core peels from 2-D dunes on the medial shoal are in sharp contrast to that of the seaward shoal in that physical structures do not dominate the entire sequence (Fig. 6.23 c,d). In flow parallel section, physical sedimentary structures record the stoss-erosional migration behaviour of the bedform. Thus, large scale flood oriented cross-beds are in erosional contact with the underlying bedding plane. Cross-bed shape changes up-sequence from shallow-concave to planar to shallow-convex, as testimony to the advancing crestline. The absence of bedding below the upper set is attributed to bioturbation, illustrating the reduced preservation potential of physical sedimentary structures in the medial shoal compared to the seaward shoal.

Illustrations of bedform structure viewed facing the flood current again show the absence of physical structures below the upper set (Fig. 6.23 c,d). Within the upper set, structures are preserved as wavy discontinuous beds. This trait is not considered to be due to partial bedform three-dimensionality, but to the presence of small scale dunes on the stoss side of the main bedform, which produce minor irregularities in the along-crest topography.

Reference has already been made to the potentially destructive influence of burrowing organisms upon primary physical structures. Within the medial shoal of the Wapengo tidal delta, bioturbation appears to be most complete below the troughs of active bedforms (Fig. 6.23 c,d). Inspection of peels of box cores and shallow cores taken on the medial set reveal the co-preservation of physical and biogenic structures at depth (Fig. 6.23). The quality of both forms of sedimentary

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structure is generally poor. Physical structures appear discontinuous and wavy, while biogenic structures exist as ill-defined sandy burrow fills, such as vertical escape burrows (*Skolithos*) formed by the soldier crab *Mictyris longicarpus*. The lack of dominance of one structural form over the other exemplifies the transitional nature of the medial shoal in the Wapengo flood tide delta.

Sedimentary structures of the landward tidal flat shoal reflect the paucity and incipient condition of dune bedforms and the increased effect of biological activity. Thus, box-core and hammer-core peels are void of physical structures, have an overall massive structure and are littered with fossil remains of resident organisms (Fig. 6.23 e,f). Burrow traces are not particularly well preserved due to the intensity of bioturbation.

6.3.6 Carbonate and total organic carbon content

(i) $CaCO_3$: Given the spatial patterns in the distribution and preservation style of physical and biogenic sedimentary structures it is expected that the concentration of fossil shell in the sediment profile will display similar trends. The hypothesis is that higher carbonate content will occur in the most intensely bioturbated sediment. Two assumptions are made in connection with this proposition. First, that bioturbation is primarily carried out by molluscs, gastropods and crustaceans rather than infauna that do not leave a carbonate signature (e.g. worms). Second, that comminuted shell is less likely to be in situ than whole gastropod or articulated bivalve fossils. No distinction is made in the analysis between broken and intact shell material. However, observations of core sections include a qualitative assessment of the general condition of fossil shell material.

Calcium carbonate percentages are plotted against sample depth on graphic core logs in Figures 6.18-6.22. Summary data are presented in Table 6.4 as mean and standard deviation values calculated from core samples representing the various morphological elements of the flood-tidal delta.

MORPHOLOGICAL ELEMENT (core)	CARBONATE CONTENT (%)		
	Mean	σ	n
Seaward shoal			
Flood ramp (PC18)	3.39	2.03	6
Ebb shield (PC3)	3.36	1.12	6
Ebb spit (PC2)	4.84	1.94	7
Medial shoal			
Flood ramp (PC5)	4.82	2.35	7
Ebb shield/spit (PC4)	5.93	3.19	7
Landward Shoal			
Channel proximal (PC14)	1.64	0.62	5
Channel distal (PC15)	5.53	4.58	7
Barrier Flats			
Seaward (PC16)	3.16	2.35	7
Medial (VC21)	5.01	4.56	10
Landward (VC18)	3.07	2.40	11

Table 6.4: Carbonate content summary statistics for representative cores from morphological elements of Wapengo flood tidal delta and barrier flats.

The summary data show carbonate content to be essentially uniform among the morphological elements of the delta. Moreover, there is no appreciable landward increase in fossil carbonate. Within vertical profiles the concentration of carbonate is sufficiently irregular to preclude using fossil shell material in the demonstration of an association between intensity of biological activity and location with respect to morphological elements of the tidal delta. The only indication of increased activity landward is from peak $CaCO_3$ values in cores from the medial shoal and landward tidal flat shoal (e.g. 11% in core PC4) which correlate with beds of shell rich sediment. Further, the shell in these beds is generally intact and presumably in situ. This is in contrast to the peak $CaCO_3$ values in seaward shoal cores (e.g. 7% in core PC18), which record concentrations of comminuted (reworked) shell. Overall, calcium carbonate content appears to be of limited use as an indicator of depositional conditions in the flood tidal delta environment.

(ii) TOC: Core observations indicate that in deposits incorporating organic material, faecal pellets constitute much of that material and plant debris are a subordinate component. Determination of TOC content may, therefore, be an additional means of gauging the relative intensity of bioturbative activity and extending the postulate that bioturbative activity is recorded in sedimentologic indicators other than primary structural signatures. As for carbonate content, it is anticipated that TOC content will increase toward areas of the delta where burrowing activity has been observed to be most prevalent.

TOC analysis was not carried out specifically on core samples from the flood tidal delta because visual inspection of the sediment indicated that TOC values would be zero or at most within the range of analytical error (+/-0.1%). An indication of the negligible TOC content within the tidal delta sediment is provided by TOC data analysis of samples from cores taken from the barrier flats that flank the delta. The sediment sequence yielded by these cores is closely analogous to that of the landward tidal flat portion of the delta (see section 6.4.3). TOC content in the barrier flat does not exceed one percent of sample weight. It is therefore assumed that total organic carbon content in the principally sandy sediment of the flood tidal delta is highest within the deposits that form the landward tidal flats but that the concentration is uniformly low (<0.7%). TOC content in sediments of the seaward shoal is presumed to be negligible to absent.

The general trend, therefore, is of a slight increase in TOC content toward distal areas of the delta but the suitability of the parameter for analysis of depositional conditions appears limited.

It is necessary to point out that TOC concentrations are assessed here in the context of the hydrocarbon source potential of the material. TOC values of between 2 and 3 per cent are regarded as optimum concentrations for hydrocarbon bearing rocks (Bjorlykke, 1989). Thus, the values cited here are below those acceptable for source rocks. However, the textural character of tidal delta sediments suggests that their reservoir potential is good. The reservoir potential of the various morphostratigraphic units will be discussed in greater detail in chapter ten.

6.4 SEDIMENTOLOGY OF THE BARRIER FLAT UNIT

6.4.1 Morphology

The barrier flat morphological unit of Zone A is defined as the partially vegetated low lying area located between the barrier/spit complex and the estuarine lagoon and often adjacent to the flood tidal delta. In Wapengo Lagoon the barrier flat is recognised as the intertidal area behind the barrier/spit occupied by mangroves and abutting the western side of the valley (Fig. 6.9). The Wapengo barrier flat also extends north alongside the western edge of the flood tidal delta, where it is colonised by salt marsh, terminating at the seaward margin of the lagoon (Fig. 6.9). The barrier flat does not possess the three shoal units recognised for the flood-tidal delta, but the terms seaward, medial and landward are retained and used in reference to core sites located parallel to each of the delta shoals.

6.4.2 Bedforms

Due to the relatively protected location of the barrier flat environment and the partially vegetated condition of the surface, systematic dune bedforms are generally absent. Instead, the sediment surface is marked by a network of narrow (<2m) and shallow (<0.20m) tidal creeks and pools that meander between the mangroves and salt marsh. Flow velocity within these channels is sufficient only to generate small-scale dunes (ripples) that are readily destroyed by burrowing infauna.

6.4.3 Subsurface sediment texture and mineralogy

Sediment constituting the barrier flat unit is predominantly sandy in texture, though the silt and clay fractions are in greater concentrations than in the flood tidal delta unit. The mineralogical makeup of barrier flat deposits is identical to that of the delta, mature and quartz dominant. Figure 6.24 illustrates the typical mineralogy of barrier flat sediments.

Table 6.5 presents a summary of the textural properties of three cores taken from seaward, medial and landward locations along the Wapengo barrier flat. Core sites are plotted on Figure 4.4. The seaward area of the barrier flat, represented by core PC16, displays a general fining upward textural trend from medium to medium/fine sands and has a capping bed of medium/coarse sands. The sediments are well sorted throughout. There is also a slight upward increase in the amount of fines. Fining is evident in frequency histograms where it is recorded by an increase in the size of the fine tail of the distribution (Fig. 6.18).

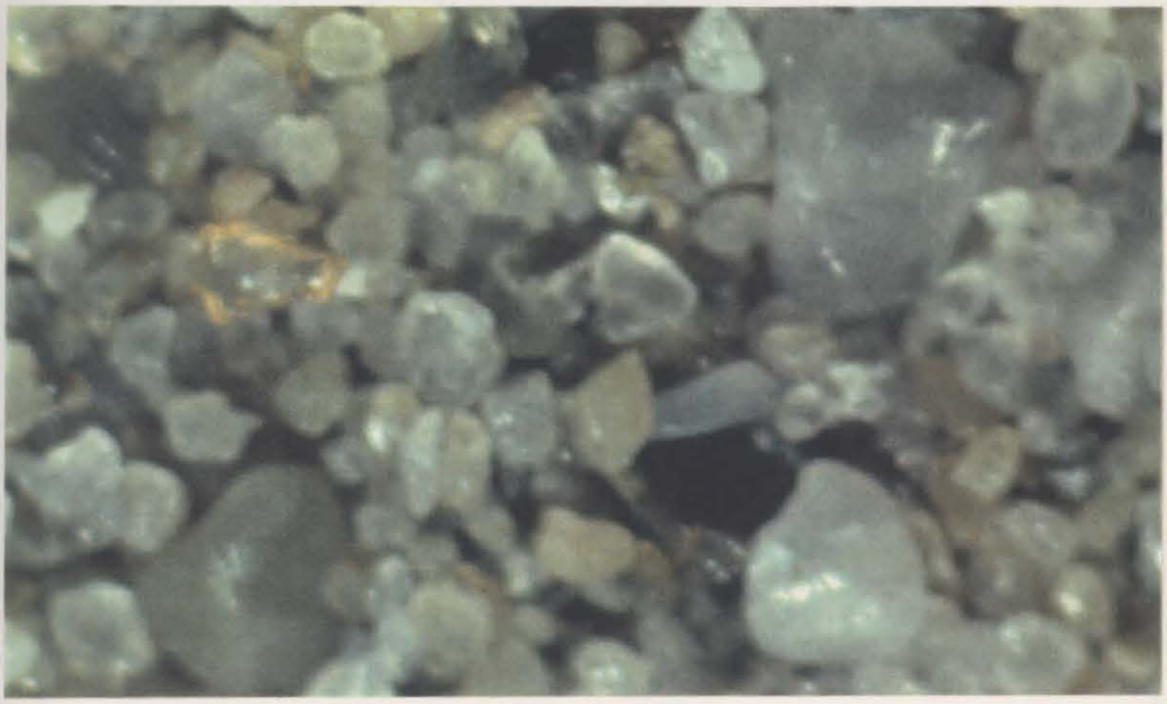

Figure 6.24: Photomicrograph of sample from core VC21 from the medial portion of the Wapengo barrier flat. Magnification= 22x

The medial portion of the barrier flat deposit is 2.25m thick and unconformably overlies a weathered compact clay unit of probable Pleistocene age. Textural variation in the sample core (VC21) is negligible, both in terms of mean sand size and the ratio of sand to the fine fractions (Table 6.5). The bed is therefore classed as massive. The uniformity of texture is reflected in the similar shape of frequency histograms (Fig. 6.25).

The landward portion of the barrier flat, represented by core VC18, is characterised by a distinct fining upward sequence that is most evident from gross textural data (sand:silt:clay ratios). Sediment texture in the upper 0.6m features the highest concentration of fines among the Zone A core samples analysed (Fig. 6.26). Sand remains the dominant texture yet silt and clay together makeup approximately 40% of the upper bed. Below 0.6m, the remainder of the barrier flat unit has alow fines content. Gravel is also present in substantial proportions below 1.0m, comprising up to 54.5% of sample weight. Mean grain size within the sand fraction does not vary appreciably (Table 6.5). Homogeneity of the size of the sand fraction is reflected by the comparable profiles of the frequency histograms (Fig. 6.26).

LOCATION	CORE	VERTICAL TREND & SAND:SILT:CLAY (%)	MEAN SIZE (PHI) ±1σ	MEAN SORTING (PHI) ±1σ	N
Seaward	PC16	Fining: 1.44-1.65ϕ 95:3:2 - 85:10:5 (coarse cap: 1.38ϕ)	1.54 ±0.11	0.43 ±0.03	7
Medial	VC21	Massive: 1.75-1.88ϕ 90:3:7 - 87:6:7	1.82 ±0.06	0.47 ±0.05	9
Landward	VC18	Fining: 1.61-1.77ϕ 98:1:1 - 60:19:21	1.68 ±0.08	0.41 ±0.06	11

Table 6.5: Summary of textural properties of sediments in three cores from the Wapengo barrier flat. Sand:silt:clay ratios are for the base and the top of the deposit. Mean and sorting values are for the sand fraction only.

6.4.4 Sedimentary structures

The structural appearance of the barrier basin deposit is closely similar to that described for the medial and landward shoals of the flood-tidal delta. That is, physical sedimentary structures are rarely preserved and where present exist as isolated and indistinct laminations. An example of the preservation style of

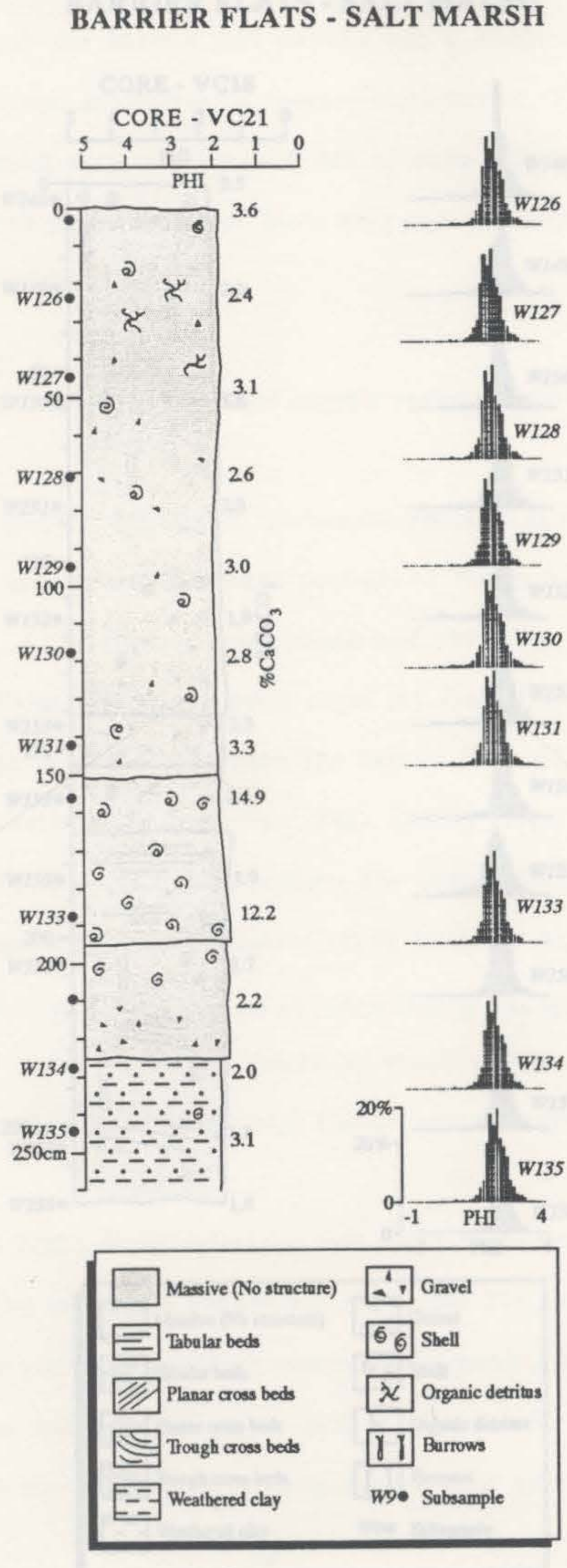

Figure 6.25: Wapengo core VC21 diagram showing: graphic log plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

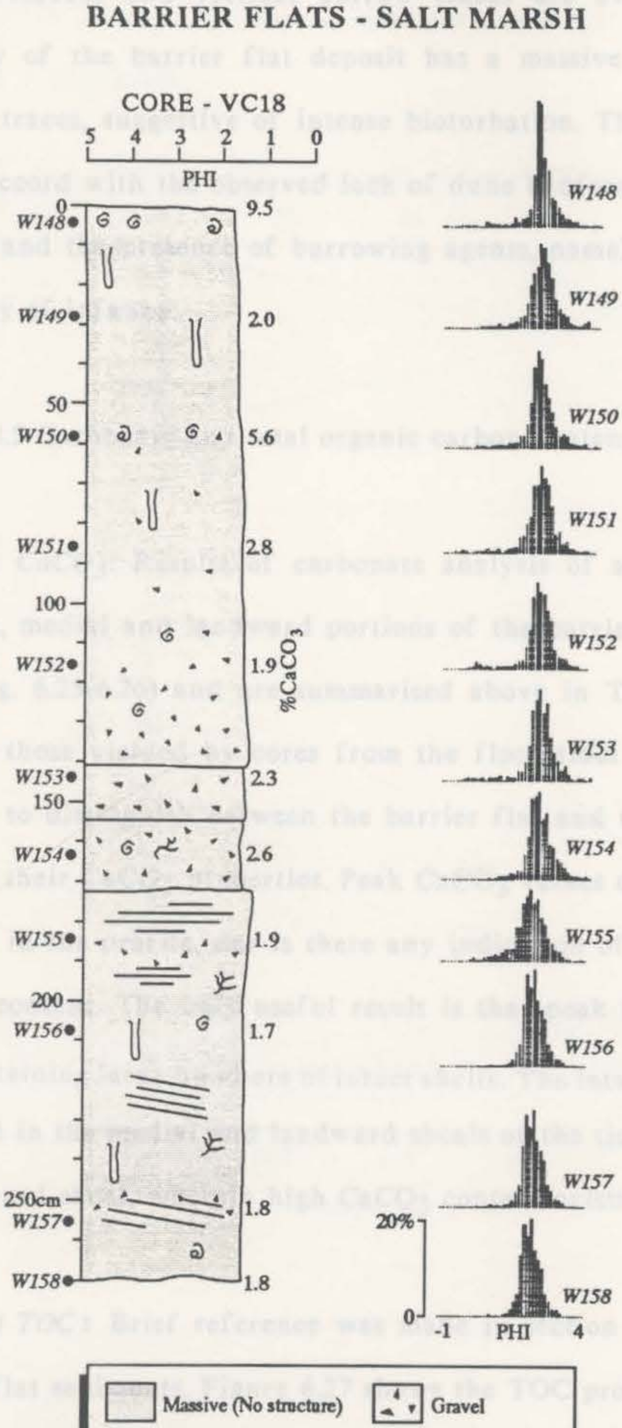

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Figure 6.26: Wapengo core VC18 diagram showing: graphic log plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

structures is shown in the lower metre of core VC18 where planar beds and low angle crossbeds and vertical burrow traces are evident (Fig. 6.26). The great majority of the barrier flat deposit has a massive appearance with occasional burrow traces, suggestive of intense bioturbation. These structural characteristics are in accord with the observed lack of dune bedforms on the present barrier flat surface and the presence of burrowing agents, namely mangroves, salt marsh and a variety of infauna.

6.4.5 Carbonate and total organic carbon content

(i) $CaCO_3$: Results of carbonate analysis of samples from cores from the seaward, medial and landward portions of the barrier flat are plotted on graphic logs (Fig. 6.25-6.26) and are summarised above in Table 6.4. $CaCO_3$ profiles are akin to those yielded by cores from the flood-tidal delta unit. Indeed, it is not possible to distinguish between the barrier flat and the tidal delta deposit on the basis of their $CaCO_3$ properties. Peak $CaCO_3$ values do not occur at any preferred position in the profile, nor is there any indication of consistent vertical trends in $CaCO_3$ content. The only useful result is that peak $CaCO_3$ values correlate with beds containing large numbers of intact shells. The intact condition of shells was also observed in the medial and landward shoals of the tidal delta and is in contrast to the seaward shoal, wherein high $CaCO_3$ content exists as comminuted shell.

(ii) TOC: Brief reference was made in section 6.3.6 to the TOC content of barrier flat sediments. Figure 6.27 shows the TOC profile for the only barrier flat core that yielded significant amounts of organics. The highest TOC value of 0.7% correlates with a 40cm thick bed of silty sands. Within the remainder of the sequence the sediment is predominantly sand and TOC was not detectable (Fig.

6.27). It is therefore concluded that, despite the presence of mangroves, saltmarsh and benthic fauna, the amount of organic material preserved within barrier flat deposits is negligible.

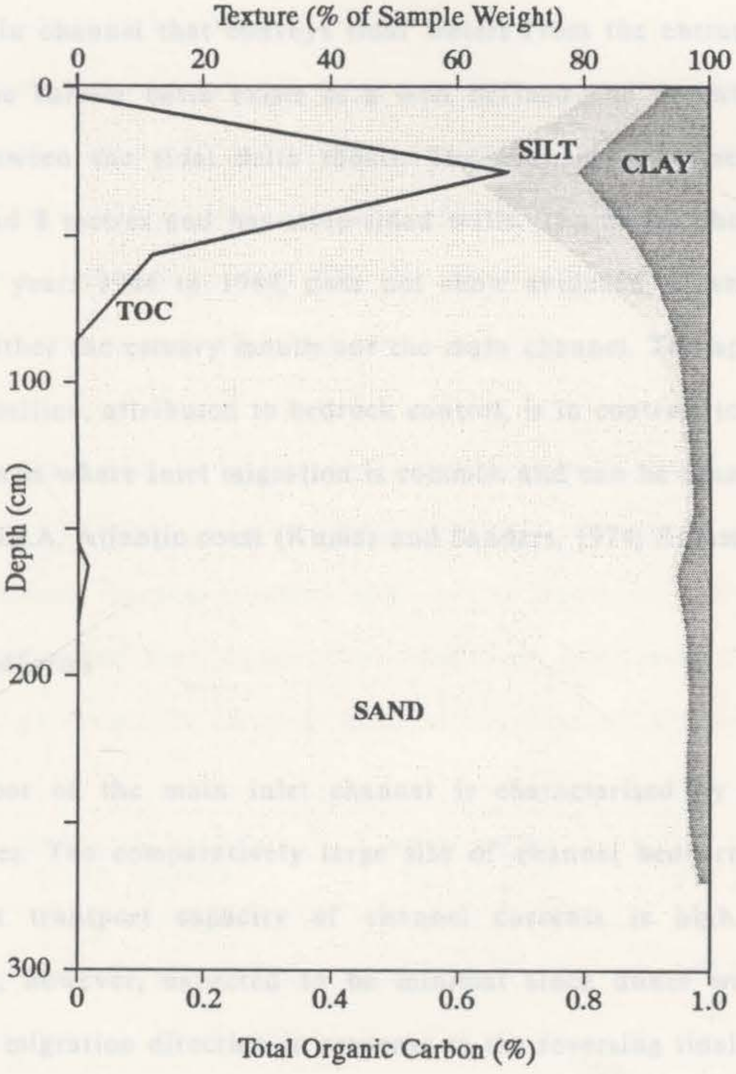

Figure 6.27: Total organic carbon and sediment texture profile for sample barrier flat core (VC18), Wapengo Lagoon.

6.5 SEDIMENTOLOGY OF THE INLET CHANNEL

6.5.1 Morphology

The main channel that conveys tidal waters from the entrance of Wapengo Lagoon to the barrier basin exists as a well defined and perennial course that meanders between the tidal delta shoals. The channel is incised to depths of between 5 and 8 metres and has steep-sided walls. The aerial photograph record, covering the years 1944 to 1984, does not show evidence of any shifts in the position of either the estuary mouth nor the main channel. The apparent stability of channel position, attributed to bedrock control, is in contrast to the tidal inlets of barrier coasts where inlet migration is common and can be dramatically sudden such as the U.S.A. Atlantic coast (Kumar and Sanders, 1974; Reinson, 1984).

6.5.2 Bedforms

The floor of the main inlet channel is characterised by large-scale 2-D subtidal dunes. The comparatively large size of channel bedforms suggests that the sediment transport capacity of channel currents is high. Net sediment movement is, however, expected to be minimal since dunes were observed to reverse their migration direction in response to the reversing tidal flows. In parts, the channel floor is armoured by deposits of very coarse sand, gravel and cobbles. Where the bed is armoured dune bedforms are absent and the channel floor is flat.

6.5.3 Sediment Texture

Logistical constraints precluded core sampling of the subtidal bed of the Wapengo inlet channel. In addition, due to the stability of the channel it was not possible to sample a channel fill sequence. However, a substitute sequence is provided by cores taken from Narrabeen Lagoon inlet, located north of Sydney. The entrance to Narrabeen was artificially opened and subsequent closure allowed direct sampling of the channel fill. The fill sequence is not particularly thick, (1-1.5m), due to a shallow bedrock sill at the inlet mouth.

Specific grain size of Narrabeen inlet sediments differs from values cited from Wapengo because of contrasting lithologic character of source rocks supplying sediment to the southern and central coasts of N.S.W. Nevertheless, given the assumption that depositional conditions are essentially alike among N.S.W. barrier estuaries, the resultant textural trends should also be comparable.

CORE	VERTICAL GRAIN SIZE TREND	MEAN SIZE (PHI) ±1σ	MEAN SORTING (PHI) ±1σ	N
NC8	Fining: 0.91-1.31φ	1.07 ± 0.17	0.36 ± 0.04	7
NC4	Fining: 1.35-1.68φ	1.47 ± 0.14	0.29 ± 0.01	8

Table 6.6: Summary of textural properties of inlet channel sequence from Narrabeen Lagoon.

The sequence yielded by cores NC8 and NC4 are both characterised by a distinct fining upward trend. Core NC8 penetrated the washover deposits capping the primary channel fill behind the berm that had formed across the inlet mouth.

Sand is by far the dominant sediment grade, with silt and clay making up less than 1% of sample weight. Mean grain size in the 1.2m thick channel fill decreases up-sequence from moderately sorted coarse shelly sands to well sorted medium sands. (Fig. 6.28). Summary textural statistics are presented in Table 6.6

Core NC4 sampled a secondary channel fill that was abandoned prior to inlet closure. The vertical trend in sediment texture are not as clear as NC8, however, the overall pattern is again upward fining. The 1.5m thick bed grades upward from a well sorted medium sand to a well sorted medium/fine sand (Fig. 6.28).

6.5.4 Sedimentary Structures

In the absence of direct bedform sampling in the Wapengo channel, it is not possible to present data specific to the structural character of active dunes and Narrabeen data is offered instead. The fill section represented by core NC8 features well preserved primary physical structures throughout. Landward dipping planar foresets (flood flow oriented) are the most common structural feature. The steepness of foresets decreases up-sequence from high angle (15-20^{o}) beds in the basal coarse shelly sands to low angle (<5^{o}) and parallel beds in the overwash capping sediments (Fig. 6.28). Sedimentary structures in the secondary channel fill (core NC4) also record an up-section decrease in the angle of landward dipping cross-beds, though some ebb-oriented foresets are preserved (Fig. 6.28). Trough bedding is not preserved in either channel fill. The lack of trough bedding is attributed to the 2-D morphology of dunes observed on the channel floor. By definition, 2-D dunes produce planar crossbeds only. A 3-D morphology is required to generate trough beds (Rubin, 1987).

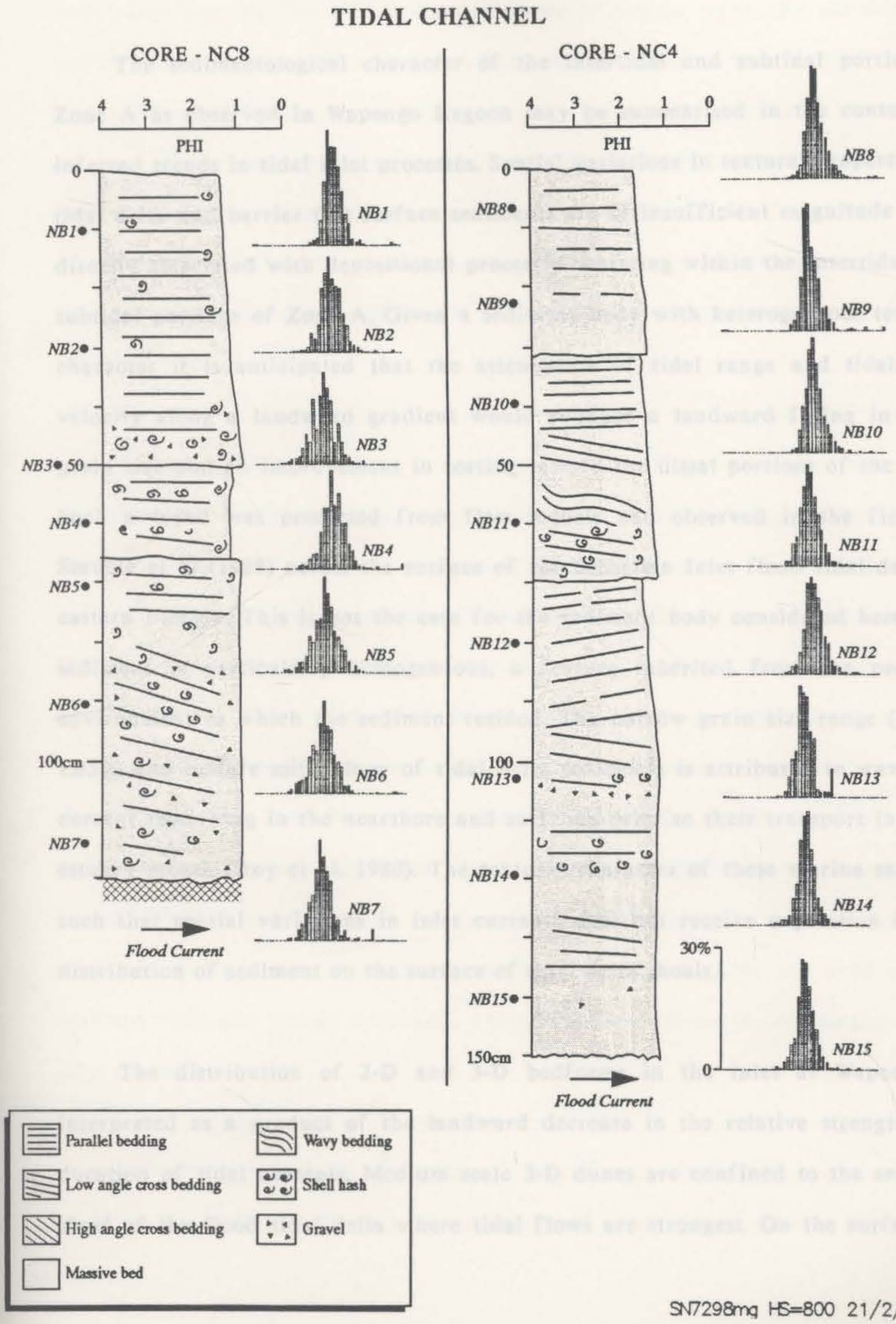

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Figure 6.28: Narrabeen cores NC8 and NC4 showing: graphic logs plotted as mean grain size of sand fraction; subsample depths; carbonate content; and, frequency distribution histograms at one-tenth phi intervals for the sand fraction.

6.6 SUMMARY: FACTORS CONTRIBUTING TO THE SEDIMENTOLOGIC PROPERTIES OF ZONE A

The sedimentological character of the intertidal and subtidal portion of Zone A as observed in Wapengo Lagoon may be summarised in the context of inferred trends in tidal inlet processes. Spatial variations in textural properties of tidal delta and barrier flat surface sediments are of insufficient magnitude to be directly associated with depositional processes operating within the intertidal and subtidal portions of Zone A. Given a sediment body with heterogeneous textural character it is anticipated that the attenuation of tidal range and tidal flow velocity along a landward gradient would produce a landward fining in mean grain size and an improvement in sorting toward the distal portions of the delta. Such a trend was predicted from flow models and observed in the field by Stauble et al (1988) across the surface of the Sebastian Inlet flood tidal delta in eastern Florida. This is not the case for the sediment body considered here. The sediment is particularly homogeneous, a feature inherited from the previous environment in which the sediment resided. The narrow grain size range (1.20ø-1.85ø) and mature mineralogy of tidal delta sediments is attributed to wave and current reworking in the nearshore and surfzone prior to their transport into the estuary mouth (Roy et al. 1980). The textural character of these marine sands is such that spatial variations in inlet currents does not receive expression in the distribution of sediment on the surface of tidal delta shoals.

The distribution of 2-D and 3-D bedforms in the inlet at Wapengo is interpreted as a product of the landward decrease in the relative strength and duration of tidal currents. Medium scale 3-D dunes are confined to the seaward shoal of the flood tidal delta where tidal flows are strongest. On the surface of the medial shoal three-dimensionality is restricted to the smallest sized dunes in response to weaker tidal flows. In addition, lower current velocities provide conditions suitable for burrowing organisms to impact upon the character of sediments by destroying primary sedimentary structures and leaving burrow traces. Of the three shoals the medial shoal in Wapengo is considered transitional because it features both undisturbed and disturbed (bioturbated) dunes. The landward shoal is influenced by the weakest tidal flows in the intertidal portion of the inlet. Consequently, dunes are incipient and restricted to channel margins. The vast majority of the landward shoal lacks topographic variation and is intensely bioturbated.

Spatial trends in bedform morphology have been shown to exist in response to variations in the relative strength of tidal flows. Inferring relative flow strength from bedform size, shape and internal structure in an environment influenced by reversing flows is difficult. Rubin (1987) observed that bedforms formed by reversing flows tend to be more 2-D in form than those resulting from uni-directional flows. Yet, Dalrymple (1987) contends that there are no fundamental differences between the geometry and internal structure of bedforms occurring in uni- and bidirectional flows. Nevertheless, the formation of 3-D bedforms has been well correlated with increased flow velocities at a fixed depth (Allen, 1968). Given that flow depth varies in tidal flows, it is postulated here that 3-D bedforms develop during the peak flow period in the area of the seaward shoal and remain essentially unmodified throughout the remainder of the tidal cycle.

Subsurface variations in sediment texture exist within the same range of variation for surface sediments, but variations are manifest as upward fining and upward coarsening trends that may be related to changes in depositional conditions bought about by accretion of the sediment surface. Thus, vertical sections from the seaward shoal feature a subtle upward coarsening trend within a narrow size range. The relatively high energy conditions that prevail toward the estuary mouth are interpreted to favour a limited size range and good sorting as a result of winnowing of fine sand, silt and clay. Tidal currents, swell waves and localised wind waves all provide mechanisms for the winnowing process. As a shoal accretes and flow depth is reduced, winnowing becomes more effective because the sediment surface is elevated to within wave base and tidal currents are focussed into a restricted water column. As a result, tidal currents are concentrated to the point where only the coarsest fraction of the available sediment remains. This relationship is most evident on the flood ramp element of the seaward shoal, where the coarse capping bed is most distinct. An additional mechanism to account for the presence of coarse beds is provided by high energy storm swell waves. Large ocean swell waves have the ability to penetrate far into an inlet and carry with them coarse sediment from the shoreface. Although such events may not occur frequently, their impact upon the sedimentologic character of tidal delta deposits must not be discounted.

An upward coarsening trend also exists in vertical sections through the ebb shield and ebb spit elements but it is less distinct. That is, winnowing of fines from the upper bed of the sequence has not been as complete as on the flood ramp. This is attributed to the different manner in which the ebb elements interact with tidal flows and to their greater distance from the estuary mouth. Specifically, because of their elevated position relative to the flood ramp, the ebb elements are last to be submerged by the rising tide and first to emerge during the ebb. Moreover, they are only affected by the weaker flows of the tidal cycle.

That being the period prior to, during and following slack water. Because winnowing and reworking occurs over a shorter period and under lower energy conditions it is less effective in removing fines than on the flood ramp. In addition, the greater distance of the ebb elements from the estuary mouth means that these elements are less exposed to ocean swell waves, hence the delivery of coarse sediment is less likely. The result is a poorly developed upward coarsening sequence in the ebb shield and a massive sequence in the ebb spit.

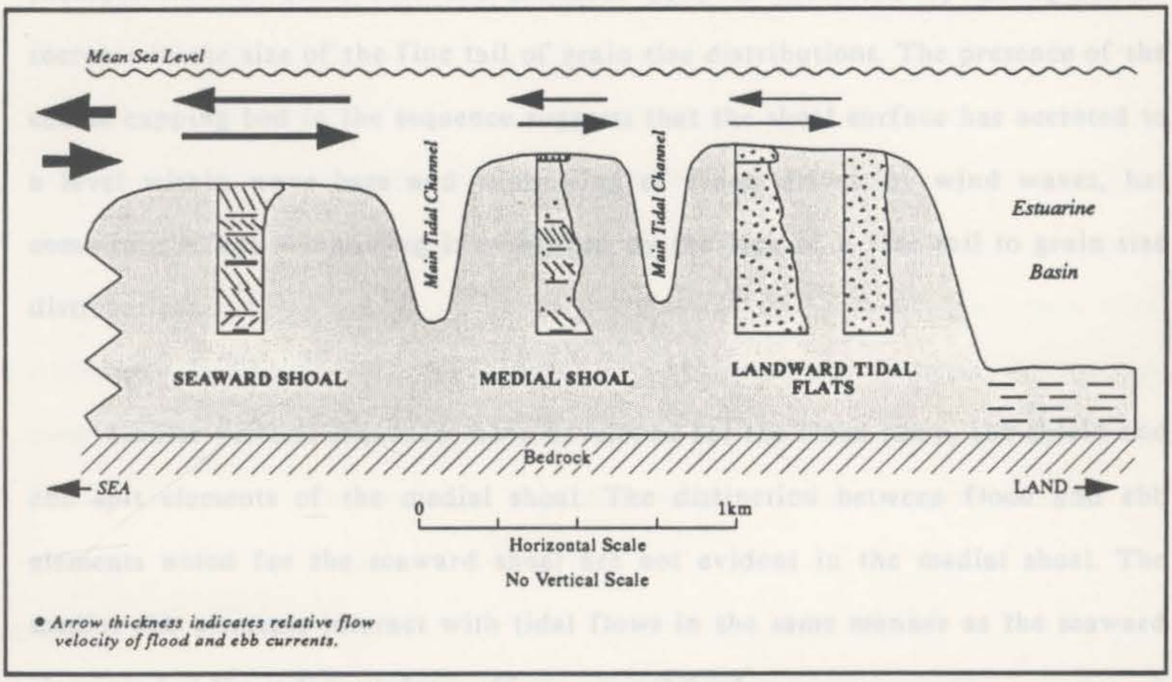


Figure 6.29: Sketch showing inferred interaction between tidal delta shoals and tidal currents and resultant vertical depositional sequences.

Subsurface textural variation within the medial shoal differs to that for the seaward shoal by taking the form of an upward fining trend that is overlain by a thin cap of slightly coarser sediment. The up-sequence decrease in mean grain size is interpreted to be a product of shoal accretion. As demonstrated by tidal data from other south coast inlets, the majority of flood tidal energy loss occurs across the seaward shoals and ebb flow velocity is less across inner shoals due to the smaller tidal head. While absorption of tidal energy produces a coarsening upward sequence in the seaward shoal, areas further landward are characterised by a fining upward trend. The contrast is attributed to the increased protection from tidal currents and swell waves given to the medial and landward shoals by the accreting seaward shoal (Fig. 6.29). In addition, accretion of the medial shoal will further reduce the energy of tidal currents and promote retention of fines. Incorporation of fines into the sediment body is indicated by an up-section increase in the size of the fine tail of grain size distributions. The presence of the coarse capping bed in the sequence suggests that the shoal surface has accreted to a level within wave base and winnowing of fines, driven by wind waves, has come into effect. Winnowing is evidenced by the lack of a fine tail to grain size distributions.

Similar vertical sequences have developed for the flood ramp, ebb shield and ebb spit elements of the medial shoal. The distinction between flood and ebb elements noted for the seaward shoal are not evident in the medial shoal. The medial ebb elements interact with tidal flows in the same manner as the seaward elements but the sedimentologic effects are subdued.

Textural variation within vertical sections from the landward shoal is relatively limited, being most apparent in locations adjacent to tidal channels. Subtle upward fining sequences with a coarse capping bed have developed in channel proximal sites. The mechanisms invoked to account for subsurface trends in the medial shoal are also appropriate for the tidal flats. Shoal accretion provides increased resistance to tidal flow, thereby reducing sediment transport capacity. Again, the coarse cap is attributed to wave winnowing and the possible effect of infrequent storm swell waves. At sites removed from the main channel the vertical profile lacks any significant textural trend. Textural homogeneity is credited to the combined effects of the low energy conditions associated with distal sites and thorough mixing by burrowing infauna.

Further sedimentologic expression of the landward tidal energy gradient is found in the form and preservation of sedimentary structures. In summary, physical and biogenic structures record the surface distribution of bedform type and intensity of biological activity. Thus, physical structures are best preserved and most variable within the seaward shoal. Planar cross-beds and trough cross-beds are the prime structural signature of 2-D and 3-D dunes, respectively. That the shoal is a product of flood tide deposition is recorded in the preponderance of landward dipping (flood flow) foresets over seaward (ebb flow) oriented beds. Also, the dominance of planar beds over trough beds reflects the greater preservation potential of the larger 2-D dunes over smaller 3-D forms. Biogenic structures are not incorporated into the modern sediment body despite the presence of benthic fauna.

In accord with lower energy depositional conditions, physical structures in the medial shoal are predominantly planar cross-beds that are not fully preserved. Rather, the 2-D foresets are present as discontiuous beds in association with massive and burrowed beds. The transitional nature of the medial shoal is, therefore, emphasised by the co-preservation of physical and biogenic structures.

At the opposite extreme to the seaward shoal, the landward shoal and the barrier flat units are void of physical structures. Low energy depositional conditions are such that dunes are poorly developed, bioturbation is rife and the sediment profile uniformly massive. The base of the barrier flat deposit does display some poorly preserved physical structures. The presence of crossbeds is interpreted to represent a period during the early formation of the Zone A deposit when relatively high energy depositional conditions prevailed throughout the inlet.

The carbonate and total organic carbon content of intertidal sediments indicates that depositional conditions within the intertidal portion of Zone A in Wapengo do not favour the accumulation of significant amounts of organic material in the sediment column. Two mechanisms are attributed to the low organic content. First, the relatively high energy conditions toward the inlet mouth act to winnow and flush the inlet shoals of low density organic detritus. Second, within the medial and landward portions of the inlet, where tidal currents may not be as effective in transporting organic material, relatively dense populations of infauna consume the vast majority of organic material incorporated in the sediment.

Finally, to preface the discussion in chapter ten, it is useful to consider the value of the suite of characteristics of Zone A sediments beyond being mere sedimentologic descriptors. One gauge of their usefulness is the applicability of each parameter to assisting the interpretation of ancient deposits. Clearly, at the first-order level of identification of general depositional environment it would be prudent to employ all descriptors considered in this chapter. As will be demonstrated in following chapters, the texture, mineralogy, bedform type and internal structure of Zone A sediments are the most distinguishing properties with respect to Zone B and C deposits. Given the more difficult interpretative task of orienting oneself within an ancient Zone A deposit, the most useful parameter is considered to be sedimentary structures. For it is structures that best record the landward change in tidal energy, hence depositional conditions. All other parameters appear insensitive to this subtle, yet important, gradient.

CHAPTER 7: SEDIMENTOLOGY OF THE CENTRAL ESTUARINE FACIES ZONE (ZONE B)

7.1 INTRODUCTION

The sedimentological properties of the three morphostratigraphic units that constitute Zone B, which occupies the central area of wave dominated estuaries between the marine derived deposits of Zone A and the terrestrially derived sediments of Zone C are described in this chapter. The three morphostratigraphic units are the barrier basin, intertidal shoreline and supratidal shoreline. The general nature of depositional conditions in the central estuarine zone are discussed at the outset. Pre-existing process data namely, tidal range, tidal flow velocity, turbidity and salinity, measured from other south coast estuaries are again utilised. One theme to be developed in this chapter is the sediment filtering function played by the central estuarine zone. Thus, the majority of process data and sedimentologic information presented is concerned with the barrier basin morphostratigraphic unit which, in volumetric terms, is the dominant unit in Zone B. Each morphostratigraphic unit is described in terms of the following sedimentological parameters: texture and grain size distribution of the sand fraction; physical and biogenic sedimentary structures; and organic carbon and carbonate content. Data are presented in the subsurface context only. Variation of sediment properties between the margins and centre of the barrier basin are assessed by comparing cores sited along a transect on the fluvial delta. Discussion of bedforms is limited to a description of the general morphology of Zone B units. Information pertaining to the specific character of subaqueous dunes is not available, thereby precluding an analysis of the nature of interaction at the sediment-water interface. However, a partial record of bed topography is provided by primary sedimentary structures preserved in the subsurface.

As identified in the morphometric analysis presented in chapter five, relative variability in the degree of valley infill among estuaries of the study area is quite high. This variability allows for a comparison of the sedimentological characteristics at different stages of Zone B infill. Thus, Wapengo lagoon is taken to represent an estuary that has achieved only limited Zone B filling, whereas Narrawallee is an example of maximum Zone B filling having evolved from estuarine basin to tidal-fluvial/floodplain conditions. Sedimentologic data collected by Hunter (1989) from the barrier basin of Lake Conjola will also be included. Lake Conjola is an example of an estuary at the earliest stages of infill. The comparison will be directed toward determining whether common sedimentologic properties and styles of facies development can be identified in systems that appear to have evolved at different rates. The Late Quaternary evolution of Wapengo and Narrawallee estuaries and the preservation potential of Zone B deposits are addressed in chapters nine and ten, respectively.

7.2 PROCESS FRAMEWORK

Situated between the seaward facies zone (Zone A) in which tides dominate depositional processes and the fluvial facies zone (Zone C) in which fluvial processes prevail, Zone B is subject to a combination of distal tidal and fluvial processes. In effect, Zone B defines the cross-over between tidal and fluvial processes (see Fig. 2.11). Both processes must be considered in an analysis of the sedimentary character of the central estuarine zone. The following description of the process framework for Zone B includes data collected in Lake Illawarra, Wagonga Inlet, Lake Merimbula, Pambula Lake and Burrill Lake. These data are related to similar environmental conditions observed at Wapengo and Narrawallee.

7.2.1 Tidal range and velocity

(a) Tidal Range: The trend in the behaviour of tides within the seaward zone of N.S.W. estuaries, described in the chapter six, continues within the central zone. That is, tidal range in the barrier basin is further reduced from the range at the estuary mouth. Figure 7.1 shows tidal curves as measured on the inner (landward) shore of the barrier basin of Lake Illawarra plotted with ocean tidal curves. Tideboard locations are shown in Figure 6.1. Water levels on the distal lake shore fluctuated by a mere five centimetres, 95.8% less than the spring tidal ocean range.

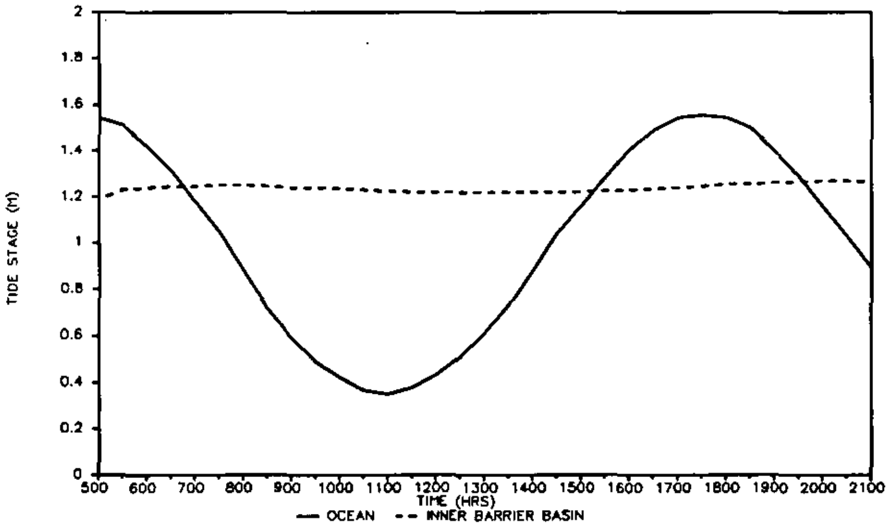


Figure 7.1: Lake Illawarra tidal curves, 2 May 1974. Tideboard locations are: Ocean- Port Kembla; Basin- Power station on western (distal) lake shore.(Source: N.S.W. Public Works Department, 1982).

Tidal measurements in Wagonga and Merimbula barrier basins were taken at less distal locations and recorded greater tidal oscillations than Illawarra. In Wagonga Inlet a 60cm tidal range, 52.7% less than ocean range, was measured midway along the basin shoreline (Fig. 7.2). In Lake Merimbula a range of 56.5cm, representing a 61% reduction from ocean tidal range, was measured from a tideboard located within 500m of the inner edge of the flood-tidal delta (Fig. 7.3).

It is apparent, therefore, from these three similarly configured estuaries that tidal range in broad barrier basins decreases markedly, to the point of being negligible, with increasing distance from the estuary inlet. Field observations of tidal fluctuations in water levels in the Wapengo Lagoon barrier basin indicated a tidal range of less than 0.5m, suggesting that tides in Wapengo behave in a similar fashion to that described for Wagonga and Merimbula estuaries.

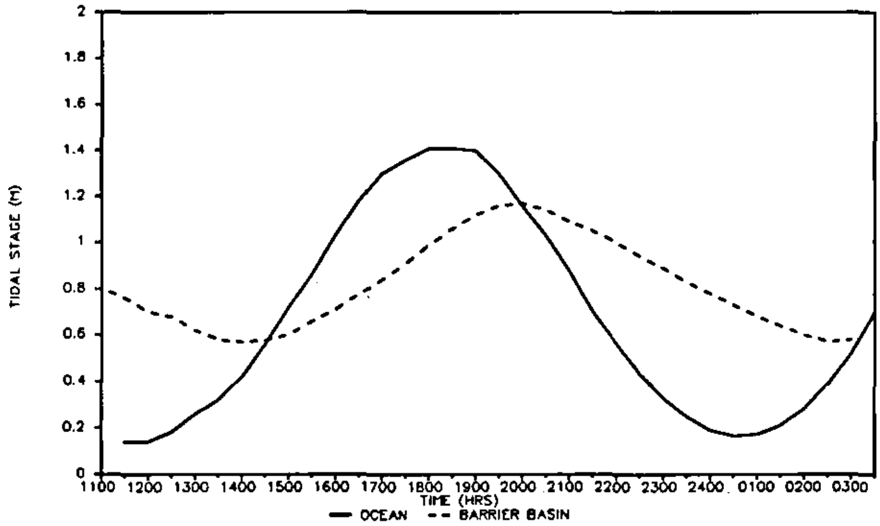


Figure 7.2: Wagonga Inlet tidal curves, 11 May 1976. Tideboard locations are: Ocean: immediately seaward of estuary mouth; Basin- Barlows Bay on northern shore of lake. (Source: N.S.W. Public Works Department, 1978).

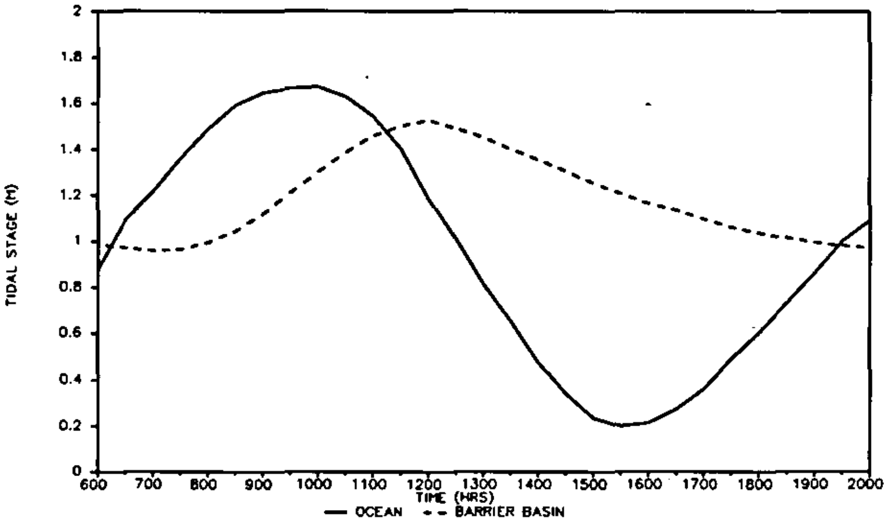


Figure 7.3: Lake Merimbula tidal curves, 8 October 1979. Tideboard locations are: Ocean- Fort Denison; Basin- northern lake shore close to inner edge of flood-tidal delta. (Source: N.S.W. Public Works Department, 1983).

It was shown in chapter six that differences in tidal range between the open coast and the entrance channel in Pambula estuary are notably less than in Lakes Illawarra, Wagonga and Merimbula. The trend is continued for Zone B. Despite the presence of a relatively large barrier basin, tidal range on the distal shore of Pambula Lake was measured as 1.2m, only 25% less than ocean range (Fig. 7.4). The narrow dimensions of the entrance to Pambula estuary and the paucity of tidal delta shoals were invoked previously to account for the comparatively large tidal range within the entrance. The basin also lacks sizable sand shoals to attenuate the tidal prism. Consequently, tidal exchange throughout the estuary is efficient and fluctuations in basin water levels are of similar magnitude to those of the open coast.

In the context of tidal conditions within Zone A, Lake Pambula was taken as analogous to an estuary at an advanced stage of infill, such as Narrawallee. It is not intended that the analogy be extended to Zone B for infilled estuaries. In such systems Zone B sediments are buried and therefore represent an evolutionary stage characterised by very different process conditions to those operating at present. The behaviour of tidal waters in Zone B of Pambula estuary are regarded as atypical for the N.S.W. south coast.

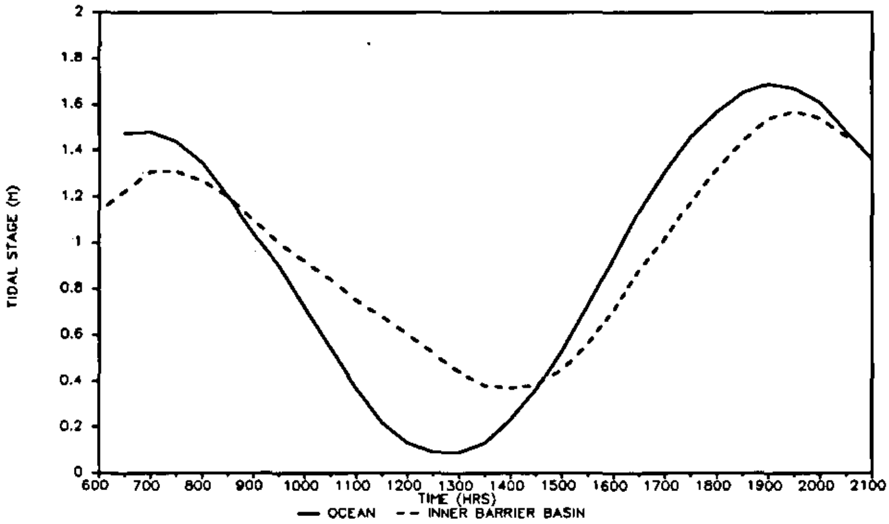


Figure 7.4: Pambula Lake tidal curves, 4 October 1979. Tideboard locations are: Ocean- Fort Denison; Basin- mouth of Pambula River on northwestern lake shore. (Source: N.S.W. Public Works Department, in prep.).

(b) Tidal Flow Velocity: Measurements of tidal currents flowing into south coast barrier basins for which data are accessible have not been made. The best available substitute are data collected at the landward end of the Lake Illawarra flood-tidal delta and at the mouth of the Pambula river which flows into Lake Pambula. Figure 6.7 shows the longitudinal velocity profile for the Lake Illawarra tidal inlet channel. Extrapolating the distal end of this profile indicates that tide generated currents in the barrier basin probably flow at an average *maximum* rate of 0.20m/sec.

Flow velocities at the landward end of the barrier basin, as monitored in Pambula Lake, are up to an order of magnitude less than the estimated velocities at the seaward end of Lake Illawarra. Figure 7.5 illustrates variations in tidal flow velocity throughout a 12 hour tidal cycle for four sites across the mouth of the Pambula River channel. Peak velocities are in the range 0.13-0.17m/sec and limited to a two hour period. For the remaining 10 hours of metering, velocities were below 0.10m/sec and as low as 0.01m/sec. As stated earlier, the tidal characteristics of Pambula are considered anomalous among estuaries of the study area. Since tidal range at the inner edge of the Pambula barrier basin is considerably larger than other south coast estuaries it is probable that tidal flow velocities are also exaggerated. In sum, it is within reason to describe tidal flow conditions in Zone B as very low energy verging on quiescent.

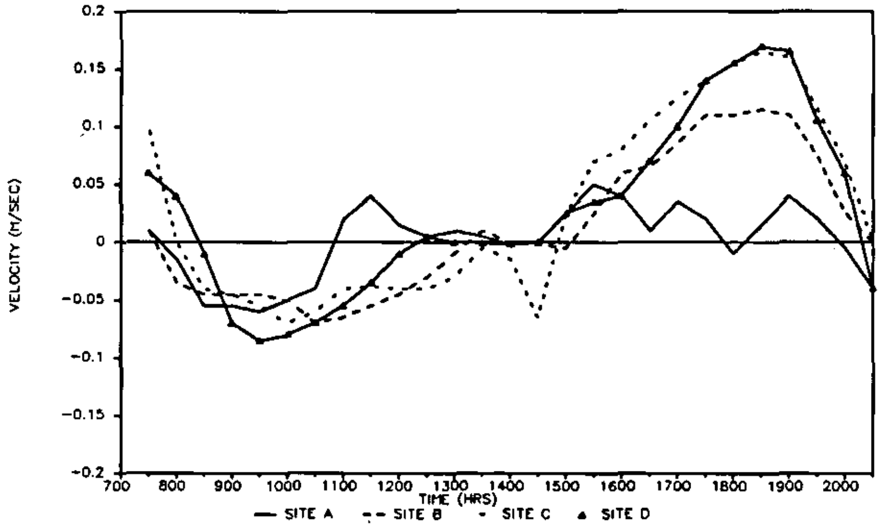


Figure 7.5: Pambula River mouth tidal flow velocities, 4 October 1979. Metering sites are: A- left side of channel; B & C- mid channel; D- right side of channel. (Source: N.S.W. Public Works Department, in prep.).

7.2.2 Fluvial currents

During periods of low fluvial discharge, river generated flow velocities in Zone B are negligible and, as suggested by the Pambula River data (Fig. 7.5), overwhelmed by tidal flows. However, during extreme river flood events the barrier basin can be strongly influenced by fluvial flow. Unfortunately, fluvial discharge data representing 'average' and high flow periods are scarce, particularly for south coast rivers. Long term monitoring has only been carried out on the larger rivers, such as the Bega and Towamba Rivers where gauging stations are located in the headwaters (Kidd, 1978). Data representing river generated flow in the barrier basin are simply not available.

As substitute for river discharge data, turbidity and salinity data are presented for Burrill Lake estuary, located 12km south of Narrawallee Inlet. Burrill Lake was selected here because it provides an excellent example of the nature of fluvial influence upon the barrier basin environment. These data were collected as part of a C.S.I.R.O. study of eight south coast estuaries during the 1970's (Anderson and Storey, 1981). It should be noted that turbidity was measured using a secchi disc which expresses suspended sediment in terms of water clarity and is therefore a second-order measure. Figure 7.6 shows the relationship between water depth and maximum depth of secchi disc visibility for low and high river discharge conditions in Burrill Lake. The same data are plotted against distance from the estuary mouth in Figure 7.7. Relative river discharge is inferred from records of monthly rainfall totals at Kioloa, the nearest gauging station. Thus, a low flow period occurred during July 1977 when six millimetres fell over a four day period (Bureau of Meteorology, 1984).

Rainfall at Kioloa for the high discharge period was 231mm over 11 days in May 1978 (Bureau of Meteorology, 1984).

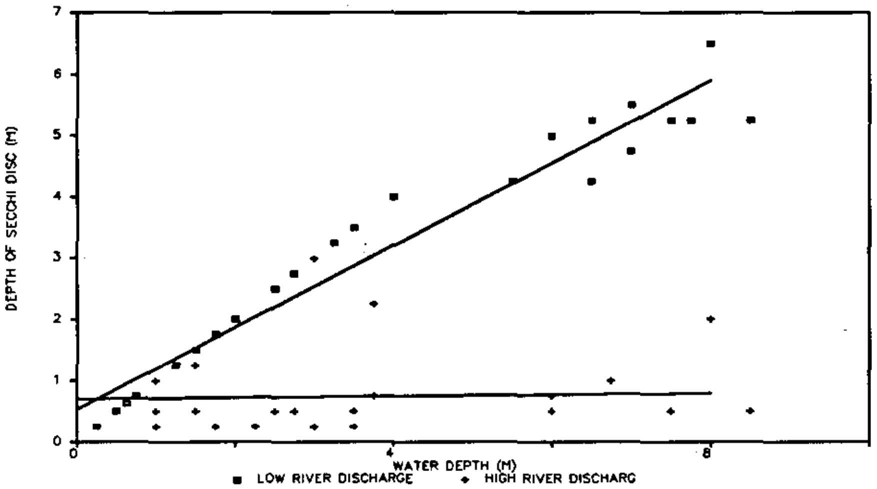


Figure 7.6: Turbidity in Burrill Lake during low river discharge (23/7/77) and high river discharge (23/5/78) determined by secchi disc measurements. (Source: Anderson and Storey, 1981).

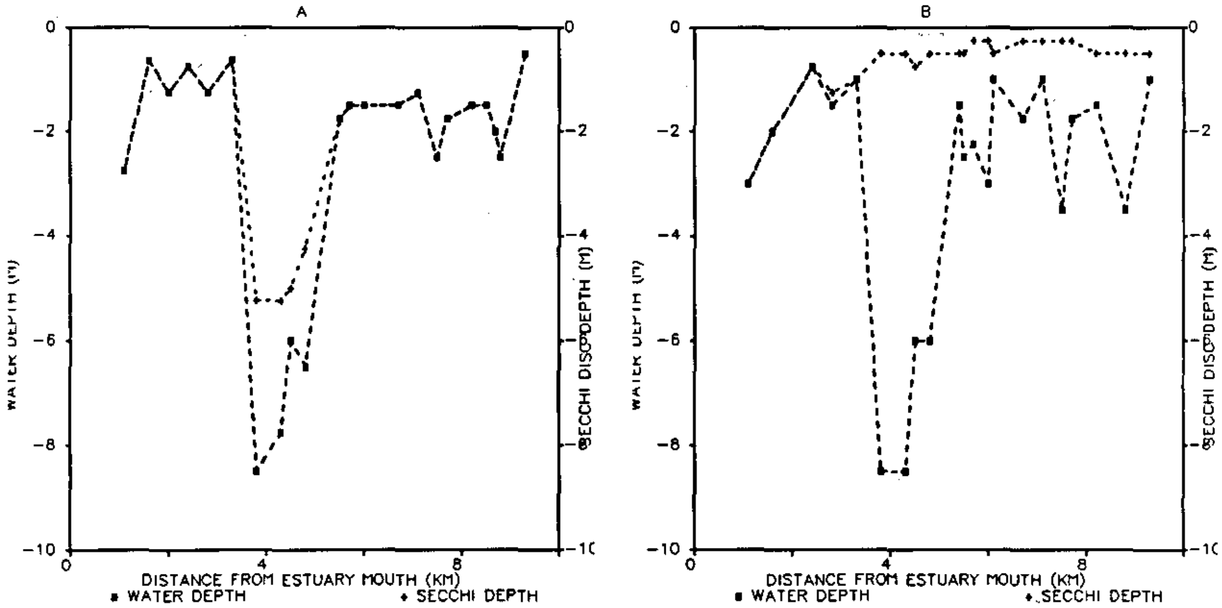


Figure 7.7: Water depth and secchi disc visibility versus distance from estuary mouth during, (a) low river discharge and, (b) high river discharge in Burrill Lake. (Source: Anderson and Story, 1981).

There is close agreement between water depth and depth of secchi disc visibility during low river discharge, indicating low to negligible suspended sediment concentrations throughout the length of the estuary (Fig. 7.6 and 7.7a). In contrast, within the barrier basin and in the vicinity of the river mouth (3.5-5.7km from estuary mouth), the maximum depth of secchi disc visibility (0.25-0.75m) during the period of high river discharge was significantly less than water depth (Fig. 7.6 and 7.7b). Disc depths within the tidal inlet (Zone A), however, were close to or equal to water depths. The conclusion to be drawn from these observations is that river floods initiate transport of significant volumes of suspended sediment into the barrier basin but not into the tidal inlet of Burrill Lake.

Salinity data provide further evidence of a direct relationship between fluvial discharge and suspended sediment concentrations in Burrill Lake. Salinity profiles at the water surface and at 1-2m depth in Burrill Lake are plotted for the same low and high river discharge periods in Figure 7.8. Two important points are evident from the salinity profiles.

First, during high river discharge periods surface salinity in the vicinity of the river mouth and in the barrier basin is greatly reduced, whereas during low discharge the basin is well mixed. Salinity values in the range 1.8-10.3 parts per thousand (ppt) were measured at stations located 3.5-5.7km from the estuary mouth on 23/5/78 (Fig. 7.8a). By comparison, during the low river flow conditions of 23/7/77, salinities in the range 27.4-29.7 ppt were recorded both at the surface and at depth, indicating thorough mixing of lagoon waters (Fig. 7.8b). Mixing and circulation effects are also evident in the Burill tidal entrance channel, located between 0km and 3.5km from the mouth (Fig. 7.8a). Surface salinities close to that of sea-water (25-32 ppt) were recorded on 23/5/78, indicating minimal incursion of fresh water into the entrance channel during that flood.

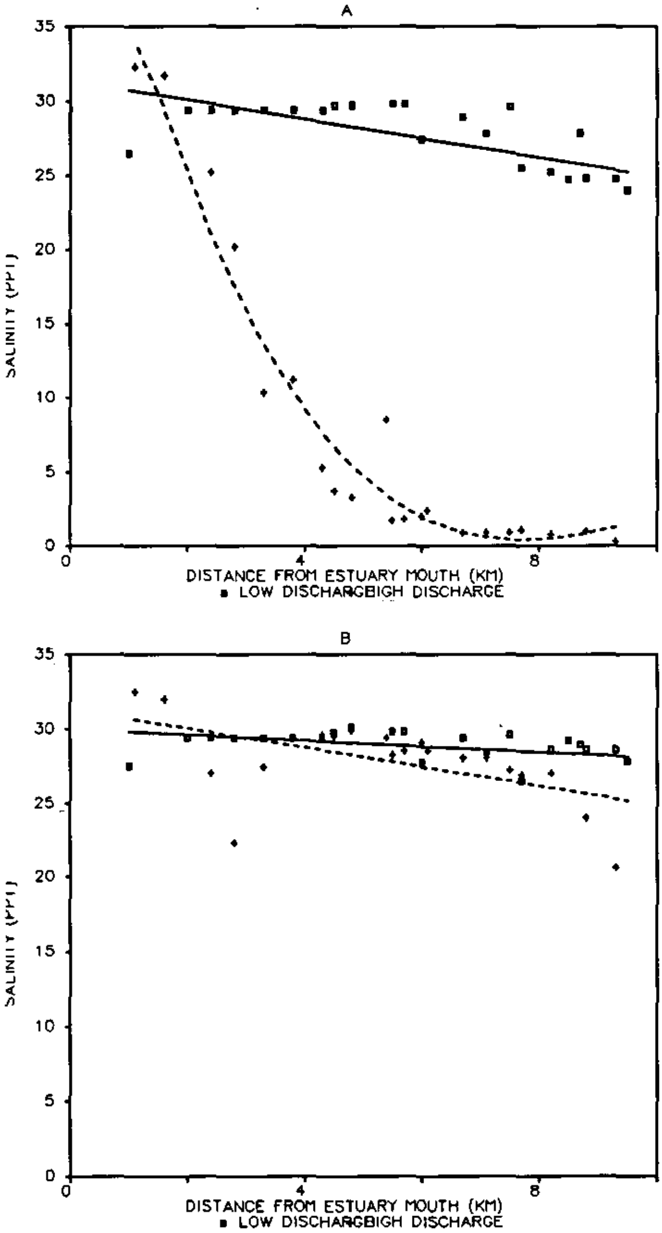


Figure 7.8: Salinity profiles at (a) the water surface and (b) at 1-2m water depth in Burrill Lake during low river discharge on 23/7/77 (solid line) and high river discharge on 23/5/78 (dashed line). (Source: Anderson and Storey, 1981).

The second point regarding fresh water influences in the barrier basin is that basin waters are strongly stratified in Burrill Lake during high river discharge. That is, low salinity waters are confined to the upper metre of the water column. Below this depth, salinity values are only slightly depressed and within the range for low river discharge periods. For example, at a depth of -1m near the river mouth, a salinity value of 28.5 ppt was registered. (Fig. 7.8b).

The observations of variable salinity levels in Burrill Lake are consistent with those made in other south coast estuaries. In Lake Illawarra, for example, Ellis et al. (1977) report that mixing and circulation of lake waters produced salinity variations of no more than 3 ppt in both lateral and vertical dimensions. However, Gibbs (1986) recorded distinct salinity stratification of the lagoon waters after major river flooding. Likewise, in Mallacoota Inlet, Reinson (1973, 1977) observed a poorly stratified to well mixed water column during low river discharge and a well stratified (two-layer flow) water column during above average river discharge. In addition, the configuration of the floor of the Mallacoota barrier basin is such that lenses of saline water are trapped in topographic lows (15-20m water depth) and remain undisturbed even during floods (Reinson, 1977).

The maintainance of high salinity levels at depth within the barrier basin is interpreted to play a major role in controlling depositional conditions in the basin. That is, fresh to brackish sediment laden river waters flowing as a surface layer into the basin will ultimately be diluted in the saline basin waters allowing suspended fines to flocculate and settle out. Low turbidity in tidal inlet waters suggests that the vast majority of the suspended load is deposited within the low energy environment of the basin. In this way, the barrier basin acts as a filter of terrestrially derived sediment, provided the accretionary surface remains below the depth of wave reworking (Nichols, 1989). The role of waves in the barrier basin is considered in the next section.

While the magnitude of high discharge river flows is not known in absolute terms, temporal and spatial trends in salinity and turbidity provide an indication of the potential impact of variable river flow upon depositional conditions in the barrier basin. For example, flooding is also often associated with depletion of dissolved oxygen near the sediment-water interface (Yassini and Jones, 1989). Variations in the oxygen content of bottom waters will influence oxidation-reduction reactions in the basin sediments and in turn induce stressful habitat conditions for estuary fauna and flora. The implications of habitat stress in terms of faunal abundance and diversity and relationships with physical properties of the sediment are discussed in section 7.5.

7.2.3 Wind waves

Wind generated waves have the potential to be an effective sediment transport mechanism in barrier basin and basin shoreline units of Zone B. The effectiveness of wave reworking depends upon the size, depth and orientation of a basin water body (Orme, 1973; Nichols, 1989). Roy and Peat (1976, Appendix 2) graphically depicted a positive relationship between lake water depth and maximum fetch for 12 N.S.W. central and south coast estuaries. Statistically, the correlation between depth and fetch, as measured by Roy and Peat (1976), is moderately stong with r^2=0.47. In general terms, the relationship indicates that the greater the fetch the deeper the lake basin.

The fetch-depth relationship was interpreted as an expression of the effective depth of wave reworking, termed the "threshold depth" (Roy and Peat, 1976). Maintenance of the threshold depth requires an open tidal inlet through which sediment suspended by wind waves is flushed. If an estuary is closed to tidal exchange, reworked sediment is trapped and the basin floor will aggrade to the depth of wave base (Roy and Peat, 1976). Shoaling is usually concentrated along the basin shore, leading to progradation of shoreline deposits into the basin. Progradation in turn reduces the available fetch and consequently the relative size and energy of wind generated waves is diminished. Bird (1967a,b) recognised this process when he described the segmentation of the extensive coastal lakes of the Gippsland region into smaller water bodies, separated by jetties of wave reworked sediment. Orme (1973) documented the same process in barrier lagoons along the Zululand coast of South Africa, noting that segmentation is best developed in tideless lagoons, wherein tidal currents do not disturb spit construction.

Segmentation is not evident in the bedrock controlled estuaries of the N.S.W. south coast, presumably because the fetch required to generate the necessary wave power is not available. In addition, the majority of estuaries have open entrances, thereby allowing tidal currents to impede spit growth in basins. What is evident in estuaries of the study area, is the winnowing effect of wave reworking upon basin shoreline surface sediments. Field observations of fairweather wave activity in the Wapengo barrier basin indicate that the largest waves are generated by south to southeast winds. Wave height in the centre of the basin varies between 0.5m and 1.0m and waves arriving at the northern shoreline are approximately 0.5m high. Waves reaching the eastern and western shorelines during southerly wind activity were no larger than 0.25m high. Presumably, waves generated during storm events are considerably larger and more powerful than those observed during 'average' wind activity. It will be shown in section 7.4 that intertidal and supratidal shoreline deposits are typically coarser than the adjacent and underlying barrier basin sediments and that waves are the primary mechanism for the contrast in sediment texture.

7.3 SEDIMENTOLOGIC PROPERTIES OF THE BARRIER BASIN UNIT

7.3.1 Morphology

The planform shape, valley depth and valley profile of the barrier basin, indeed of the whole estuary, is determined by antecedent topography (Roy, 1984a; Belknap and Kraft, 1985). In the case of estuaries of the N.S.W. south coast, antecedent topography is an expression of multiple episodes of fluvial scouring during Quaternary sea-level lowstands and the partial preservation of late Pleistocene fluvial and estuarine deposits in drowned coastal valleys.

In planform, barrier basins that have experienced limited sedimentation and which lack Pleistocene remnants appear irregular with numerous small embayments that mimic the incised valley topography. One example of such a basin is Lake Conjola, an estuary immediately to the north of Narrawallee (Fig. 1.4). Bottom profiles reconstructed from seismic surveys in L. Conjola indicate that the floor of the barrier basin, at a water depth of 5-10m, is uniformly flat and lacking significant dune bedforms (Hunter, 1989). The seismic response of basin sediments was poor but extrapolation of valley sides suggests that the bedrock valley is roughly v-shaped, up to 30m deep and with valley side gradients estimated by Hunter (1989) to range between 0.02 and 0.07.

Barrier basins that are partially infilled and which possess Pleistocene deposits preserved below sea-level are characterised by a smooth shoreline, giving the basin an oval shape. The Wapengo Lagoon barrier basin is a good example. The Wapengo basin is three to four metres deep in the centre but shoals significantly toward the shore. It is therefore presumed that the basin bed is gently sloping, probably dish shaped, and also bedform deficient.

7.3.2 Sediment texture and mineralogy

Wapengo Lagoon: For logistical reasons, vibracore sites in Wapengo Lagoon were confined to intertidal and supratidal areas. Direct core samples from the subtidal basin bed were not collected in Wapengo. Sampling of barrier basin sediments was therefore accomplished by taking cores from the distal portion of the fluvial delta that has prograded across the basin floor. Subtidal basin deposits have been cored in Lake Conjola by Hunter (1989). Textural data produced by Hunter (1989) will be included here for comparative purposes.

Vibracore VC1, was taken from next to the fluvial channel on the eastern levee bank of the supratidal fluvial delta at a point considered close to the predicted palaeo-shoreline of the barrier basin in the early stages of delta growth (Fig. 4.5). The basal unit in the core is 1.5m thick and comprises sediments considered to be consistent with a low energy barrier basin depositional environment. That is, sediments are uniformly fine-grained dominated by silty muds with a minor fraction of fine sands. A gradual coarsening upward trend is evident from the plot of gross textural properties (Fig. 7.9). Thus, at the base of the unit sand comprises only 13% of sample weight, while silt (54%) and clay

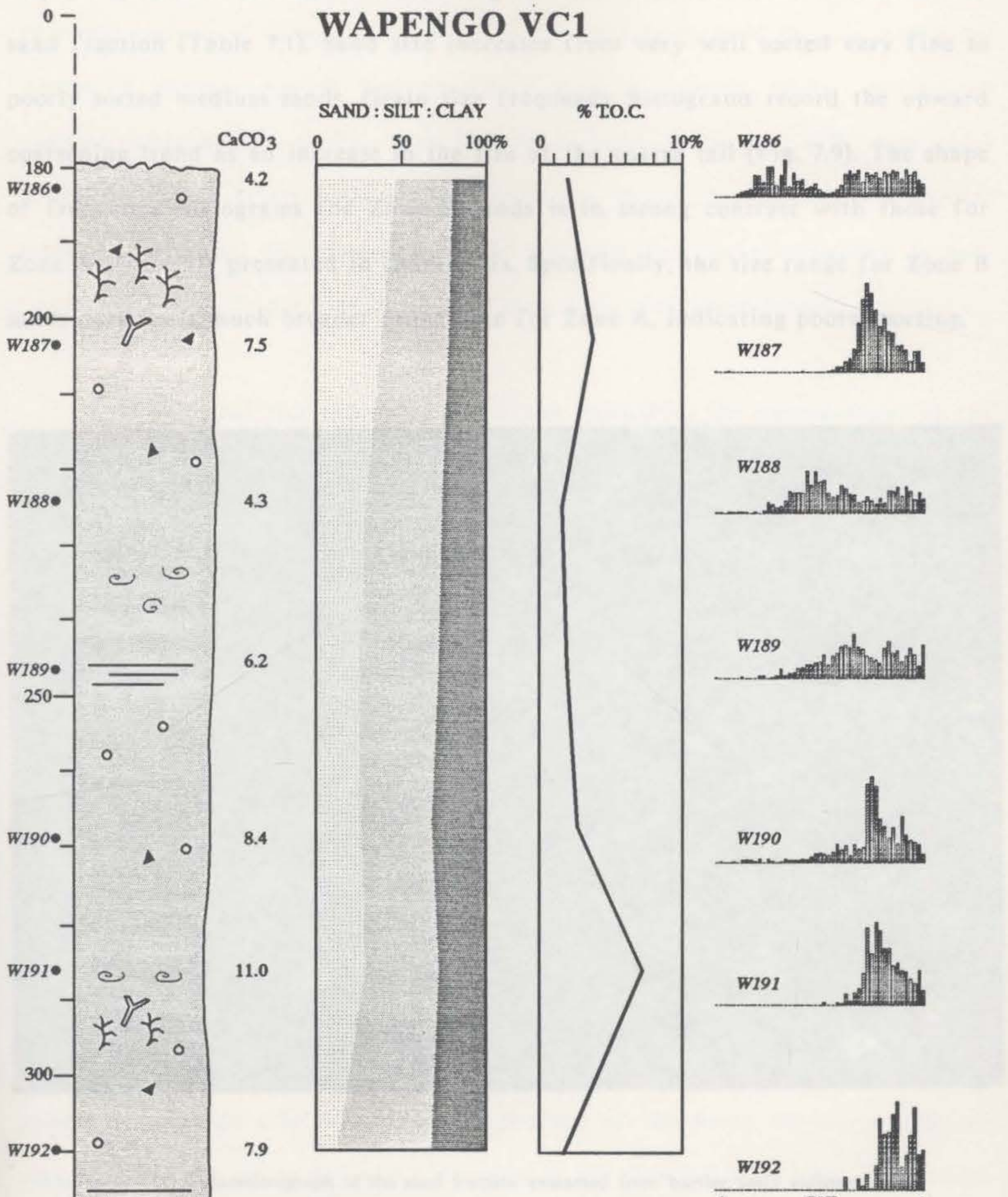


Figure 7.9: Wapengo core VC1 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

(33%) dominate. Sand increases up-sequence to 47% and, conversely silt (33%) and clay (19%) content decrease. A coarsening upward trend is also evident within the sand fraction (Table 7.1). Sand size increases from very well sorted very fine to poorly sorted medium sands. Grain size frequency histograms record the upward coarsening trend as an increase in the size of the coarse tail (Fig. 7.9). The shape of frequency histograms for Zone B sands is in strong contrast with those for Zone A sediments presented in chapter six. Specifically, the size range for Zone B sands occupies a much broader range than for Zone A, indicating poorer sorting.

Figure 7.10: Photomicrograph of the sand fraction extracted from barrier basin sediments, core VC7, 1.4m. Magnification= 22x

Zone B sands are notably more texturally diverse than those of Zone A, but also they are composed of a less mature mineralogical suite. Figure 7.10 shows a photomicrograph of sample sands from the barrier basin unit. Quartz is still the dominant mineral but is less abundant than in marine sands, making up approximately 80-95% (Kidd, 1978). Lithics (3-15%), feldspar (2-15%) and micas (2-5%) are all in relative abundance, indicating recent liberation of the clastics from source rocks. The diversity of the minerals and the sub-rounded to sub-angular shape of sand grains emphasises their first generation nature.

Core VC2 was also collected from a site located on the eastern flank of the supratidal fluvial delta but 250m away from the present fluvial channel (Fig. 4.5). Barrier basin deposits are represented in the core by a 3.0m thick basal unit of silty muds with thin (<5cm) interbeds of fine silty sands (Fig. 7.11). Overall, the unit coarsens upwards with sand content increasing up-sequence and the gross textural character is very similar to VC1. Silt is the dominant texture through much of the deposit, comprising between 40% and 60% of sample weight. Clay decreases upward from 36% to 20% and sand increases from 6% to 50% at the top of the unit. Sandy interbeds are best defined toward the base of the core and are recorded by sand contents of between 20% and 35% (Fig. 7.11). Within the sand fraction, mean grain size increases up-core from well sorted very fine grains to moderately sorted fine sands (Table 7.1). Sand interbeds are slightly coarser than sands in the graded beds (Fig 7.11). Notable trends in grain size frequency histograms include a leftward shift in position of the mode, an increase in the magnitude of the coarse tail and a decrease in the fine tail (Fig. 7.11). The remote location of VC2 relative to the present fluvial channel is reflected by smaller coarse tails than at the proximal site of VC1.

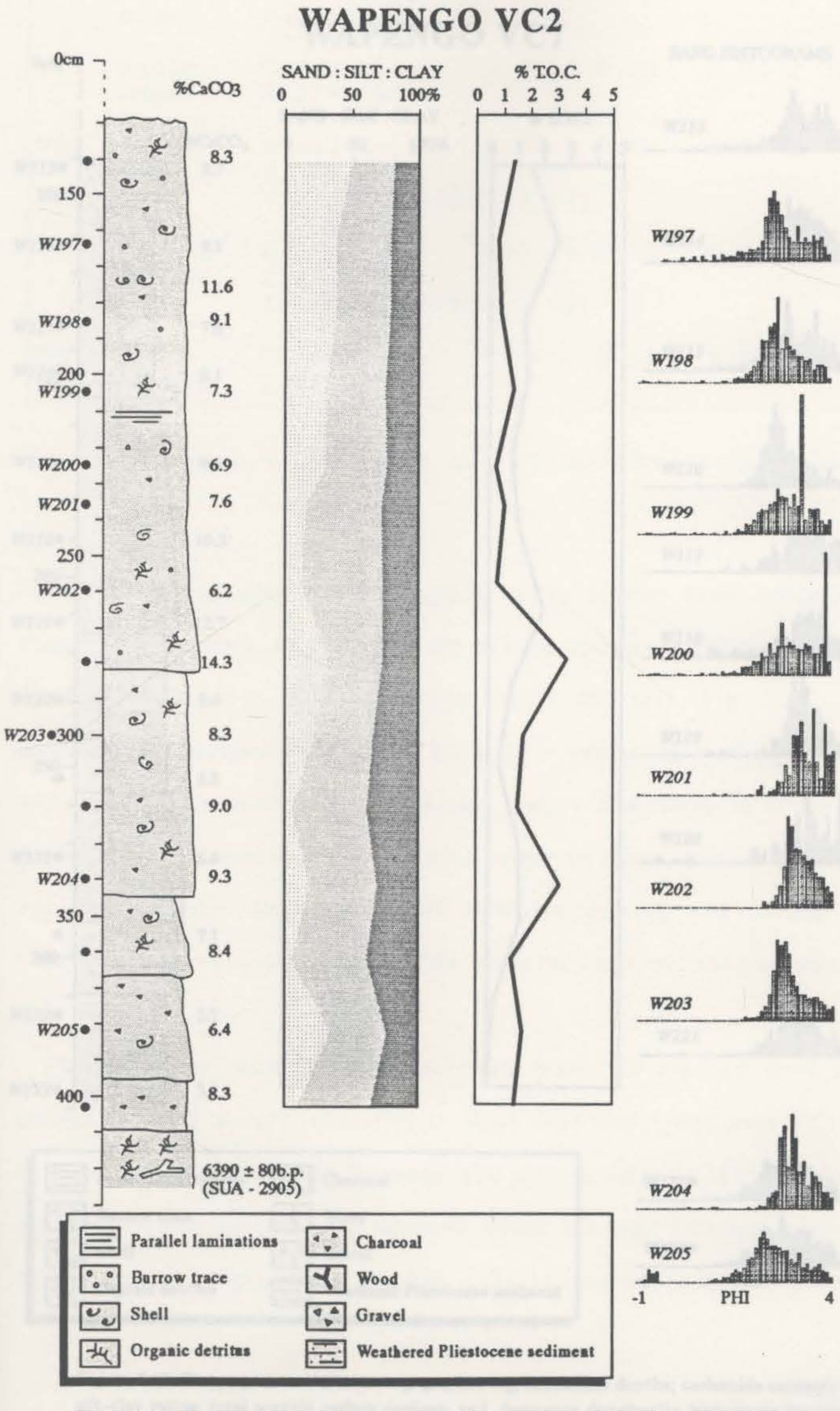


Figure 7.11: Wapengo core VC2 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

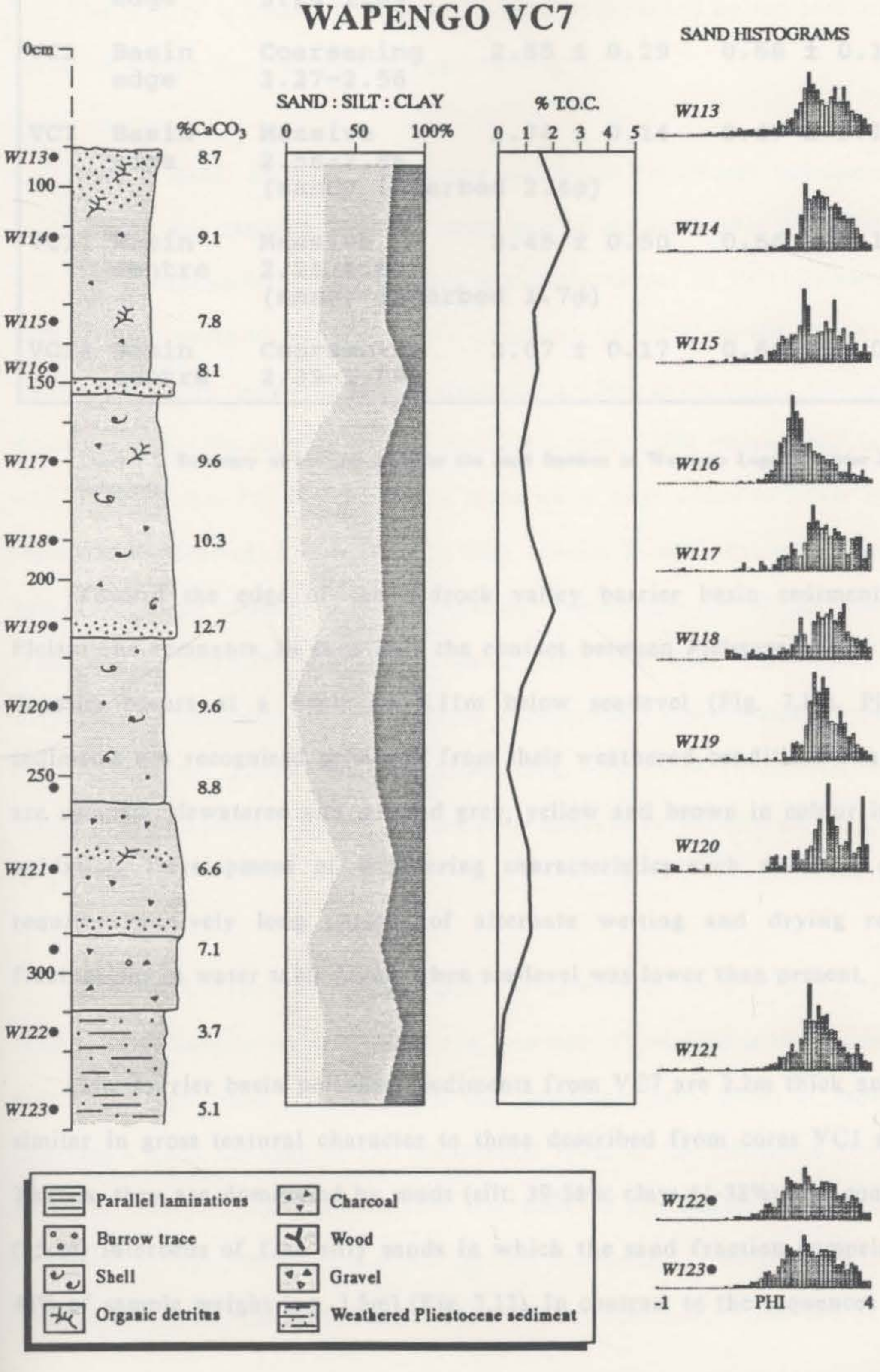


Figure 7.12: Wapengo core VC7 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

CORE	LOCATION	VERTICAL TREND (PHI RANGE)	MEAN SIZE PHI ±1σ	MEAN SORTING PHI ±1σ	N
VC1	Basin edge	Coarsening 3.23-1.89	2.56 ± 0.49	0.75 ± 0.33	7
VC2	Basin edge	Coarsening 3.27-2.56	2.85 ± 0.29	0.58 ± 0.18	9
VC7	Basin edge	Massive 2.58-2.86 (sandy interbed 2.4ϕ)	2.74 ± 0.14	0.67 ± 0.12	9
VC11	Basin centre	Massive 2.25-2.87 (sandy interbed 1.7ϕ)	2.45 ± 0.50	0.66 ± 0.12	5
VC12	Basin centre	Coarsening 2.39-1.89	2.07 ± 0.17	0.66 ± 0.09	7

Table 7.1: Summary of textural data for the sand fraction in Wapengo Lagoon barrier basin sediments.

Toward the edge of the bedrock valley barrier basin sediments overlie Pleistocene remnants. In core VC7 the contact between Pleistocene and Holocene deposits occurs at a depth of 3.11m below sea-level (Fig. 7.12). Pleistocene sediments are recognised primarily from their weathered condition. That is, they are compact, dewatered and mottled grey, yellow and brown in colour indicating oxidation. Development of weathering characteristics such as those described requires relatively long periods of alternate wetting and drying related to fluctuations in water table levels when sea-level was lower than present.

The barrier basin periphery sediments from VC7 are 2.2m thick and closely similar in gross textural character to those described from cores VC1 and VC2. That is, they are dominated by muds (silt: 39-58%; clay: 11-38%) and contain thin (<5cm) interbeds of fine silty sands in which the sand fraction comprises up to 44% of sample weight (e.g. 1.5m) (Fig. 7.12). In contrast to the sequences analysed from VC1 and VC2, however, there is no clear vertical trend in grain size within the sand fraction. The sands are moderately sorted and fine throughout (Table 7.1). The lack of a trend in the sand fraction is reflected by the lack significant variation among the frequency histograms (Fig. 7.12).

Barrier basin deposits also overlie weathered Pleistocene sediments in core VC11 which was sampled from the distal end of the supratidal fluvial delta (Fig. 4.5). The Holocene-Pleistocene contact is slightly deeper in VC11 (3.54m) than in VC7 (3.11m), probably because of the proximity of VC11 to the fluvial channel. The barrier basin deposit is characterised by a 1.86m thick bed of uniformly silty muds (e.g. silt: 45%; clay: 46%) with very little sand (8.3%) which itself is fine and well sorted (Table 7.1; Fig. 7.13). The sequence is interrupted at 3.01m by an 8cm thick bed of fine sand in which the clay content is half that of the rest of the bed (23%). Sand content is also substantial toward the top of the unit but silt remains the dominant size grade (sand: 29%; silt: 44%; clay: 27%). Overall, variations in sediment texture describe a coarsening upward pattern that is less distinct than the trends observed in the basin edge cores. Histograms reflect the subtlety of the trend with a slight up-core increase in the size of the coarse tail (Fig. 7.13).

The final Wapengo core included for description here is VC12, which was taken approximately midway along the intertidal fluvial delta that is prograding into the lagoon basin (Fig. 4.5). The core recovered only 2.75m of sediment but provides a good example of the gradational form of the transition from barrier basin to fluvial delta deposits at a site close to the centre of the basin. The transition is represented by a subtle upward coarsening trend over an interval of 1.6m. Sand content increases from 28% to 72%, silt decreases from 49% to 17% and

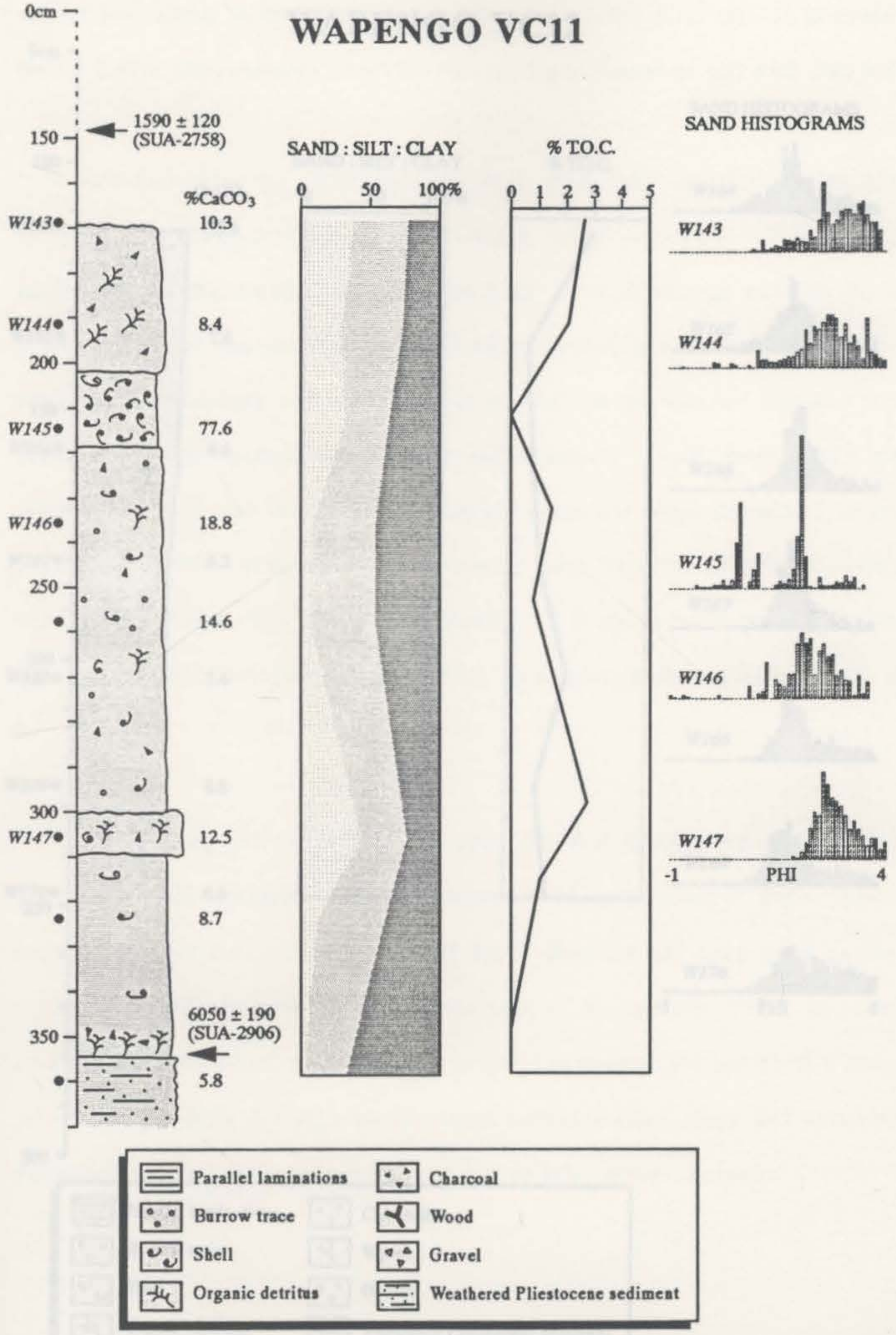


Figure 7.13: Wapengo core VC11 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

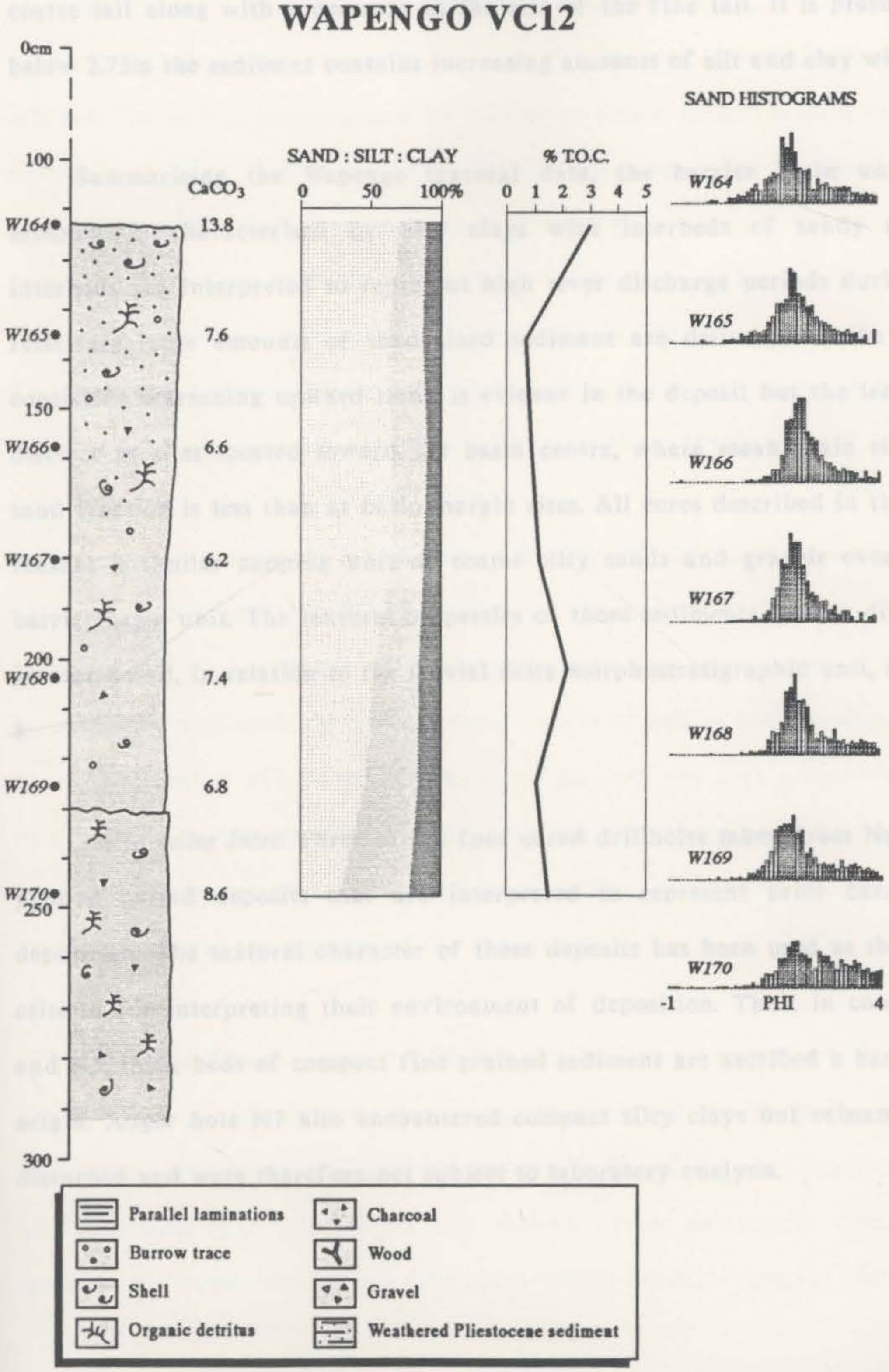


Figure 7.14: Wapengo core VC12 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

clay from 23% to 11% (Fig. 7.14). The mean particle size within the sand fraction also increases up-sequence, from fine to medium. Sand sorting is moderate throughout. Frequency histograms show a marked increase in the size of the coarse tail along with a decrease in the size of the fine tail. It is presumed that below 2.75m the sediment contains increasing amounts of silt and clay with depth.

Summarising the Wapengo textural data, the barrier basin unit, where sampled, is characterised by silty clays with interbeds of sandy silts. The interbeds are interpreted to represent high river discharge periods during which relatively large amounts of sand sized sediment are delivered to the basin. A consistent coarsening upward trend is evident in the deposit but the trend is less distinct at sites located toward the basin centre, where mean grain size of the sand fraction is less than at basin margin sites. All cores described in this section feature a similar capping unit of coarse silty sands and gravels overlying the barrier basin unit. The textural properties of those sediments will be discussed in greater detail, in relation to the fluvial delta morphostratigraphic unit, in chapter 8.

Narrawallee Inlet: Three of the four cored drillholes taken from Narrawallee yielded buried deposits that are interpreted to represent prior barrier basin deposition. The textural character of these deposits has been used as the primary criteria for interpreting their environment of deposition. Thus, in cores N2, N3 and N5, thick beds of compact fine grained sediment are ascribed a barrier basin origin. Auger hole N7 also encountered compact silty clays but subsamples were disturbed and were therefore not subject to laboratory analysis.

Core N2, situated at the landward end of the Narrawallee floodplain represents a depositional site that is proximal to the lower slopes of the estuary catchment (Fig. 4.6). A unit of fine grained sediment was recovered from an interval between 7.4m and 11.1m below the floodplain surface. It should be noted that core recovery was not complete, with the interval between 9.2m and 10.5m missing. The unit is characterised by silty clays with a moderate sand content and interbeds of sand rich clayey silts. In addition, the entire barrier basin unit recovered in N2 has a mottled orange/yellow and brown/grey colour which is indicative of intense oxidation associated with in situ weathering. The age of the Narrawallee barrier basin deposit is discussed in chapter nine, suffice to note here that the weathering characteristics are consistent with those described for Pleistocene deposits elsewhere on the N.S.W coast (Roy, 1980).

Figure 7.15 includes a textural profile for N2. Silt content varies between 36% and 48% within the finest portion of the unit, 7.4-8.5m. Clay constitutes between 24% and 45% of the sediment within the same portion. The sandy interbeds are distinguished by high sand content of 64% to 80% between 8.4m and 8.6m, compared to 15% to 36% in the finer portion. The high proportion of sand in the lower beds is attributed to the proximity of the core site to the sediment source. The fine grained unit in N2 is, therefore, considered representative of deposition toward the margins of the barrier basin.

Of the sediment recovered in N2, the apparent vertical trend is upward fining rather than upward coarsening, as observed in Wapengo. Grain size frequency histograms indicate subtle upward fining of the sand fraction between 8.6m and 8.0m (Fig. 7.15). Grain size decreases from moderately sorted medium sands to moderately sorted very fine sands within the same interval (Table 7.2). A

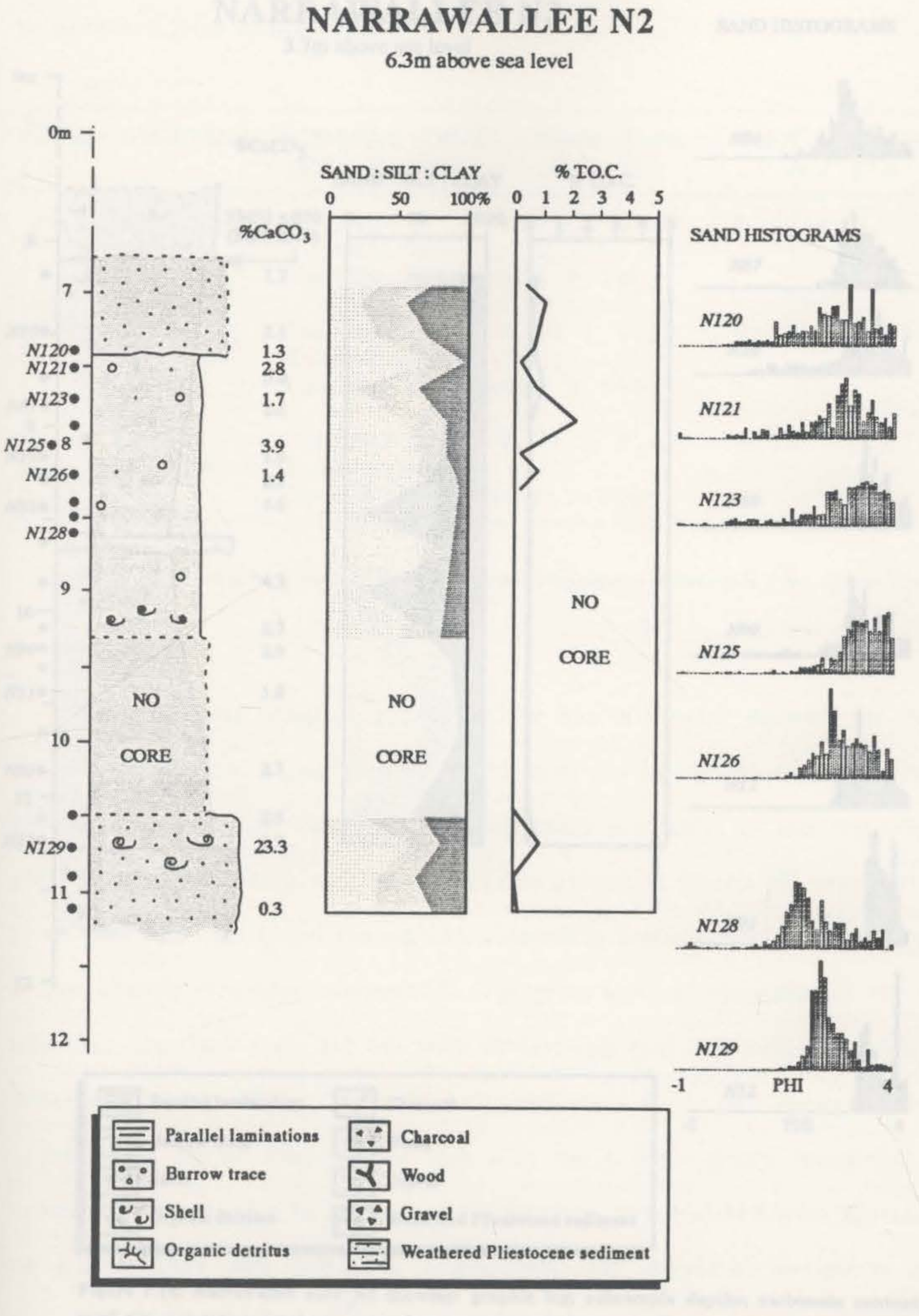


Figure 7.15: Narrawallee core N2 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

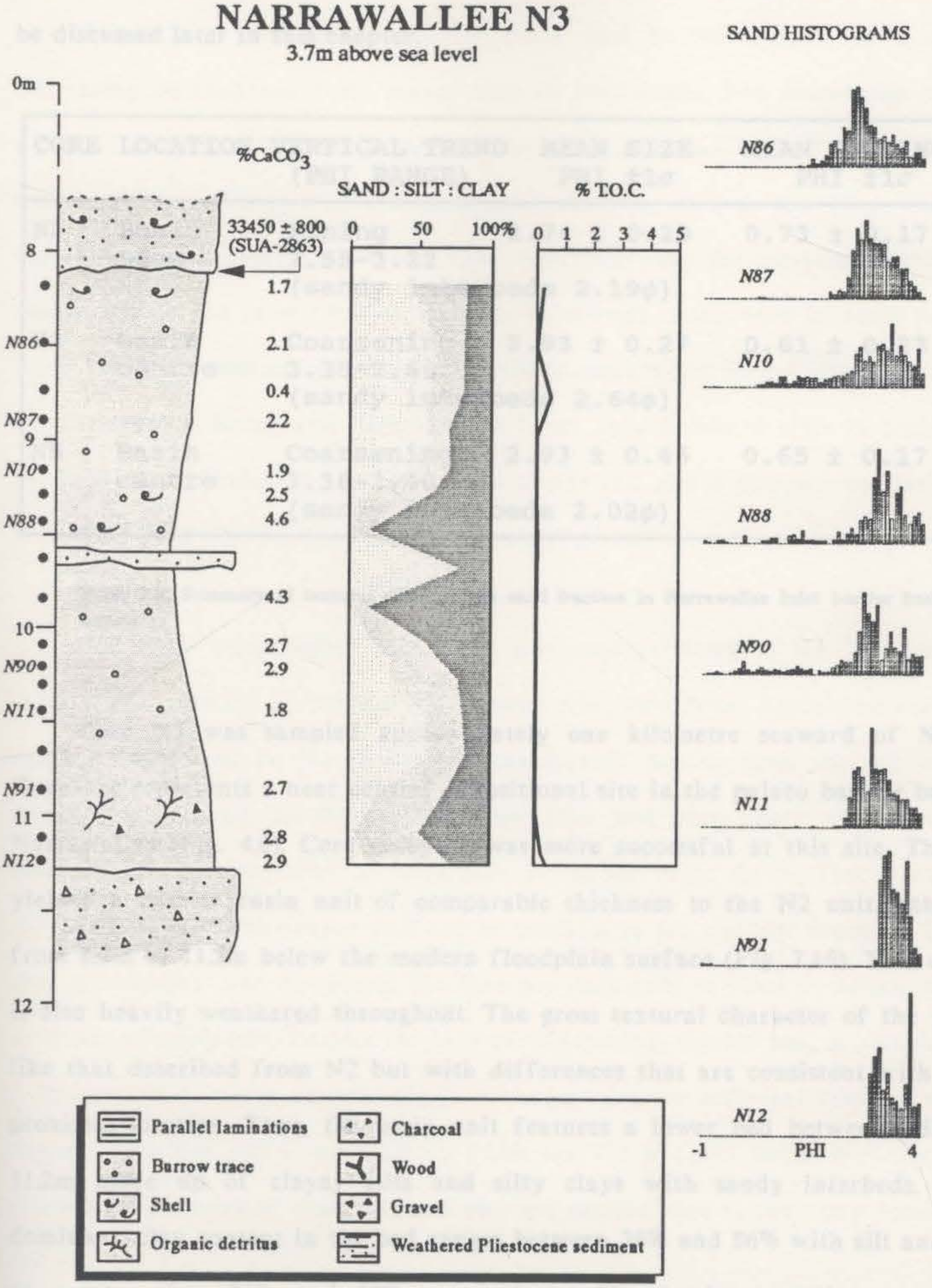


Figure 7.16: Narrawallee core N3 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

second, though less obvious upward fining trend in the sand fraction exists between 7.85m and 7.53m. Histogram plots show a decrease in the coarse tail. The significance of this contrast in textural trends for N2 barrier basin deposits will be discussed later in this chapter.

CORE	LOCATION	VERTICAL TREND (PHI RANGE)	MEAN SIZE PHI ±1σ	MEAN SORTING PHI ±1σ	N
N2	Basin edge	Fining 2.55-3.22 (sandy interbeds 2.19φ)	2.74 ± 0.29	0.73 ± 0.17	10
N3	Basin centre	Coarsening 3.35-2.66 (sandy interbeds 2.64φ)	2.93 ± 0.27	0.61 ± 0.23	9
N5	Basin centre	Coarsening 3.36-2.40 (sandy interbeds 2.02φ)	2.93 ± 0.45	0.65 ± 0.17	9

Table 7.2: Summary of textural data for the sand fraction in Narrawallee Inlet barrier basin sediments.

Core N3 was sampled approximately one kilometre seaward of N2 and therefore represents a near central depositional site in the palaeo barrier basin of Narrawallee (Fig. 4.6). Core recovery was more successful at this site. The core yielded a barrier basin unit of comparable thickness to the N2 unit, extending from 8.2m to 11.2m below the modern floodplain surface (Fig. 7.16). This deposit is also heavily weathered throughout. The gross textural character of the unit is like that described from N2 but with differences that are consistent with a less proximal location. Thus, the basin unit features a lower bed between 9.5m and 11.2m made up of clayey silts and silty clays with sandy interbeds. Where dominant, clay content in the bed ranges between 36% and 86% with silt and sand no greater than 36% and 29%, respectively. Silt dominant sediments contain between 39% and 56% silt and the sandy interbeds comprise 55%-69% sand. There is no clear up-sequence textural trend in this lower bed (Fig. 7.16).

The upper 1.3m of the barrier basin unit in N3 consists of a distinct coarsening upward bed from clayey silts to silty sands. The coarsening trend is uniform between 9.3m and 8.5m wherein sand increases from 16% to 63%, silt decreases from 43% to 17% and clay decreases from 41% to 20% (Fig. 7.16). The top of the basin deposit is slightly finer (silt rich) than the material immediately below. Within the sand fraction there is an overall upsequence increase in mean grain size from well sorted very fine sands to moderately sorted fine sands (Table 7.2). Frequency histograms illustrate the trend by a leftward shift in position of the mode, an increase in the size of the coarse tail and a decrease in size of the fine tail of the distributions over the interval of 10.9-8.5m (Fig. 7.16)

The final Narrawallee core to be discussed in detail is N5. The core was taken 1.3km seaward of N2 and represents a relatively distal depositional site. The barrier basin unit in N5 is buried considerably deeper than the N2 and N3 deposits, occupying an interval between 21m and 28m below the floodplain. Bedrock was encountered at this site at 28.5m (Fig. 7.17). The weathering characteristics of the deeper unit are in contrast to the shallow deposits. That is, they are compact and dewatered but they are dark grey to black in colour with no evidence of oxidation. Despite the lack of weathering, the N5 unit is also ascribed a Pleistocene age (see chapter nine). In terms of gross sediment texture, the N5 deposit does not differ appreciably from the N2 and N3 units. Differences in relative proportions of sand, silt and clay are attributable to the distal location of N5.

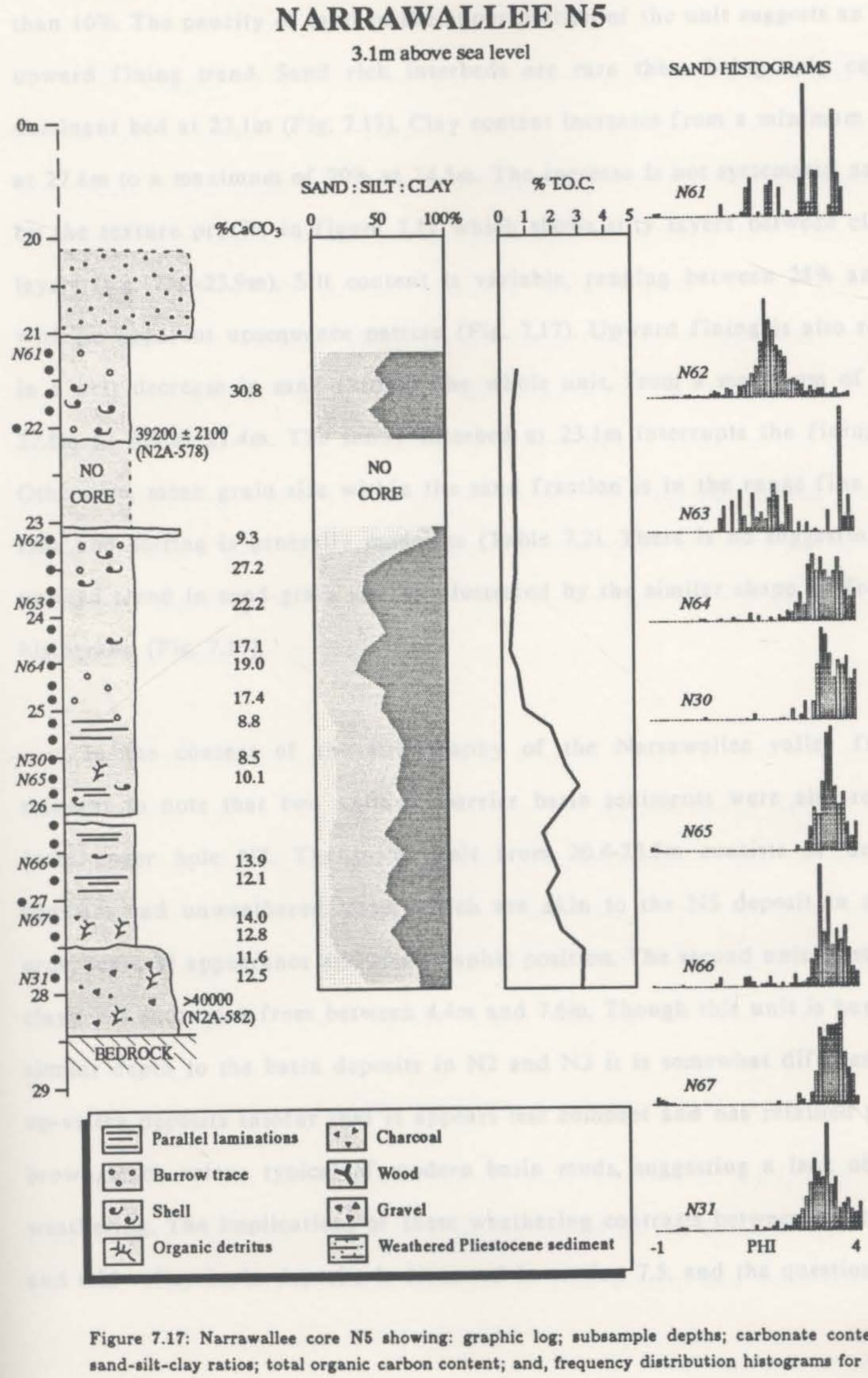


Figure 7.17: Narrawallee core N5 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

The sediments are predominantly clayey silts and silty clays with very low sand content, especially within the upper four metres of the unit where it is less than 10%. The paucity of sand in the upper portion of the unit suggests an overall upward fining trend. Sand rich interbeds are rare there being only one sand dominant bed at 23.1m (Fig. 7.17). Clay content increases from a minimum of 24% at 27.8m to a maximum of 70% at 24.5m. The increase is not systematic, as shown by the texture profile in figure 7.17 which shows silty layers between clay rich layers (e.g. 25.3-25.9m). Silt content is variable, ranging between 28% and 58%, with no apparent upsequence pattern (Fig. 7.17). Upward fining is also recorded in a nett decrease in sand through the whole unit, from a maximum of 38% at 27.8m to 3% at 21.4m. The sandy interbed at 23.1m interrupts the fining trend. Otherwise, mean grain size within the sand fraction is in the range fine to very fine and sorting is generally moderate (Table 7.2). There is no suggestion of an upward trend in sand grain size as illustrated by the similar shape of frequency histograms (Fig. 7.17).

In the context of the stratigraphy of the Narrawallee valley fill it is relevant to note that two units of barrier basin sediments were also recovered from auger hole N7. The lower unit from 20.4-28.5m consists of dewatered compact and unweathered clays, which are akin to the N5 deposit in terms of gross textural appearance and stratigraphic position. The second unit of stiff silty clays was recovered from between 4.4m and 7.6m. Though this unit is buried at a similar depth to the basin deposits in N2 and N3 it is somewhat different to the up-valley deposits insofar that it appears less compact and has retained the dark brown/black colour typical of modern basin muds, suggesting a lack of in situ weathering. The implications of these weathering contrasts between the up-valley and mid-valley basin deposits is discussed in section 7.5, and the questions of the numeric age of the Narrawallee basin deposits and differences in burial depths are addressed in chapter nine.

Lake Conjola: Five vibracores were collected from a transect along the axis of the Lake Conjola barrier basin by Hunter (1989). Gross textural analysis of these cores reveal trends consistent with those described for Wapengo and provide additional data related to sediment properties at depositional sites away from the basin edge. Figure 7.18 presents summary textural plots for the four of the Conjola cores. In essence, these cores reveal Conjola basin sediments to be dominated by mud (silt and clay) but also suggest that the amount of mud is not spatially uniform. That is, barrier basin sediments are finest in the central and deepest area of the basin. In the vicinity of the fluvial delta and the flood tidal delta sediments have a coarse (sand) element that is manifest as upward coarsening trends in cores. Thus, the core transect in Conjola describes both a seaward and landward fining trend.

Core LC1 located near the mouth of Conjola Creek features two coarsening upward cycles within the 1.8m of core (Fig. 7.18 a). The lower cycle is recorded by an increase in sand content from 41% to 66% over 40cm and the upper cycle represented by an increase from 36% to 62% between 1.2m and 0.2m. Within the mud fraction silt sized particles dominate, comprising between 20% and 49% in the samples analysed. Clay content ranges between 14% and 33% (Fig. 7.18a) (Hunter, 1989).

Core LC2 was taken approximately 800m seaward of LC1, and LC3 was sampled a further 750m and represents the centre of the Conjola basin. Between LC2 and LC3 there is a notable decrease in sand content and suppression of the upward coarsening trend (Fig. 7.18 b,c). Thus, in LC2 mud is the dominant texture with sand percentages ranging between 7% and 31%. A subtle coarsening upward trend between 2.4m and 0.8m depth is suggested by an overall increase in sand from 11% to 30% but the trend is not uniform (Fig.7.18 b) (Hunter, 1989). In core LC3 the sand content is low, varying between 2% and 7% with no indication of vertical trends (Fig. 7.18 c). Within the fine fraction of these two cores clay content is dominant in the distal core, increasing from a mean of 32% in LC2 to 51% in LC3 (Fig. 7.18 b,c) (Hunter, 1989).

Finally, core LC5 taken 100m from the inner edge of the Conjola flood tidal delta is characterised by a marked upward coarsening pattern. Sand content increases from 9% at 1.8m to 74% at 0.2m and peaks at 85% at 0.8m (Fig. 7.18 d). In the lower metre of LC5 the clay fraction dominates, comprising between 43% and 70% of the sediment (Hunter, 1989). The coarsening upward trend at this site is readily attributed to proximity to the flood tidal delta as the sands are rounded and quartz dominant, properties indicative of a marine origin.

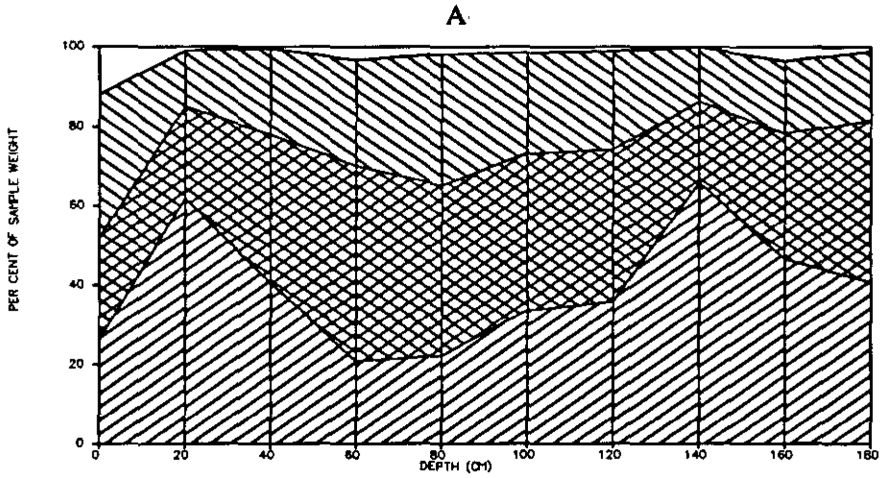


Figure 7.18: caption over page...

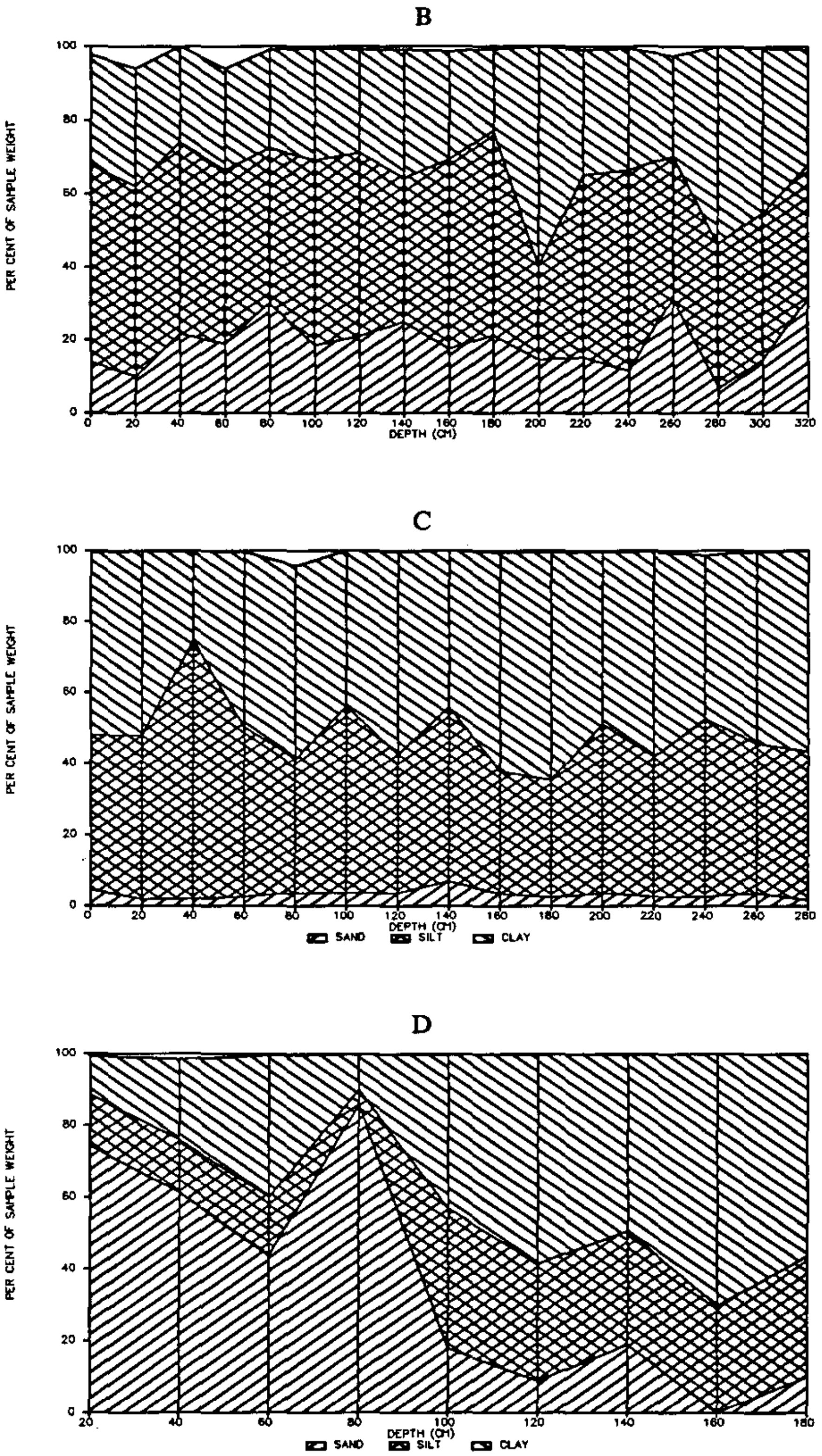


Figure 7.18: Sand-silt-clay profiles for four vibracores from the barrier basin of Lake Conjola. (a) LC1 (b) LC2 (c) LC3 (d) LC5. Note the use of different scales on the axis indicating sample depth (Source: Hunter, 1989).

7.3.3 Sedimentary structures

Physical and biogenic sedimentary structures in fine grained barrier basin sediments are only observable via x-ray radiographs of cores. X-rays of Wapengo Lagoon basin sediments revealed a variety of structural features, including: pin-stripe parallel laminations, wavy beds, horizontal and vertical burrow traces, and massive (structureless) beds. Physical structures are not common and most of the radiographs feature thick (0.5-1.0m) massive beds that are presumably intensely bioturbated. Hunter (1989) described a similar suite of structures from the Lake Conjola cores. Figure 7.19 shows samples of typical sedimentary structures revealed in x-ray prints of Wapengo cores and of high resolution x-rays from the Hawkesbury River estuary valley fill.

The absence of sets of cross-bedding structures from barrier basin sediments is interpreted to reflect the lack of medium or large scale subaqueous dune bedforms on the floor of the basin. Wavy beds may be interpreted to represent small scale dunes (ripples) but even these are rarely evident from x-rays. Physical structures, notably pin-stripe laminae, appear to be more prevalent than biogenic structures toward the base of the Wapengo and Hawkesbury barrier basin deposits. The laminations in Figure 7.19a are preserved at 18.1-18.7m below the floodplain, one to one and a half metres above the base of the basin unit. The remaining upper four metres of the deposit is heavily bioturbated. Hunter (1989) reported a similar trend from Lake Conjola cores. Cores collected from the deepest part of the lake in water depths between 4 and 9.5 metres were noted to record a transition at approximately 2.0m below the lake bed from a dominance of biogenic structures to dominance of physical structures.

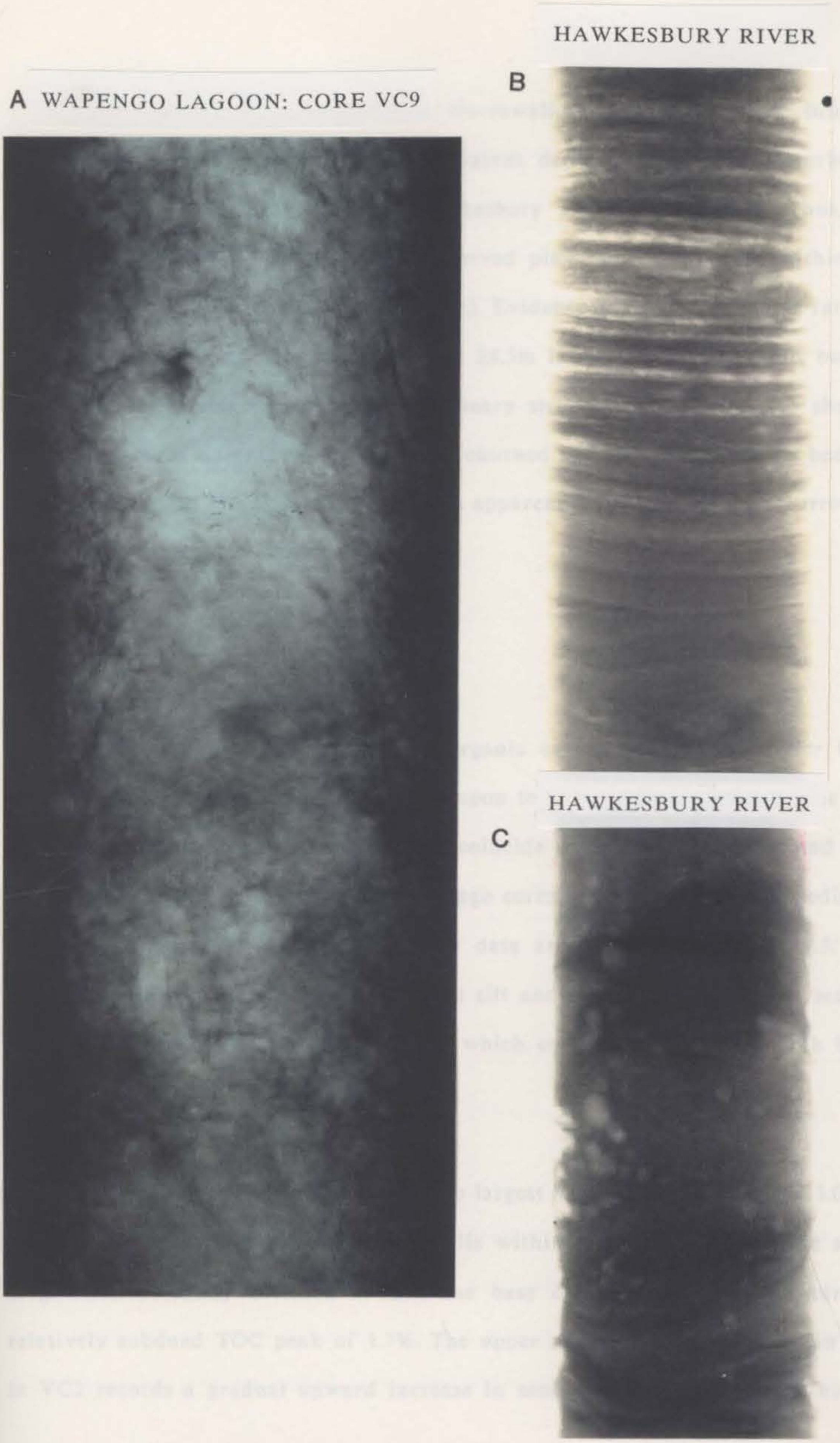


Figure 7.19: Prints of x-ray radiographs of modern barrier basin deposits from Wapengo Lagoon and the Hawkesbury estuary, N.S.W., showing (a) bioturbated massive structure, (b) pin-stripe laminations, (c) horizontal burrow traces. Scale of x-rays is 1:1.

Relict barrier basin deposits in Narrawallee display the same suite of sedimentary structures as well as the apparent depth control over bioturbation observed in the modern Wapengo, Hawkesbury and Conjola cores. Thus, the deepest deposits in N5 feature well preserved pin-stripe laminations within the lower three metres of the unit (24.5-27.5m). Evidence for bioturbation is rare. In contrast, the sediment between 21.0m and 24.5m is marked by numerous burrow traces and negligible preservation of primary structures. Similarly, the shallow deposits of cores N2 and N3 are intensely churned and burrowed with no bedding evident in x-rays. The implications of this apparent depth control over burrowing intensity are discussed in section 7.5.

7.3.4 Total organic carbon content

Wapengo Lagoon: The amount of organic carbon present in barrier basin deposits appears to be largely dependent upon textural characteristics of the host sediment. In particular, peak TOC values coincide with peaks in the silt and sand fractions. Vertical TOC profiles for Wapengo cores are plotted alongside sediment texture in Figures 7.9-7.14 and summary data are presented in Table 7.3. The positive correlation between TOC and the silt and sand fractions is best seen in the plots for cores VC2, VC7 and VC11 which collectively represent both basin margin and basin centre depositional sites.

In VC2, a basin margin core, the two largest TOC peaks of 3.3% and 3.0% at depths of 2.79m and 3.41m respectively, lie within interbeds of silty fine sands (Fig. 7.11). A sandy interbed toward the base of VC2, at 3.81m, features a relatively subdued TOC peak of 1.7%. The upper metre of the barrier basin unit in VC2 records a gradual upward increase in sand content (30% to 50%) but no notable rise in TOC concentrations. There is also a significant reduction in silt content (60% to 32%) within the upper metre of the unit.

CORE	MEAN %TOC ± 1σ	MEAN %$CaCO_3$ ± 1σ	N
WAPENGO			
VC1	2.94 ± 2.02	7.07 ± 2.41	7
VC2	1.51 ± 0.78	8.64 ± 2.13	14
VC7	1.32 ± 0.59	8.94 ± 1.67	11
VC11	1.53 ± 1.01	21.50 ± 24.98	7
VC12	1.48 ± 0.81	8.14 ± 2.61	7
NARRAWALLEE			
N2	0.68 ± 0.63	2.22 ± 1.11	5
N3	0.09 ± 0.16	2.53 ± 1.05	14
N5	1.35 ± 0.91	15.90 ± 6.89	14
CONJOLA			
LC1	not available	1.66 ± 0.84	10
LC2	not available	1.08 ± 0.62	17
LC3	not available	0.33 ± 0.12	15
LC5	not available	0.45 ± 0.49	9

Table 7.3: Summary of TOC and $CaCO_3$ data for all Wapengo, Narrawallee and Conjola Zone B cores.

Of the three silty sand interbeds present in VC7, another basin edge core, only one, at 2.1m, displays a clear peak in TOC content with a value of 2.1% (Fig. 7.12). Sand content in this bed is 26% and silt 44%. The other two interbeds, at 1.5m and 2.7m, are associated with relatively subdued TOC peaks of 1.4% and

1.1%, respectively. Sand content in these beds is 43% and 40% and silt content 45% and 39%, respectively. A second major TOC peak of 2.5% occurs at 1.13m. Rather than being aligned with a well defined sandy interbed this peak lies within the upward coarsening sequence of the basin deposit. Sand content is 29% and silt 46%. The only difference between the sediments with high TOC content and those with subdued TOC peaks is that sand content in the latter is 13-17% higher than in the former. Sand content increases at the expense of the clay fraction and silt content remains uniform among all four samples (Fig. 7.12).

A similar relationship between TOC concentrations and sediment texture is evident in core VC11. This core is presented as an example of a depositional site close to the basin centre. Only one sandy interbed is present within VC11, at a depth of 3.05m. TOC content in the bed is the highest for the core, peaking at 2.7% (Fig. 7.13). The textural composition of the bed is 44% sand, 32% silt and 23% clay. In the basin edge cores discussed above, high sand content (>40%) in barrier basin sediments is associated with subdued (<1.5%) TOC peaks. This is not the case for the distal site represented by VC11, although in the upper portion of the basin unit, at 2.14m, a TOC value of zero was measured in sediment composed of 31% sand and 32% silt.

Narrawallee Inlet: The TOC content of barrier basin sediments recovered in Narrawallee cores indicates a relationship between sediment texture and organic concentrations similar to those observed in Wapengo, but with some interesting variations. Figure 7.15 includes a plot of the sediment texture and TOC profile for Narrawallee core N2. Summary data are presented in Table 7.3. Peak TOC concentrations in barrier basin sediments are somewhat less than peak values in the modern Wapengo sediments. For example, the maximum TOC value of 2.1%

was measured at a depth of 8.20m in a silty sand interbed (sand: 53%; silt: 31%). Moderately high values (1-2%) were yielded by sediment in which silt is the dominant fraction, comprising between 32% and 47% of the sample. Most TOC readings were, however, less than one per cent.

Barrier basin deposits in core N3, lying between 8.20 and 11.21 metres, possess consistently low to negligible TOC concentrations (Fig. 7.16 and Table 7.3). The majority of samples analysed yielded TOC values within the range of analytical error (+/-0.1%) and are reported here as 0%. The highest TOC value recorded was 0.4% at a depth of 11.11m. Sediment texture within this source proximal core is particularly variable, featuring clay rich (up to 86%) beds and sand rich (up to 57%) interbeds. The silt fraction is only dominant (45-57%) toward the base of the unit, where the TOC was detected (Fig. 7.16).

TOC values in the range 1.5% to 3.0% were measured within the lower three metres of the barrier basin unit (25-28m) of core N5. (Fig. 7.17 and Table 7.3). Sediment texture within this interval is predominantly silt (39-58%) and clay (23-49%). The upper three metres of the basin unit in N5 yielded low TOC values, in the range 0.0% to 0.6%, in association with predominantly silt and clay rich (70%) sediment (Fig. 7.17).

The low to negligible TOC values yielded by sand dominant samples in cores N5 and N3 is consistent with trends described from Wapengo cores. That low TOC content is also aligned with clay rich sediment is somewhat surprising given the apparent propensity for organic material to be concentrated in fines. Mechanisms likely to bring about a reduction in TOC content in fine grained sediment will be identified in section 7.5.

Lake Conjola: TOC data for Lake Conjola cores are not presented here because the loss-on-ignition (LOI) method employed by Hunter (1989) is considered inaccurate and moreover yields exaggerated results. The degree of error for the LOI method was discussed in detail in chapter 4 with reference to coal standards and shown to be 15% greater than the LECO method. While tempting, it is not considered valid to apply a correction factor to the LOI data from the Conjola cores because there is considerable uncertainty as to what components of the sediment are actually burnt off during LOI analysis.

Summarising the TOC data from the Wapengo and Narrawallee cores, it is apparent that organic material is predominantly silt sized because peak TOC values require dominance of the silt fraction. In general, TOC content is diluted if the sand fraction is dominant. Moreover, it is likely that a threshold sand concentration exists, above which TOC is significantly reduced. The specific threshold value for sand content is not spatially constant and presumably changes over time at a given location. In the simplest terms, barrier basin depositional sites that are proximal to the basin margin appear to have a lower sand threshold (approximately 30%) than basin centre sites (>45%). That is, more sand is required per unit of sediment to dilute TOC concentrations at basin centre sites than at the basin margin. The significance of the TOC-texture relationship as an indicator of spatial variation in depositional conditions will be discussed in section 7.5.

7.3.5 Calcium carbonate content

Wapengo Lagoon: Calcium carbonate percentage values are plotted adjacent to graphic logs of select Wapengo cores in Figures 7.9-7.14. Summary data are listed in Table 7.3. Variations in carbonate content in the barrier basin sediments of

Wapengo Lagoon, unlike TOC content, appear to be independent of textural trends in the vertical profile. That is, peak carbonate percentages do not consistently correspond with either silty mud beds or sandy interbeds. For example, in core VC2 carbonate values are more or less uniform throughout the barrier basin deposit with a mean of 8.6%. Two peak values of 11.6% and 14.3% are associated with comparatively sand rich intervals, 38% and 33% respectively but other sandy beds contain very similar amounts of shell to silt and clay rich beds (Fig. 7.11). Cores VC1, VC7 and VC12 display carbonate profiles in the barrier basin sediments that are essentially equivalent to the VC2 profile with respective means of 7.1%, 8.9% and 8.1% (Figs. 7.9, 7.12, 7.14 and Table 7.3). In all cores the shell held within barrier basin sediments consisted of broken bivalves (e.g. *Tellina albinella*, *Notospisula sp.*) and whole gastropods (e.g. *Gazameda sp.*) that in most cases are in relative isolation and interpreted to be in situ.

The only shell-rich basin deposit was recovered from core VC11. This core features a 16cm thick bed of shell hash at 2.14m with a very high carbonate content of 77% (Fig. 7.13). All shell is in a partially comminuted condition and is associated with sediment that is composed of equal proportions of sand (31%), silt (32%) and clay (37%). The core location, condition of shell and the textural properties of the sediment suggest a moderate degree of reworking of Zone C deposits upstream and subsequent distal deposition during a river flood. Apart from discrete shell hash deposits such as this, the carbonate profiles presented here do not appear to be useful indicators of changes in barrier basin depositional conditions.

Narrawallee Inlet: Analysis of the carbonate content in Narrawallee barrier basin deposits yielded results that in some cases are comparable to the Wapengo data but in others are notably different. The non-weathered basin sediments of core N5 possess a roughly similar carbonate profile to those in Wapengo cores, though peak values are slightly greater (Fig. 7.17). Shell recovered from barrier basin sediments in N5 included gastropods and bivalves typical of estuarine environments (e.g. *Chlamys (Chlamys) asperrima, Ostrea sp., Tellina albinella, Gazameda subsquamosa, Eumarcia fumigata*). Due to the burial depth of 21m+ and the compact state of the sediment few shells were preserved unbroken, yet most are considered to be in situ because fragments of individual shells shell are found close to one another.

Carbonate percentages in N5 range between 8.8% and 30.8% with a mean of 15.5%. Peak carbonate values occur within the upper two metres of the unit where the deposit features the greatest amount of clay. For example, carbonate values of 30.8% and 27.2% were measured in samples containing 58% and 62% clay, respectively. Between these samples, a sandy interbed yielded only 9% carbonate (Fig. 7.17). However, within the lower four metres of the barrier basin unit textural variations do not impact upon shell concentrations. Instead, carbonate percentages are relatively uniform (Fig. 7.17). The correlation between shell content and sediment texture, hence depositional conditions remains, at best, tenuous.

Cores N3 and N2 yielded carbonate values that are the lowest for all barrier basin deposits analysed here. Many of the samples from both cores contained less than 0.5% carbonate by weight (Figs. 7.15, 7.16 and Table 7.3). Such values are considered to be within the range of measurement error for the method employed in this study. Peak carbonate values of 3%-5% lifted the respective means in N3 and N2 to 1.96% and 1.95%. Comparatively high carbonate values of 23.3% and

29.5% were recorded in a 15cm interval at the base of the basin unit in N2. The contrast between these values, the N5 values, and those of the remainder of the basin deposit in N2 and N3 is interpreted to be related to the diagenetic properties of the sediment. That is, the shallower basin sediments of cores N3 and N2 which are characterised by orange, yellow and brown mottling have been subject to oxidation related to subaerial weathering processes. Weathering of this type is invoked as a mechanism for the dissolution and removal of carbonate material. In contrast, the deeper deposits of core N5 and the base of core N2 exhibit little evidence of oxidation having retained the dark brown to black colour that is typical of modern basin sediments. Consequently, the carbonate content of these buried sediments has probably remained unaltered since deposition.

Lake Conjola: Hunter (1989) reports a similar lack of trends in calcium carbonate content in Lake Conjola basin sediments. Actual $CaCO_3$ values are slightly less than those measured in the Wapengo sediments, but this may be due to the slightly different analytical methods employed by Hunter (1989). Nevertheless, vertical $CaCO_3$ profiles record essentially uniform concentrations in the four Conjola cores and marginally higher content at sites closer to the basin shore. Summary statistics reflect these characteristics (Table 7.3). Thus, mean $CaCO_3$ content in cores LC1 (1.7%) and LC2 (1.1%) are slightly higher than in the cores LC3 (0.3%) and LC5 (0.5%) (Hunter, 1989). In all Conjola cores, as noted for Wapengo sediments, peak $CaCO_3$ values are due to the presence of isolated shells. Hunter (1989) states that these individuals have a propensity to lie within the upper 0.6m of the sediment column though there is no clear association between sediment texture and fossil mollusc preservation.

However, an investigation of estuarine foraminiferal communities in Lake Illawarra identified distinct relationships between the characteristics of the foram population and habitat conditions including: sediment type, floral communities and water depth (Yassini and Jones, 1989). Specifically, the highest population density occurs in the deepest portion (>2m) of the basin where mud is the dominant sediment texture and seagrass is absent. Shallow areas of the basin occupied by seagrass beds and characterised by low turbidity and low mud content support the greatest diversity of foram species. Benthic organisms were found to be absent, however, in areas where anoxic conditions existed, notably protected waters in which organic matter was decaying (Yassini and Jones, 1989). The higher $CaCO_3$ content observed in several samples from barrier basin cores from Wapengo and Conjola appears consistent with the high population density of microfauna for deeper basin waters, whereas low $CaCO_3$ content may be a reflection of oxygen depleted conditions.

7.4 SEDIMENTOLOGIC PROPERTIES OF THE SUPRATIDAL AND INTERTIDAL SHORELINE UNITS

The characteristics of sediments found within the shoreline morphostratigraphic units of Zone B are described here with reference to Wapengo Lagoon only. As noted in chapter four, unit specific sampling was possible in Wapengo because it is yet to be completely filled with sediment. Shoreline deposits in Narrawallee, if preserved, are buried and their spatial extent is not known without detailed grid drilling. As drilling in Narrawallee was limited to a single down-valley transect an adequate description of shoreline deposits is not possible.

7.4.1 Morphology

Major intertidal and supratidal basin shoreline deposits occur only on the northern and southwestern shores of Wapengo Lagoon. The deposit along the northern shore is 200m wide at its widest point and grades laterally into the eastern levee of the supratidal fluvial delta. The southwestern deposit occupies a small embayment of the barrier basin that is approximately 750m in length and 50-450m wide. The outer edge of shoreline deposits either abuts the bedrock of the palaeovalley or grades into floodplain/delta deposits. The inner edge grades into the subtidal barrier basin terminating at approximately 1.5m water depth.

The presence of shoreline deposits on the northern and southwestern shores correlates with the dominant wind directions and maximum fetch in Wapengo. That is, south to southeast and northeast winds pass across 4.25km and 1.5km of estuary waters, respectively. Consequently, wave action in Wapengo basin is most frequent and powerful along the northern and southwestern shorelines.

7.4.2 Sediment texture and mineralogy

The texture of sediment deposited along the shoreline of the barrier basin contrasts strongly to that of the basin. In essence it is much coarser and poorly sorted. Short hammer-cores, PC8 and PC10, represent the intertidal and supratidal component of the southwestern basin shoreline unit, respectively. Figure 7.20 presents a graphic core log, plot of gross textural properties and select grain size histograms for core PC8. Table 7.4 lists summary textural data. The sequence is characterised by a clear upward coarsening trend from moderately sorted silty

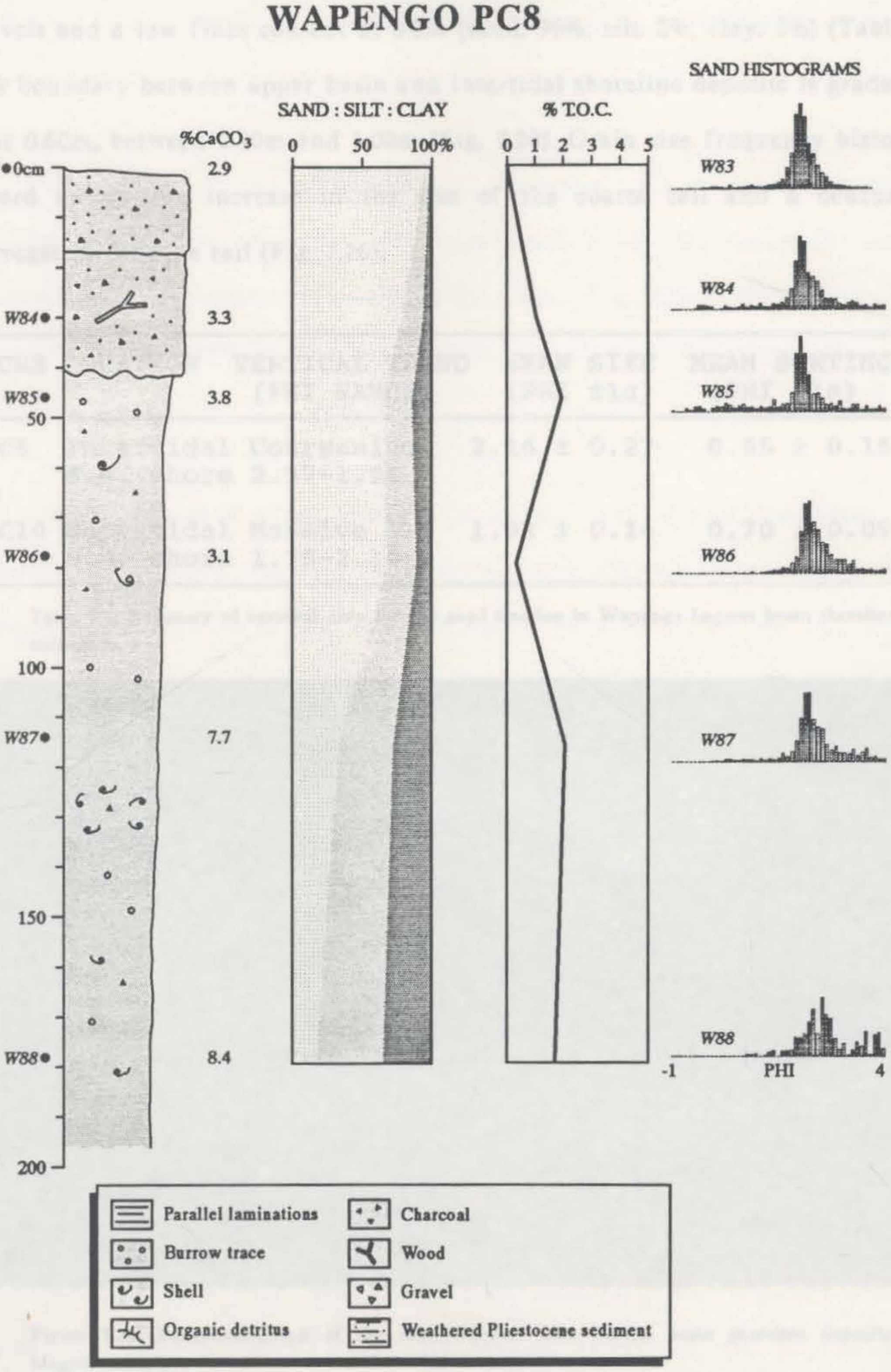


Figure 7.20: Wapengo core PC8 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic content; and, frequency distribution histograms for the sand fraction.

muds and fine sands of the upper basin deposit at 1.80m (sand: 17%; silt: 48%; clay: 36%) to well sorted subangular to angular medium sands with occasional gravels and a low fines content at 0.0m (sand: 96%; silt: 2%; clay: 2%) (Table 7.4). The boundary between upper basin and intertidal shoreline deposits is gradational over 0.60m, between 0.40m and 1.00m (Fig. 7.20). Grain size frequency histograms record an up-core increase in the size of the coarse tail and a concomitant decrease in the fine tail (Fig. 7.20).

CORE	LOCATION	VERTICAL TREND (PHI RANGE)	MEAN SIZE (PHI ±1σ)	MEAN SORTING (PHI ±1σ)	N
PC8	Intertidal S.W. shore	Coarsening 2.57-1.94	2.16 ± 0.27	0.65 ± 0.15	6
PC10	Supratidal S.W. shore	Massive 1.75-2.10	1.92 ± 0.14	0.70 ± 0.09	5

Table 7.4: Summary of textural data for the sand fraction in Wapengo Lagoon basin shoreline sediments.

Figure 7.21: Photomicrograph of the sand fraction from barrier basin shoreline deposits. Magnification 22x

The mineralogy of shoreline sediments is illustrated in the photomicrograph of the sand fraction in Figure 7.21. The terrestrial source of the sands is evident from the angular shape of many grains and the mixed mineralogical suite, which includes quartz, lithic fragments, feldspars and micas.

Core PC10 yielded a predominantly massive unit of supratidal shoreline sediment. Instead of overlying Holocene basin muds, the supratidal shoreline deposit mantles compact weathered silty clays of probable Pleistocene age. An erosional surface at 1.52m marks the contact between the Pleistocene clay and the shoreline deposit.

Textural trends within the supratidal unit are not as significant nor as uniform as those described for the intertidal unit. Nett sand content does increase upsequence from 78% to 85% but with interbeds of relatively silt and clay rich sediment (e.g. 0.91m, Fig. 7.22). Silt and clay proportions are approximately equal throughout, ranging between 4% to 15% and 6% to 17%, respectively. Mean sand size varies between moderately sorted fine sands and moderately sorted medium sands (Table 7.4). Frequency histograms reinforce the uniformity of the sediment, wherein the modal size is constant and the size of tails are of similar magnitude for all samples (Fig. 7.22).

7.4.3 Sedimentary structures

Neither the intertidal nor supratidal shoreline units feature any physical crossbedding structures. The only structural traits that may be considered diagnostic of these units are graded beds associated with upward coarsening trends, particularly in the intertidal portion. Otherwise, the deposit appears massive and bioturbated. Although bioturbated, burrow traces are rarely preserved due to the intensity of biological activity in the form of burrowing crabs and worms, and mangrove and saltmarsh root penetration.

7.4.4 Total organic carbon content

TOC profiles are plotted for cores PC8 and PC10 in Figures 7.20 and 7.22. Summary statistics are presented in Table 7.5. In general, the concentration of organic material continues to be dependent upon sediment texture. TOC values are, on the whole, low (<1%) for both cores and this is attributed to the sand dominant nature of the sediment. Comparatively high TOC values of 1.93% in PC8, and 1.40% in PC10 were measured in a sediment samples that were observed to contain large isolated plant fragments. Other high TOC values in PC8 toward the base of the core (e.g. 2.05% at 1.15m) are associated with silt rich sediments from the upper portion of the barrier basin unit (Fig. 7.19).

CORE	MEAN %TOC $\pm 1\sigma$	MEAN %$CaCO_3$ $\pm 1\sigma$	N
PC8	1.17 ± 0.86	4.87 ± 2.49	6
PC10	0.52 ± 0.54	4.24 ± 2.33	5

Table 7.5: Summary TOC and $CaCO_3$ data for Wapengo Lagoon basin shoreline sediments.

7.4.5 Carbonate content

$CaCO_3$ values are plotted for cores PC8 and PC10 in Figures 7.20 and 7.22 and summarised in Table 7.5. Overall, carbonate content is moderate to low and uniform through the sediment profile. Mean $CaCO_3$ values are 3.3% in the

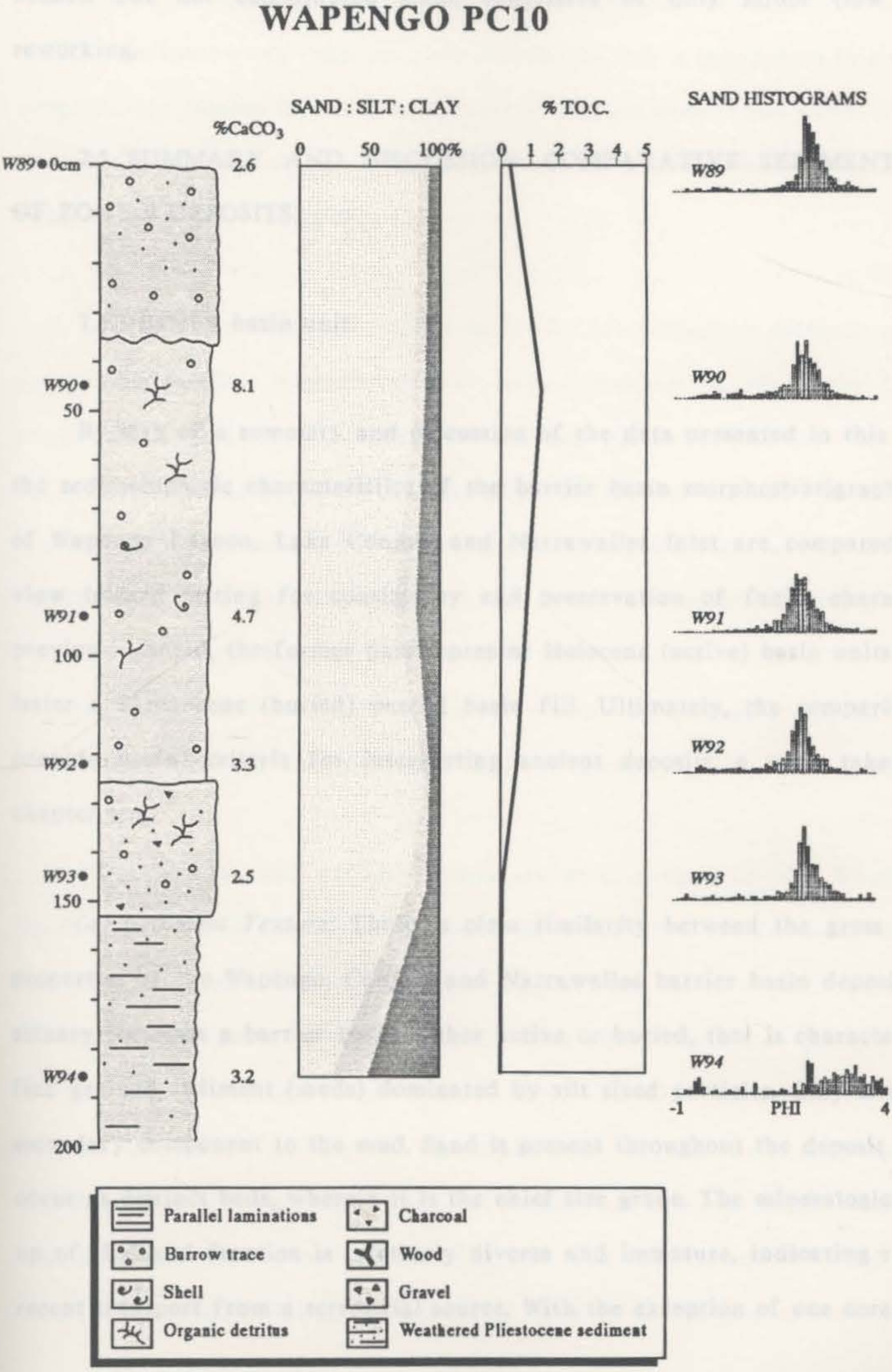


Figure 7.22: Wapengo core PC10 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic content; and, frequency distribution histograms for the sand fraction.

intertidal shoreline unit and 4.2% in the supratidal unit. Core observations noted an absence of whole or in situ shell. Where present, shells are preserved in a broken but not comminuted state, suggestive of only minor (low energy) reworking.

7.5 SUMMARY AND DISCUSSION: COMPARATIVE SEDIMENTOLOGY OF ZONE B DEPOSITS.

7.5.1 Barrier basin unit.

By way of a summary and discussion of the data presented in this chapter, the sedimentologic characteristics of the barrier basin morphostratigraphic units of Wapengo Lagoon, Lake Conjola and Narrawallee Inlet are compared with a view toward testing for consistency and preservation of facies character. As previously noted, the former pair represent Holocene (active) basin units and the latter a Pleistocene (buried) partial basin fill. Ultimately, the comparison may provide useful criteria for interpreting ancient deposits, a topic taken up in chapter ten.

(a) Sediment Texture: There is close similarity between the gross textural properties of the Wapengo, Conjola and Narrawallee barrier basin deposits. Each estuary possesses a barrier basin, either active or buried, that is characterised by fine grained sediment (muds) dominated by silt sized particles. Clay is mostly a secondary component to the mud. Sand is present throughout the deposit and can occur as distinct beds, wherein it is the chief size grade. The mineralogical make-up of the sand fraction is relatively diverse and immature, indicating relatively recent transport from a terrestrial source. With the exception of one core in Lake

Conjola (LC5), marine sediments are notably absent from the landward and central areas of the barrier basin morphostratigraphic unit. The presence of sandy interbeds in basin deposits is attributed to river floods. Mean grain size of sands tends to decrease away from the river mouth and this is interpreted to result from progressively weaker currents as the river debouches into the basin. The trend toward finer sediment in the centre of the basin also emphasises the filtering function played by the basin.

In vertical section, the barrier basin deposit features a distinct coarsening upward trend that is interpreted to reflect shoaling of the basin floor and progradation of the fluvial delta under sea-level stillstand conditions. As the floor accretes and the delta grows, the filtering efficiency of the basin is reduced due to changes in two aspects of the hydrodynamic regime. First, as the delta grows, thereby extending the fluvial channel, the energy of fluvial currents is projected further into the basin. Second, as the basin floor accretes it approaches wave base of wind generated waves and the zone of winnowing. Consequently, more sand is delivered to the basin and less clay and silt is incorporated into the deposit.

These spatial and vertical trends are most evident in the Wapengo and Conjola deposits. In Narrawallee, where the Pleistocene barrier basin deposit is only partially preserved and where sampling was less intensive, the trends are not as clear. Nevertheless, between the three cores that contain fine grained deposits there is a general down valley trend toward less sand and more silt and clay. Because the upper portion of the Pleistocene deposit has presumably been truncated it is virtually impossible to identify upward coarsening trends of the type described from Wapengo and Conjola. The deepest barrier basin deposits (core N5) record a fining upward trend. This is interpreted to represent basin deposition under transgressive conditions. That is, as sea-level rose and flooded the valley, conditions gradually became more favourable for the deposition of the finest particles. The presence of a sandy interbed toward the top of the unit is possible indication of a reversal in the fining upward trend and the onset of stillstand (or regressive) sea-level conditions during the last interglacial period. More convincing evidence for such conditions is contained within the shallower deposits up-valley. In particular, the coarsening upward trend observed in the upper portion of the basin deposit in N3 is consistent with a shoaling basin floor and prograding fluvial delta. The most landward core (N2) does not yield any clear vertical textural trend and this is attributed to the close location of the core relative to the inferred landward limit of the palaeo-basin. That is, the fluvial influences were probably too great to allow typical low energy barrier basin depositional conditions to develop.

(b) Sedimentary Structures: The structural characteristics of the modern and relict barrier basin deposits are identical in as much that they display a common suite of physical and biogenic structures. Given the low energy nature of the basin environment and fine grained texture of the sediment, the observed absence of dune crossbedding is to be expected. Furthermore, slow sedimentation rates provide conditions suitable for bioturbation, hence biogenic structures and massive (structureless) beds are more common features than physical bedding structures.

A common feature among the barrier basin deposits examined here is the tendency for physical structures, where present, to be concentrated toward the base of the deposit. Two related mechanisms may be invoked to account for this phenomenon. First, that it is the result of declining sedimentation rates.

Specifically, sedimentation rates during the early stages of basin deposition exceeded those of more recent times. It is entirely possible that rapid deposition occurred during the PMT when estuary water depths were less than present and depositional conditions were more energetic. Moreover, rapid sedimentation rates limit the opportunity for burrowing organisms to thoroughly rework the sediment.

The second mechanism that may account for the prevalence of physical structures at depth, involves changes to habitat conditions for benthic fauna. That is, during early basin filling, conditions were not favourable for dense faunal populations. Analogous conditions in modern estuarine environments may be provided by the anaerobic bottom sediments in areas rich with decaying organic material (Frey and Pemberton, 1985; Yassini and Jones, 1989). Certainly, TOC content in non-burrowed sediments tends to be higher than in burrowed sediment (e.g. core N5). Bioturbated upper basin deposits possibly equate with the muddy sediments of modern deeper basin waters that are void of sea-grasses but support a high faunal population density (Yassini and Jones, 1989).

Whether the mechanisms discussed above adequately account for the observed patterns in sedimentary structures remains unclear. Notwithstanding, vertical variations in structural properties of the barrier basin deposit appear consistent among the deposits examined. As a final comment regarding sedimentary structures, the vertical patterns observed here may prove to be valuable criteria for interpreting ancient deposits by providing stratigraphic markers which indicate relative position within a vertical sequence.

(c) TOC and $CaCO_3$ Content: Comparisons between the geochemical properties (TOC and $CaCO_3$) of the modern and relict deposits are of particular

interest because they may yield evidence for diagenetic alterations in relict deposits. Variations in measured TOC concentrations in both modern and relict sediments appear strongly linked to three factors: texture of the sediment deposited; depositional environment, and; spatial and vertical position within the deposit. These factors, themselves interrelated, provide a tangible record of processes that are inferred to have controlled the accumulation of organic material. Carbonate content, although variable, does not display any consistent association with other properties of the deposit.

The texture of sediment, which is the primary indicator of relative depositional energy, acts to influence the initial concentration of organic material in such a manner that a relative dominance of sand sized sediment dilutes TOC content. The coincidence of peak TOC with peak silt values suggests that the hydrodynamic properties of the bulk of organic material analysed correlate with those of the silt sized fraction. The energy of deposition at a site not only influences sediment texture but also sedimentation rates and intensity of biological activity, which in turn plays a major role in determining how much organic matter is preserved. Thus, TOC content in modern sediments is the result of the complex interplay between sedimentation rates and rates of biological consumption of organic material. An appreciation of these interrelationships is important when considering the hydrocarbon potential of ancient deposits (Bjorlykke, 1989).

Marked differences were noted in the TOC properties of Holocene and Pleistocene barrier basin deposits. The results from Narrawallee serve to highlight the importance of post-depositional alteration of the sediment. Subaerial exposure of the shallower portion of the Narrawallee barrier basin facies during a period of low sea-level and river downcutting led to oxidation of the sediment and virtually the complete destruction of organic and carbonate material. Biological breakdown of organic material is also inferred for this portion of the deposit because it is intensely bioturbated. By contrast, the deeper basin sediments (core N5) possess a high TOC content within the lower three metres because the deposit is neither weathered nor excessively bioturbated.

7.5.2 Shoreline units

It is not possible to compare the sedimentologic properties of the barrier basin shoreline morpohstratigraphic units of Wapengo and Narrawallee for reasons outlined previously. Nevertheless, there is scope for comment upon the nature of shoreline sediments with respect to depositional conditions prevailing along the fringe of the basin.

The significance of wind generated waves as an agent influencing sedimentation styles in Zone B was discussed earlier in section 7.2.3. To briefly reiterate, given sufficient fetch across the water surface and appropriate orientation of the estuary valley, wind waves have the potential to impact upon Zone B deposition by maintaining a threshold water depth in the basin and by promoting progradation and accretion of shoreline deposits. The ultimate expression of wind wave reworking being basin segmentation via construction of shore normal jetties of sediment.

In Wapengo, the effect of wind waves is most evident along the northern and southwestern basin shoreline. It is toward these shores that the dominant southerly and northeast winds blow, respectively. Consequently, intertidal and supratidal shoreline deposits are well developed. Given the distal location of the deposits relative to any significant fluvial influence, the upward coarsening trend is interpreted not as the result of increased flow velocities but of wind wave reworking. Waves provide a mechanism for concentrating sand sized sediment along the shoreline as well as for winnowing out of fines and organic detritus. In addition, the subangular to angular shape of the sands and the presence of large woody fragments indicate minimal transport. Contribution from a local source such as slopewash is therefore likely.

In conclusion, the sedimentological data presented from both active and relict Zone B deposits demonstrate a consistency of character in terms of the observed properties. Moreover, it is apparent that the sediment data partially validate the characteristics of ENTROPY sub-classes 1, 2A and 2B, of which Conjola, Wapengo and Narrawallee are respective examples. Specifically, of the samples analysed, the great majority of sediment is of terrestrial origin and has the signature of fluvial influences, whereas marine sands are generally absent. The paucity of marine sediment indicates that tidal and wave (including swell wave) processes are not presently capable of transporting noticeable quantities of Zone A sands into the central and landward portions of Zone B. This observation is consistent with the properties of ENTROPY classes identified in chapter five. That is, estuaries in classes 1, 2A and 2B are dominated by fluvial (Zone C) and lagoon (Zone B) morphostratigraphic units and barrier/inlet (Zone A) units are relatively minor. Further discussion of the significance of this result is reserved for chapter nine, following presentation of Zone C sedimentological data.

CHAPTER 8: SEDIMENTOLOGY OF THE LANDWARD TIDAL-FLUVIAL FACIES ZONE (ZONE C)

8.1 INTRODUCTION

The final facies zone to be described is the tide-influenced fluvial zone, termed Zone C (Fig 1.5). Following a description of the general depositional processes operating within Zone C, sedimentological data are presented in two sections. The first relates to the supratidal and intertidal fluvial delta morphostratigraphic units and the associated channel unit in Wapengo Lagoon. The second is concerned with the floodplain unit in Narrawallee Inlet. As in chapters six and seven, sediment descriptions address the following parameters: morphology and bedforms; textural properties and mineralogical composition of subsurface sediment; sedimentary structures; and, carbonate and total organic carbon content of the deposits. Finally, spatial variations in the properties of Zone C deposits are placed in the context of depositional processes, with particular emphasis on the relationship between extreme events (e.g. river floods) and facies characteristics.

8.2 PROCESS FRAMEWORK

8.2.1 Tidal range and flow velocity

Fluctuations in water levels and reversal of currents within the lower reaches of the fluvial channel in Zone C occur on a semidiurnal basis. Only the fluvial channel and intertidal fluvial delta morphostratigraphic units are influenced by tidal processes in this regular manner. The supratidal fluvial delta and floodplain units are inundated by tidal waters only when extreme events such as river flooding, wave set-up, storm surge and seiching occur, either by themselves or concurrently. The frequency of occurrence of these extreme conditions along the N.S.W. coast varies from seasonal to aperiodic (Short, 1988).

Although the frequency of tide-induced changes in depositional conditions for the fluvial channel and intertidal delta environments is consistently high, the magnitude of those changes is less impressive. Tidal range within the fluvial channel is dependent upon two interrelated factors, (i) the area and depth of the barrier basin and, (ii) the extent of channelisation within the estuary (Roy, 1984a). That is, in an estuary with a relatively large and deep basin and a short floodplain/delta channel, the tidal range in the channel will be reduced to a small percentage of the ocean range. Wapengo Lagoon is an example of an estuary with these morphological and tidal properties. Absolute tidal data from the fluvial channel reaches of those south coast estuaries discussed in previous chapters are not available. However, the following description of tidal conditions extrapolates from trends described for Zone B, and draws upon field observations in Wapengo and Narrawallee.

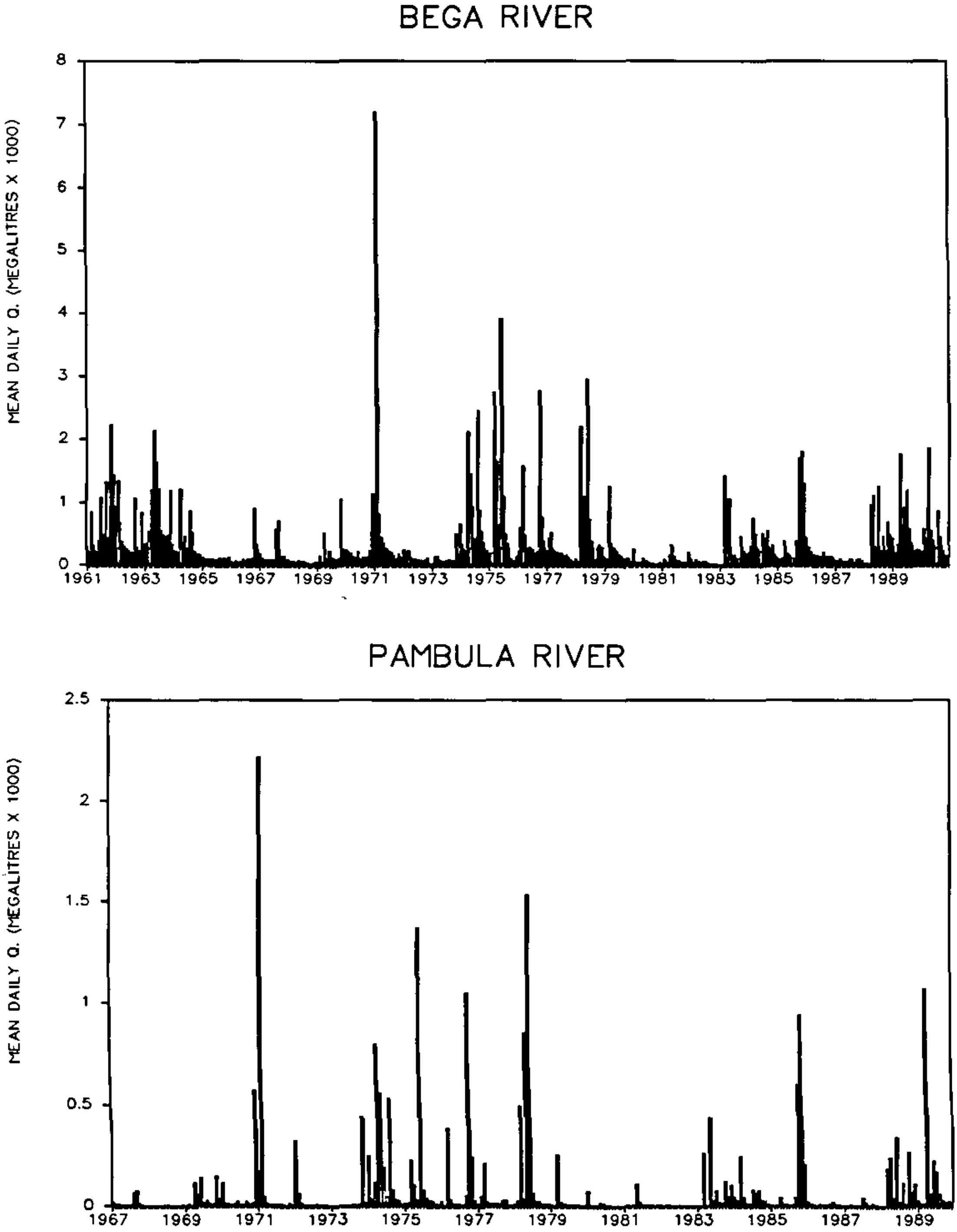
Spring tidal range within the Wapengo fluvial channel was observed to be approximately 0.3m at the mouth of Wapengo Creek, and negligible some 2.0-2.5 kilometres upstream. Likewise, tidal currents decreased in relative strength upstream. An indication of the velocity of tidal currents in Wapengo Creek may be obtained from velocity data collected at the mouth of the Pambula River by the N.S.W. Public Works Department (see Fig. 7.5). Maximum neap flood tide currents of 0.17m/sec were recorded for a limited time (30 minutes). Peak ebb flow velocities were weaker, 0.08m/sec and also of short duration. Indeed, for ten of the 12.5 hours of monitoring, flow velocties were less than 0.1m/sec. Because the degree of tidal attenuation in Pambula is less than in Wapengo (see section 7.2.1), the neap velocities from Pambula may be considered roughly equivalent to spring velocities in Wapengo. Qualitative field observations by the author in the Wapengo channel during spring tides support the analogy. Observations of low to negligible tidal flows in the fluvial channels of Lake Illawarra by Yassini and Jones (1989) and Mallacoota Inlet by Reinson (1977) further vindicate the comparison. The salient point with regard tidal currents in the fluvial channel is that their capacity to transport sediment is very limited and most likely restricted to the suspended load.

In an estuary characterised by a long channel that traverses the area previously occupied by the barrier basin, attenuation of ocean tidal range and currents is less significant. Long term observations of tidal conditions in the Tomaga River by Anderson and Storey (1981) were described in chapter six with regard to Zone A tidal characteristics (see Fig. 6.6). It was noted that the landward reaches of the Tomaga River, between eight and ten kilometres from the estuary mouth, experienced a mean tidal range 60-70% less than ocean tidal range. Spring tidal range in the upper fluvial channel would, for example, decrease from 0.64m to 0.48m over the two kilometres. It is evident from Figure 6.6 that the decrease is not linear with distance. Extrapolating the trend in the Tomaga River curve suggests that tidal conditions terminate at 11.5km from the estuary mouth. In Narrawallee, an estuary that is also at an advanced stage of channel development, tidal fluctuations in creek water levels, of the order of 0.20-0.30m, were observed to persist almost to the landward limit of the floodplain, representing an approximate channel distance of 10 km from the estuary mouth. In spite of the persistence of tidal conditions to the head of Narrawallee Creek, the velocity of tidal flows was observed to be very weak. Indeed, tidal flows in Zone C of Narrawallee appeared scarcely able to transport suspended load, yet alone mobilise the bedload.

8.2.2 Fluvial discharge

Long term gauging of discharge in south coast rivers and streams carried out by the N.S.W. Water Resources Department (WRD) has been confined to a selection of the larger rivers, including the Bega, Pambula, Tuross and Towamba Rivers. Discharge volumes are calculated from daily measurements of river level. Flow velocities have not been measured. All gauging stations are located upstream of the tidal reaches of rivers and in the case of the Bega River, upstream of lower tributaries. Consequently, the Bega River data do not represent the total discharge of the catchment. Notwithstanding, a general impression of the nature of river flow into south coast estuaries can be obtained from the records available. Figure 8.1 presents a series of plots of daily discharge, averaged for each month, for the Bega, Pambula and Tuross Rivers. The Towamba River is excluded from the discussion because of lengthy gaps in the record.

It is evident from the hydrographs that, during the rather limited period of record, there is considerable variability of river flow. This trend has been observed in many N.S.W. coastal rivers (Abrahams and Cull, 1979; Nanson and Young, 1981a; Erskine and Warner, 1988). It is described by Dury (1982) as a random step-functional temporal discharge pattern. In other words, months and years of above average and below average flow occur as separate clusters, and the transition from low to high to low flow is abrupt (e.g. 1970-1971 in the Bega River and Pambula River).



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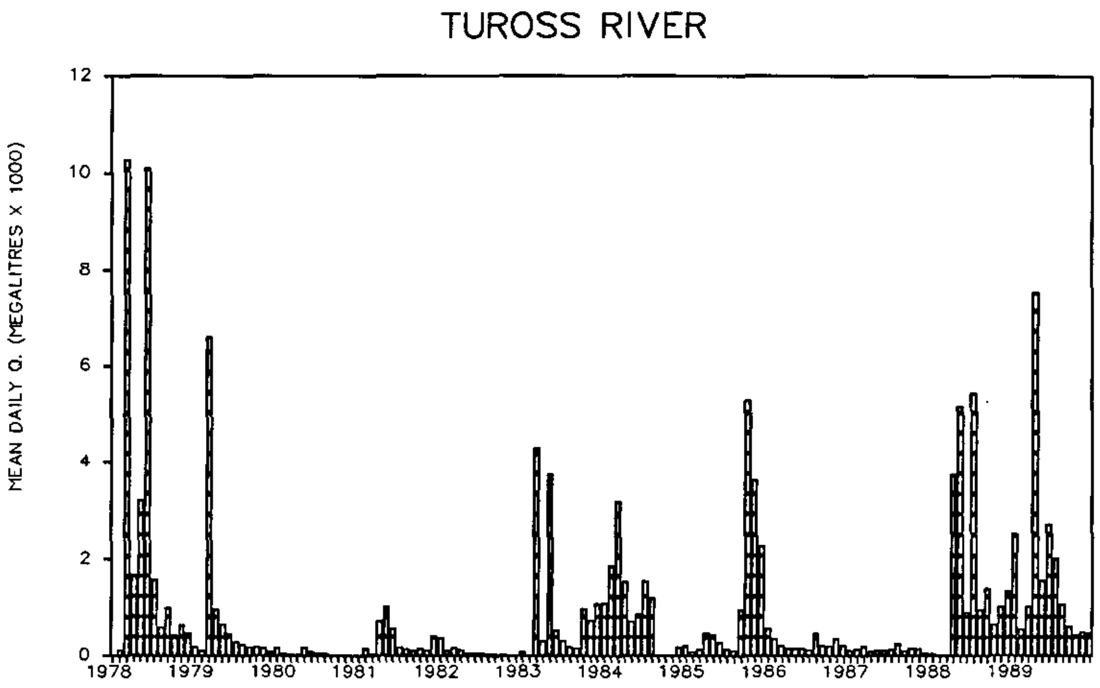


Figure 8.1 cont.: Hydrographs for the Bega, Pambula and Tuross Rivers. Discharge (Q) is expressed as mean daily flow in megalitres for each month of record. Note: Bega River data represents two of three major tributaries (Bemboka R. and Tantawangalo Ck.). Pambula and Tuross gauging stations are located 7 km upstream of tidal limit and represent total freshwater discharge (source: WRD, 1991).

With regard to seasonal trends, graphs of mean daily flow for each month indicate, for the period of record, a tendency for higher discharge to occur during late summer and autumn (February-June), particularly for the Tuross River (Fig. 8.2). It is likely, however, that the seasonal pattern is an artefact of the length of record for a particular river. Mean statistics from short records will be influenced to a greater extent by extreme events than those derived from long records. Thus, the magnitude of seasonal variation is smaller for the Bega River (29 year record) than the Tuross River (11 year record). Moreover, the mean statistic is shown to be somewhat misleading when variance statistics are considered (Table 8.1). The coefficent of variation for all months for all three rivers is close to, or well in excess of 100 per cent.

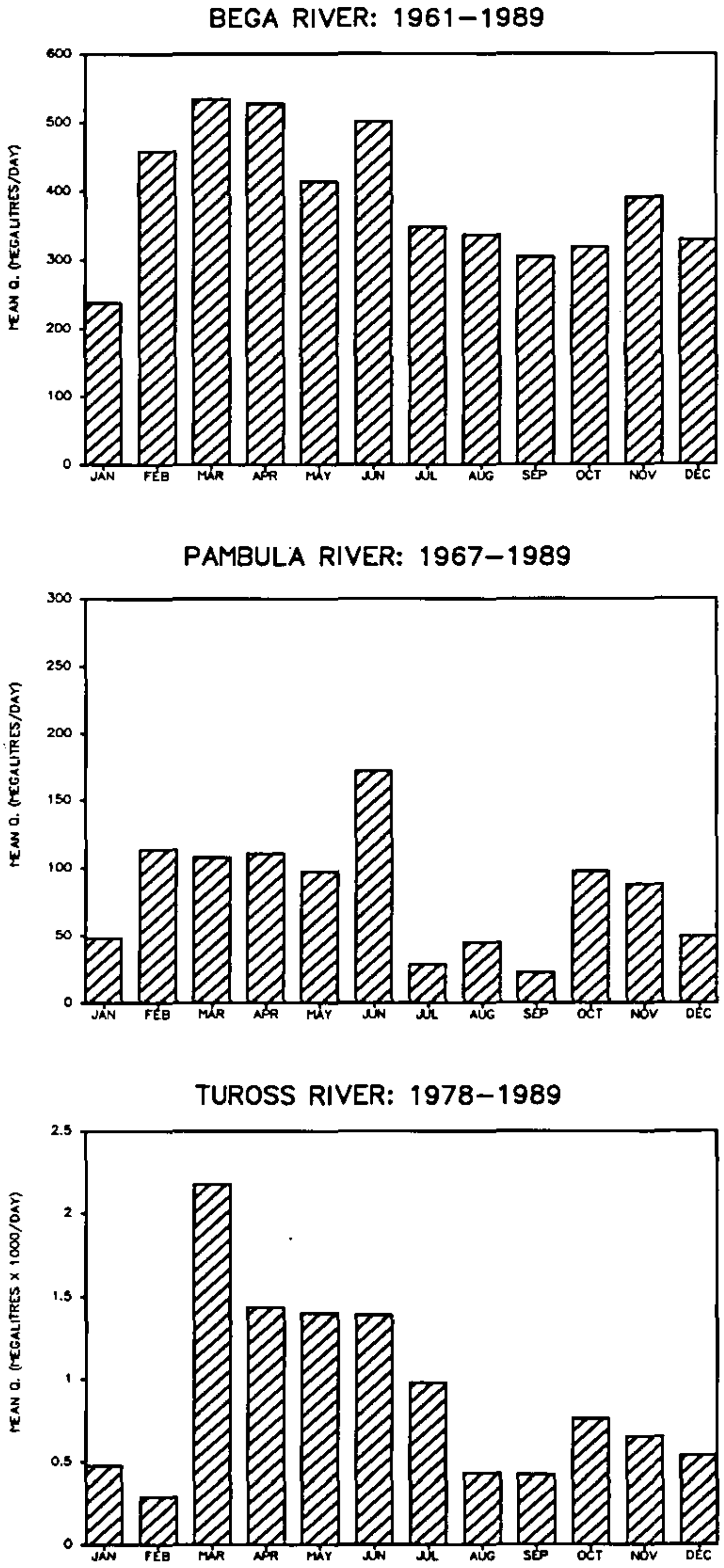


Figure 8.2: Mean daily discharge per month for the Bega, Pambula and Tuross Rivers (source: WRD, 1991).

	BEGA R.			PAMBULA R.			TUROSS R.		
YEAR AREA	1961-1989 800 sq km			1967-1989 300 sq km			1978-1989 1800 sq km		
	mean	s.d.	c.v.	mean	s.d.	c.v	mean	s.d.	c.v.
	megalitres		%	megalitres		%	megalitres		%
JAN	238	228	96	48	86	180	474	740	156
FEB	458	1297	283	113	470	416	286	519	182
MAR	533	681	128	108	145	134	2175	3330	153
APR	527	613	116	111	268	242	1434	2184	152
MAY	413	494	120	97	216	222	1401	1695	121
JUN	501	872	174	172	414	241	1391	2835	204
JUL	347	401	115	28	40	143	977	1565	160
AUG	337	464	138	45	110	246	431	420	97
SEP	304	330	108	22	25	113	423	479	113
OCT	319	556	174	97	246	253	763	1526	200
NOV	390	515	132	88	211	240	654	1033	158
DEC	329	407	124	49	124	251	539	685	127

Table 8.1: Long term mean daily discharge, standard deviation (s.d.) and coefficient of variation (c.v.) statistics for three south coast rivers (source: WRD, 1991)

The temporal variability of river discharge is further emphasised when individual events are examined. For example, the flood of February 1971, which is the largest on record, was recorded in the Bega River by a peak flow of 204,079 megalitres per day and in the Pambula River as 54,681 megalitres per day (WRD, 1971). These values translate to discharges 48,087% above the mean daily flow for the Bega River and 64,515% above mean flow for the Pambula River. At the other extreme, all three rivers have ceased to flow for considerable periods. The longest recorded period of zero flow is 17 months for the Pambula River (December 1967 to April 1969). It is clear, therefore, that river discharge on the south coast is by no means temporally uniform.

The flood-frequency curve for one tributary of the Bega River (Bemboka River) is plotted in Figure 8.3. The Bemboka was selected because it has the longest period of record (1943-1989). The curve was constructed by fitting a second order polynomial to two variables, flood recurrence interval and the ratio of the annual flood to the mean annual flood (Abrahmans and Cull, 1979). The resultant curve predicts that floods twice the size of the mean annual flood occur in the Bemboka River once every 11 years. In terms of the geomorphic impact of a flood, Abrahams and Cull (1979) nominate a discharge in excess of four times the mean annual flood as catastrophic. From Figure 8.3 catastrophic floods occur in the Bemboka every 26.5 years. The 1971 flood, which was 6.5 times the mean annual flood and certainly catastrophic, was a one in 52 year event.

The flood-frequency curve for the Bemboka River is comparable in form to that constructed by Abrahams and Cull (1979) for the Macleay River, located on the north coast of N.S.W. That is, both curves are steep in comparison to curves for coastal rivers elsewhere. For example, rivers along the east coast of the United States display relatively flat flood-frequency curves. Consequently, catastrophic flood events appear to be less common in the U.S. The return period of catastrophic floods on the U.S. east coast is greater than 100 years (Abrahams and Cull, 1979). The steep slope of flood-frequency curves that appears to be typical of N.S.W coastal rivers is attributed by Abrahams and Cull (1979) to the high temporal variability of river discharge, which in turn is a function of extreme rainfall events over catchments characterised by steep gradients, soil types and vegetation types that provide more for overland flow than groundwater flow.

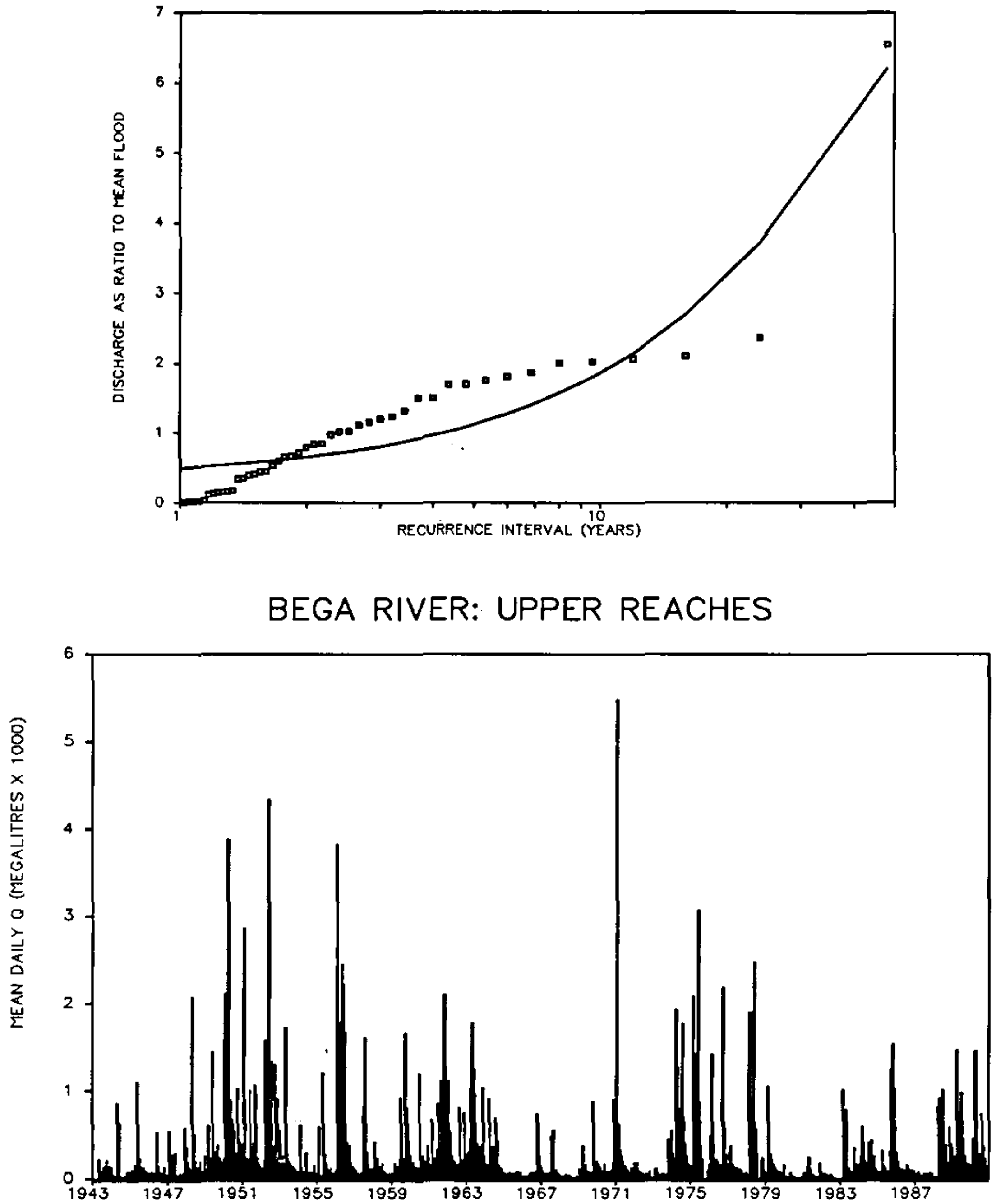


Figure 8.3: (a) Flood-frequency curve for the Bemboka River, calculated from, (b) maximum daily discharge per month of record, 1943-1990 (source: WRD, 1991).

It is not possible to determine with confidence whether the discharge record in south coast rivers corresponds to the flood-dominated (FDR) and drought-dominated regimes (DDR) of Erskine and Warner (1988), because of the virtual coincidence of the beginning of the second FDR (1947) with the earliest records (1943). The Bemboka River flood hydrograph does, however, suggest a post-1946 increase in flood magnitude and frequency, lasting until the early 1960s (Fig. 8.3b). This observation is in accord with that of Bell and Erskine (1981) who report that flood discharge in the Hunter River on the central coast increased by between 50 and 100 percent during the second FDR. In addition, the long term rainfall record indicates that the south coast did experience an increase in precipitation that corresponds with the 10 to 20 percent increase since 1945 in mean annual rainfall for eastern Australia recognised by Pittock (1975, 1981) (see Fig. 2.8 & section 2.3.1). It is, therefore, likely that the second FDR (1947-1978) occurred within south coast rivers but the evidence is incomplete.

With regard to sediment transport, it is apparent from the discharge record that there is abundant potential energy for transport. Data describing river flow velocities and sediment yields are severely lacking for Australian rivers, a deficiency noted by Hean and Nanson (1987) who stated, *"Put bluntly, there are no measured or calculated data sets known to us that are worthy of serious consideration other than a few measurements for very small experimental basins"*. Notwithstanding, Hean and Nanson (1987) applied a variety of bedload equations to several N.S.W. coastal rivers in an attempt to understand their sediment transport behaviour. They stress the gross inaccuracies of the bedload estimates derived from the 'standard' equations. However, the bedload calculations do allow for assessments of changes in *relative* yields that may result from temporal variations in discharge.

One of the rivers examined by Hean and Nanson (1987) was the Shoalhaven River, immediately north of the study area, for this thesis. Gauging records for the Shoalhaven River cover the years 1924-1976, incorporating part of the DDR of 1901-1946 and the ensuing FDR. Bedload estimates for the two periods differ significantly. In summary, the latter period (1945-1976) recorded a 60 to 100 percent increase in bedload yield (Hean and Nanson, 1987). From this result, Hean and Nanson (1987) conclude that a relatively small increase in rainfall has the potential to dramatically increase the volume of sediment in the channel, provided material is available from the adjacent slopes.

With regard to fluvial sediment delivery to estuaries, it appears from observations of downstream changes in channel morphology in the Illawarra area by Nanson and Young (1981b), that conditions observed upstream of the tidal reaches differ to those within the estuarine reaches. Specifically, the broad flat floodplain and deltaic sections of several Illawarra coastal streams display channel dimensions 50 to 65 percent smaller than their upper reaches. The decrease in channel size is attributed to several factors: (i) the decrease in flow velocity that occurs on the low gradient floodplain; (ii) the presence of the floodplain to accommodate floodwaters; (iii) and, the cohesive nature of fine-grained sediment that makes up the floodplain and channel banks. All three factors combine to deter channel widening.

A consequence of the downstream reduction in channel size is an increase in flood frequency within the lower reaches of the stream. During high discharge the channel is rapidly overtopped and floodwaters laden with suspended sediment spill onto the floodplain. For example, bankfull discharge in the lower reaches of two Illawarra streams was measured at between 10 and 18 percent of the channel volume upstream. The bulk of the floodwaters were accommodated by the floodplain. Interestingly, channel flow velocities did not weaken downstream

(Nanson and Young, 1981b). It is evident, therefore, that the lower estuarine reaches of south coast streams are not only sensitive to variable river discharge, but also that relationships between the flow regime and channel form differ between downstream and upstream reaches. That is, the role of overbank flow is of greater importance downstream than channel flow during floods. It will be shown in the following section that the observed dominance of overbank processes is reflected in the character of Zone C sediments.

8.3 SEDIMENTOLOGY OF THE FLUVIAL DELTA AND CHANNEL UNITS

8.3.1 Morphology and bedforms

The fluvial delta in Wapengo Lagoon consists of readily defined supratidal and intertidal levees that protrude into the barrier basin and flank a predominantly straight channel (Fig. 8.4). Subtidal delta levees are not evident in Wapengo Lagoon. In the terminology of Coleman and Wright (1975), the Wapengo fluvial delta may be classified as a Type I delta because it "...consists of a widespread body of sand composed primarily of distributary-mouth-bar deposits. Within the sand body are definite fingerlike thickenings of sands associated with individual distributaries." (Coleman and Prior, 1980: 152). The Wapengo delta possesses only one distributary channel. It is deepest along the straight lower reaches, where the depth to the channel bed at spring high tide is between two and three metres. The supratidal portion of the delta has two sub-parallel levees that grade landward into the floodplain of Wapengo Creek, and occupies an area of 0.44 km^2, representing 5.6% of the palaeovalley area. The boundary between the supratidal fluvial delta and the floodplain is not clear, and in Wapengo it is defined as the position of the inferred palaeoshoreline of the barrier basin (Fig. 8.4). It will be shown later that, in terms of sedimentary properties, the floodplain and delta units are one in the same.

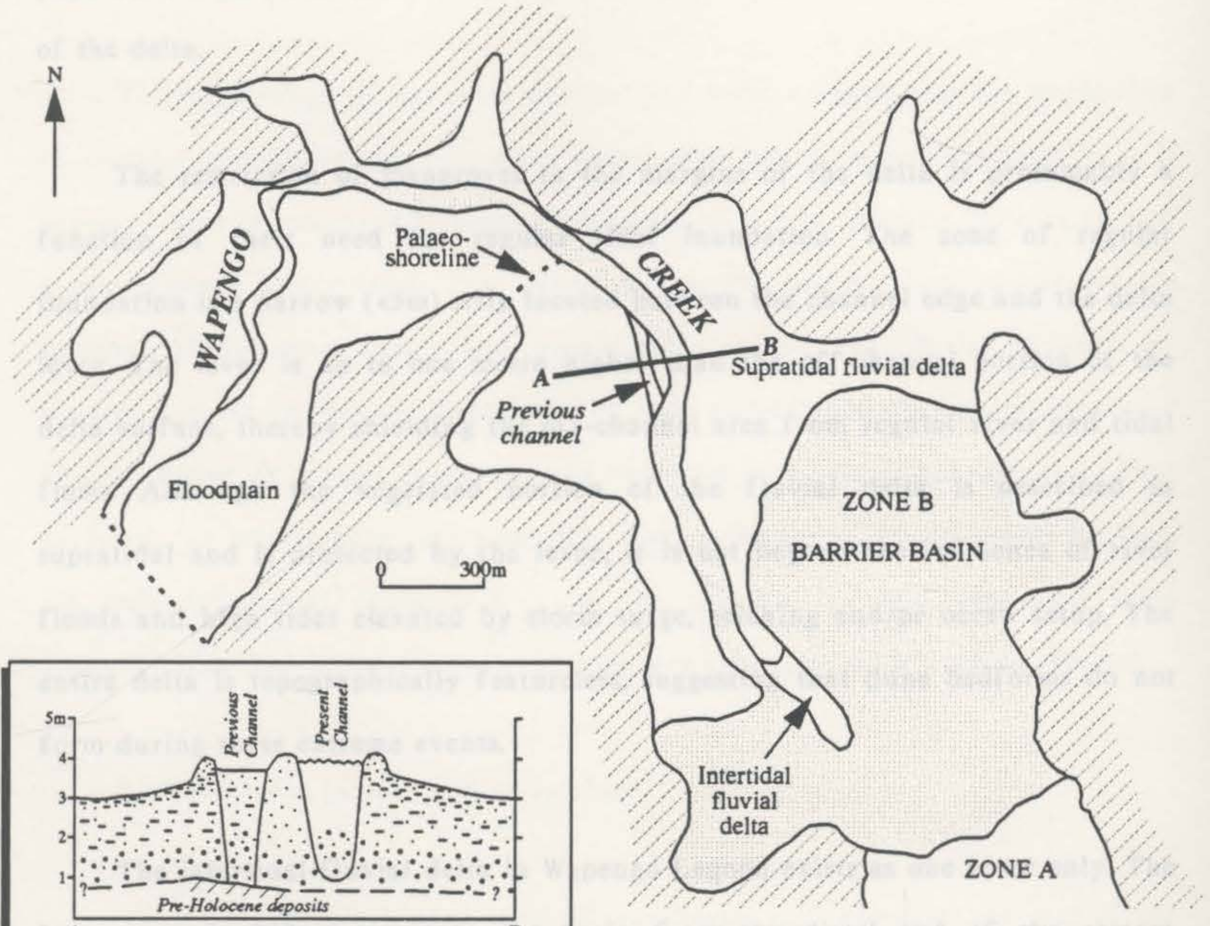


Figure 8.4: Sketch showing the plan form and cross-section profile of the present and abandoned fluvial channels of Wapengo Creek.

The intertidal and supratidal delta surface is colonised by: mangroves (*Avicennia marina*) along channel margins; grasses (*Stipa stipoides* and *Gahnia filum*) on the elevated levee adjacent to the channel; succulent saltmarsh (*Sarcocornia quinqueflora*) on the off-channel (overbank) surface of the delta; and, paperbark trees *(Melaleuca ericofolia)* at the landward and most elevated portion of the delta.

The restriction of mangroves to the margins of the delta is presumably a function of their need for regular tidal inundation. The zone of regular inundation is a narrow (<5m) strip located between the channel edge and the delta levee. The levee is up to one metre higher than the off-channel portion of the delta surface, thereby shielding the off-channel area from regular river and tidal flows. Although the vegetated portion of the fluvial delta is described as supratidal and is protected by the levee, it is not beyond the influence of river floods and high tides elevated by storm surge, seiching and/or ocean setup. The entire delta is topographically featureless, suggesting that dune bedforms do not form during these extreme events.

The intertidal fluvial delta in Wapengo Lagoon exists as one levee only. The levee extends 350 metres into the basin from the distal end of the eastern supratidal levee (Fig. 8.4). The delta surface is 0.03 km^2 in area, which is 0.38% of the estuary valley. Seagrasses (*Zostera*, *Possidennia*) grow on the intertidal delta surface and act to impede the movement of sediment as traction load. Therefore, dune bedforms are rare.

The morphology of the fluvial delta complex suggests that channel changes have been minor since its formation and confined to the middle to upper reaches.

The only clear morphological evidence of channel change is along the middle reach of the channel. Here the eastern bank of the supratidal delta consists of an infilled prior channel and levee, separated from the present channel by the levee that defines the eastern bank of the present channel (Fig. 8.4). The prior channel is only 400m long and terminates at both ends where it meets the present channel.

The morphology of the prior channel and levee suggests that the mechanism of channel change was abandonment rather than lateral migration. That is, it is proposed that at one stage Wapengo Creek existed as two channels flowing around a mid-channel shoal/island. That island is now the eastern levee of the present channel. Mid-channel shoals and islands exist within the fluvial channels of numerous other south coast estuaries, with good examples in the Tuross River and Murrah River. If lateral migration had occurred then one would expect to find evidence for lateral point bar accretion. That evidence is not apparent. Further, the sedimentological characteristics of the channel fill and associated levee deposits, described in the following section, are consistent with a stable channel.

8.3.2 Sediment texture and mineralogy

Vibracores were collected from the supratidal and intertidal portions of the Wapengo fluvial delta along a transect parallel to the present fluvial channel, starting at the inferred palaeoshoreline of the barrier basin and ending at the distal end of the intertidal levee. In addition, several cores were sampled at sites located away from the present channel (off-channel sites). Figure 4.5 shows the location of cores collected from Zone C in Wapengo Lagoon.

The most landward core (VC345) was taken from the site of the abandoned creek channel, described in section 8.3.1, and yielded a 3.25m thick fluvial deposit characterised by a clear upward coarsening pattern. The sequence disconformably overlies compact, dewatered and heavily weathered sandy clays of probable Pleistocene age (Fig 8.5). The lower 2.25m of Holocene sediment comprises 10-40cm thick massive beds of moderately sorted silty medium to fine sands with occasional gravel (<5%). These upper sands appear not to be oxidised, despite their supratidal elevation. The coarsening pattern is evident from a decrease of fines through the lower bed. Thus, silt content decreases from 48% to 32% and clay decreases from 40% to 23%. Table 8.2 presents summary statistics for the textural properties of all Zone C cores analysed. Frequency histograms for samples of the sand fraction from the lower 2.25m record a gradual upward coarsening pattern by a leftward shift in the position of the distribution (Fig 8.5). The upper metre of the landward delta deposit in VC345 displays a dramatic increase in grain size, manifest as 2-10cm thick massive beds of moderately to poorly sorted silty coarse sands and gravels. Gravel constitutes up to 20% of the sediment, whereas the silt and clay fraction together comprise less than 10%. Frequency histograms clearly illustrate the coarse texture of these beds (Fig 8.5). Toward the top of the sequence, 5-10cm thick fining upward beds are present and these in turn are capped by an organic rich bed of silty muds, thereby defining the modern delta levee surface.

Located midway along the supratidal fluvial delta, core VC1 embodies a 1.8m thick fining upward sequence of deltaic sediment. The fining pattern is represented by beds, ranging in thickness from 10cm to 130cm, that collectively describe a trend from moderate to poorly sorted medium/coarse gravelly sands toward moderately sorted silty fine sands (Fig. 8.6). Sand content decreases

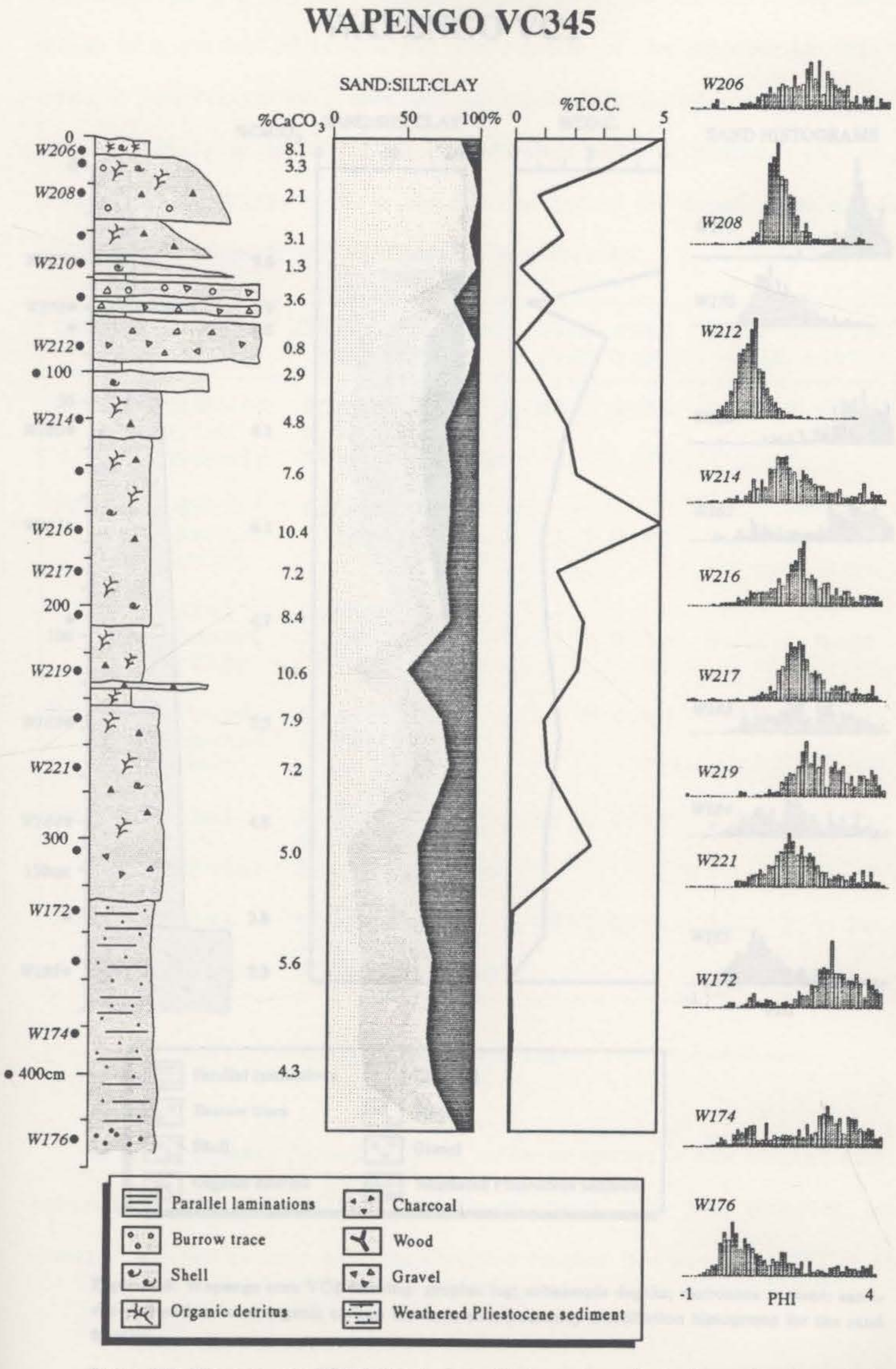


Figure 8.5: Wapengo core VC345 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

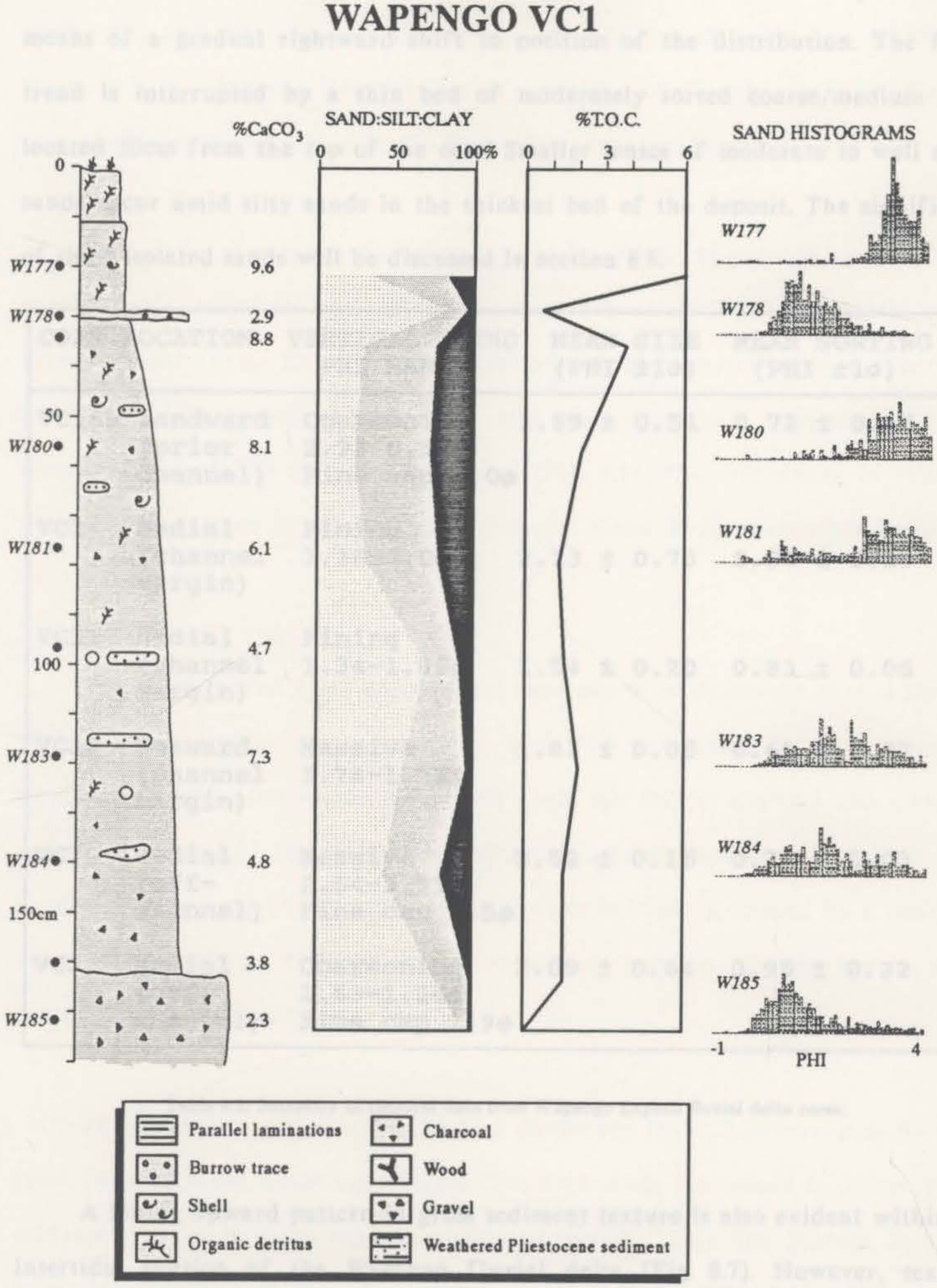


Figure 8.6: Wapengo core VC1 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

up-core from 95% to 24%, whereas silt increases from 3% to 46% and clay increases from 2% to 25%. Frequency histograms illustrate the fining pattern by means of a gradual rightward shift in position of the distribution. The fining trend is interrupted by a thin bed of moderately sorted coarse/medium sands located 30cm from the top of the core. Smaller lenses of moderate to well sorted sands occur amid silty sands in the thickest bed of the deposit. The significance of these isolated sands will be discussed in section 8.5.

CORE	LOCATION	VERTICAL TREND PHI RANGE	MEAN SIZE (PHI ±1σ)	MEAN SORTING (PHI ±1σ)	N
VC345	Landward (prior channel)	Coarsening 2.92-0.55φ Fine cap 2.0φ	1.89 ± 0.51	0.72 ± 0.16	17
VC1	Medial (channel margin)	Fining 1.18-3.0φ	2.13 ± 0.73	0.84 ± 0.19	9
VC11	Medial (channel margin)	Fining 1.34-1.86φ	1.54 ± 0.20	0.83 ± 0.06	7
VC12	Seaward (channel margin)	Massive 1.78-1.94φ	1.83 ± 0.06	0.65 ± 0.07	5
VC7	Medial (off-channel)	Massive 2.64-2.31φ Fine cap 2.5φ	2.52 ± 0.15	0.77 ± 0.03	4
VC2	Medial (off-channel)	Coarsening 2.63-1.26φ Fine cap 1.9φ	2.09 ± 0.64	0.95 ± 0.32	4

Table 8.2: Summary of textural data from Wapengo Lagoon fluvial delta cores.

A fining upward pattern in gross sediment texture is also evident within the intertidal portion of the Wapengo fluvial delta (Fig 8.7). However, textural contrasts are not as clear as those observed further landward. Core VC11 yielded a 1.5m thick bed containing moderately to poorly sorted medium shelly sands with occasional gravel at the base that grade upward to moderately sorted medium/fine sands. Silt and clay content throughout the bed is relatively low (<20%) for fluvio-deltaic sediments. The subtlety of textural variation is exemplified by the lack of significant variation in the form of frequency histograms (Fig. 8.7).

The distal portion of the intertidal fluvial delta, represented by core VC12, consists of a relatively thin (1.1m) massive bed of sediment overlying barrier basin deposits (Table 8.2). The bed contains moderately sorted medium/fine sands with occasional gravel particles. Silt and clay content is comparatively low, remaining below 15% throughout the bed (Fig. 8.8). The uniformity of sediment texture is illustrated by the common uni-modal shape of frequency histograms for the sand fraction.

The final fluvial delta depositional sequence to be described here is that for off-channel locations. Core sites VC2 and VC7 are examples of off-channel locations. Each is situated 50-100m away from the fluvial channel and therefore represents relatively low energy depositional conditions. The off-channel delta deposit displays a massive to coarsening upward bed that is capped by a relatively thick capping bed of fine sediment. The contact between the two beds is sharp but it is not interpreted as erosional.

The upward coarsening bed is best developed in VC2, where it is 60-70cm thick and comprises moderately sorted fine silty sands that grade to poorly sorted medium silty sands with minor amounts of gravel (<2%). Silt content decreases from 24% to 8% and clay decreases from 13% to 5% (Fig. 8.10). The up-core increase in mean grain size is clearly recorded in the frequency histograms

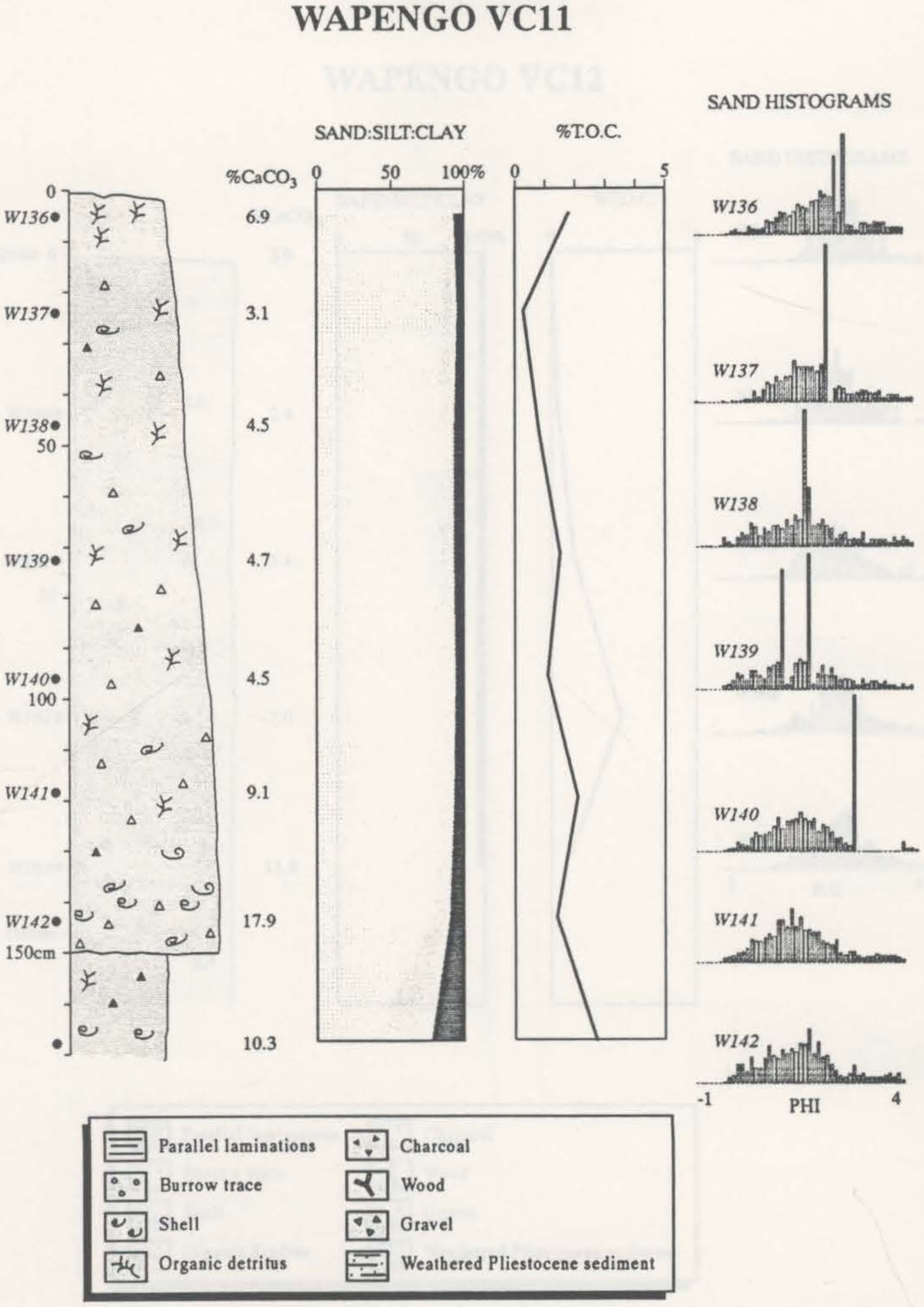


Figure 8.7: Wapengo core VC11 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

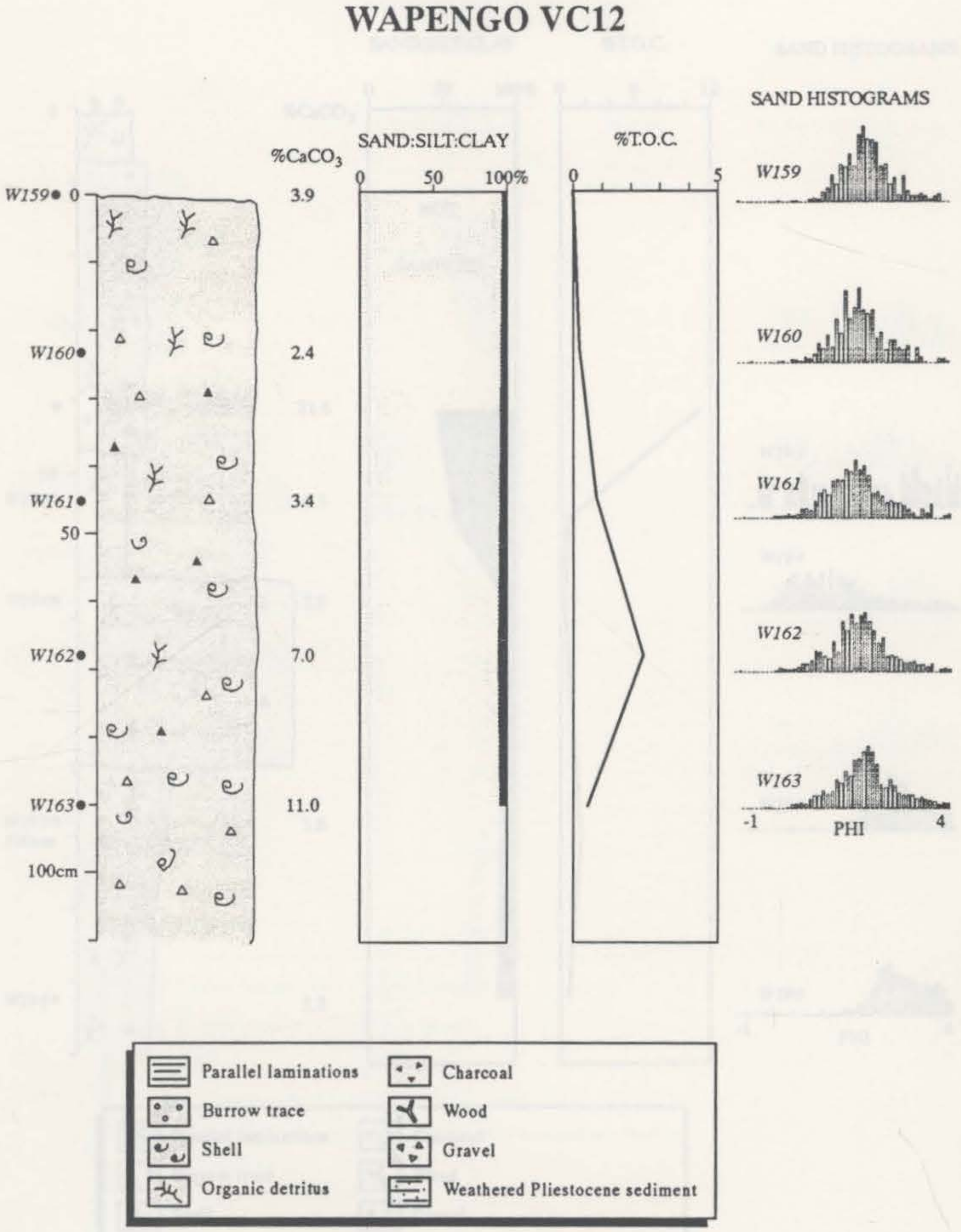


Figure 8.8: Wapengo core VC12 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

WAPENGO VC2

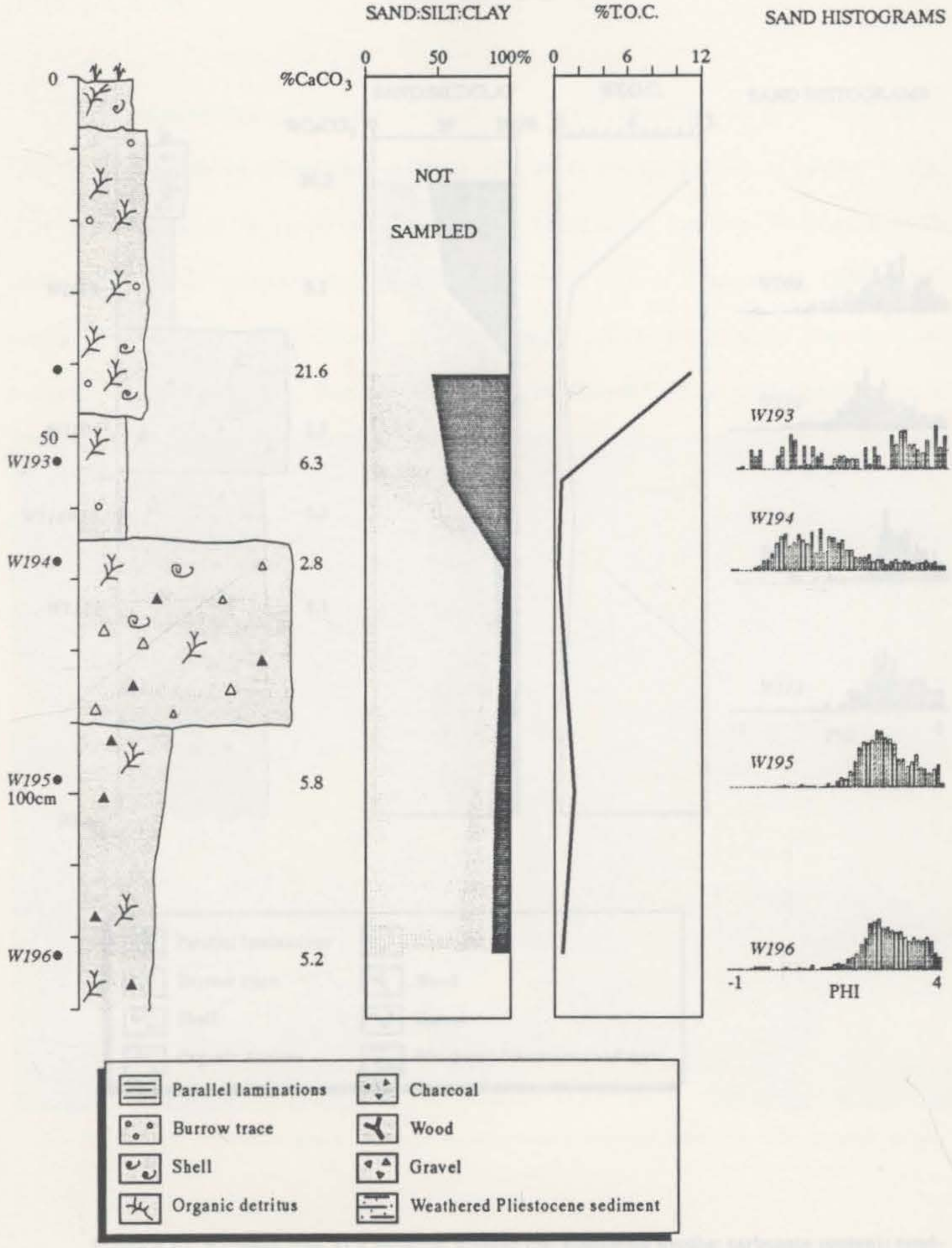


Figure 8.9: Wapengo core VC2 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

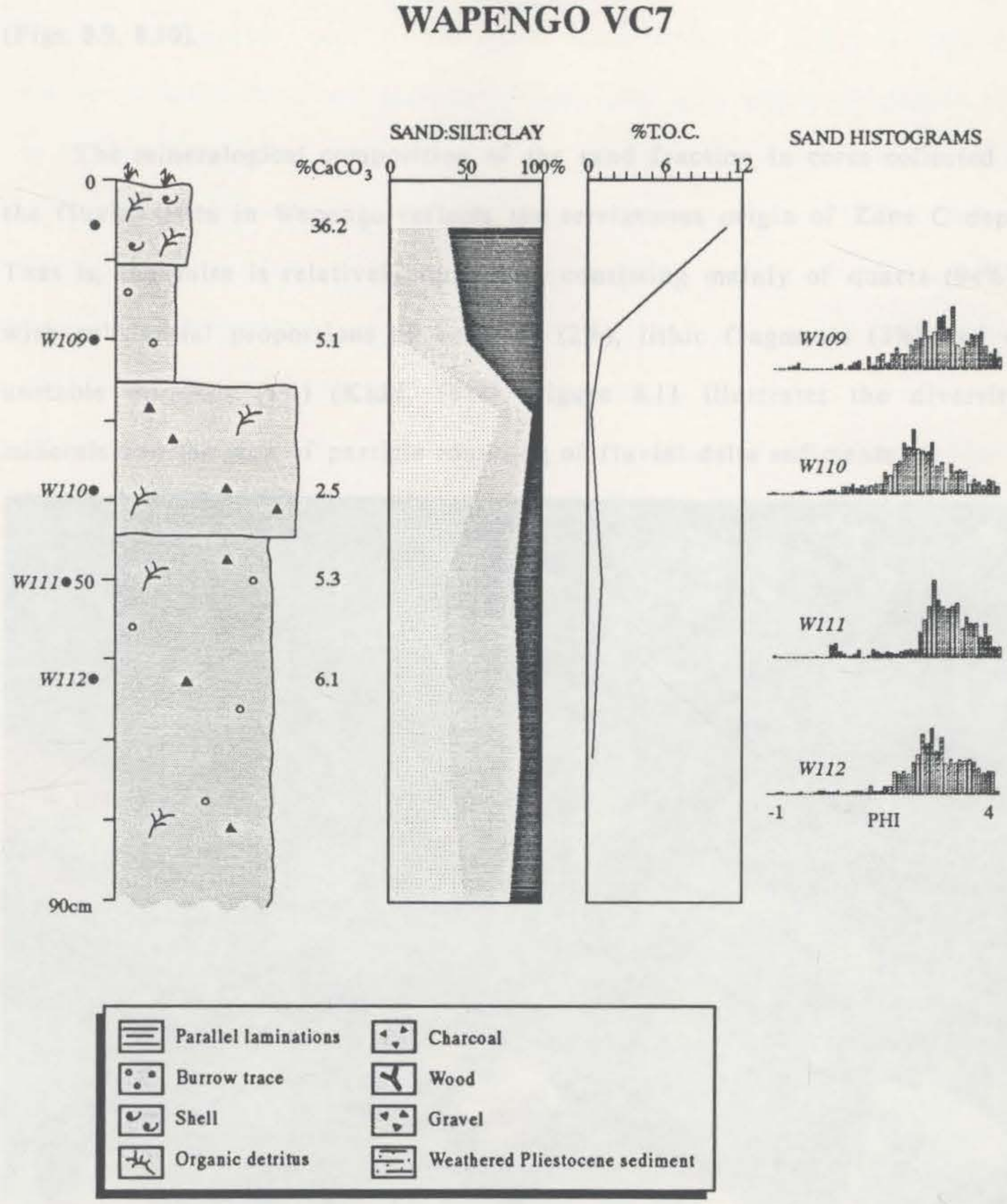


Figure 8.10: Wapengo core VC7 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic carbon content; and, frequency distribution histograms for the sand fraction.

as a leftward shift in the position of the distribution. The fine upper bed in cores VC2 and VC7 is a 25-75cm thick massive unit of organic rich muddy silts with a relatively minor component (0% to 8%) of moderately sorted medium to fine sands (Figs. 8.9, 8.10).

The mineralogical composition of the sand fraction in cores collected from the fluvial delta in Wapengo reflects the terrigenous origin of Zone C deposits. That is, the suite is relatively immature, consisting mainly of quartz (94%) but with substantial proportions of feldspar (2%), lithic fragments (3%) and other unstable minerals (1%) (Kidd, 1978). Figure 8.11 illustrates the diversity of minerals and the lack of particle rounding of fluvial delta sediments.

Figure 8.11: Photomicrograph of fluvial delta sediment sampled from core VC7. Magnification= 22x

8.3.3 Sedimentary structures

The most prevalent structural characteristics of fluvial delta sediments are massive and graded beds within cores taken from the landward and medial reaches of the delta. The definition of individual beds within the deposit appears to be less distinctive at distal sites. For example, the landward core (VC345) displays numerous well defined beds, whereas the seaward core (VC12) possesses a single massive bed (Fig. 8.12). Burrow traces are also present but they are not well preserved, particularly in the coarser sediments. The clearest examples of burrow traces exist in beds that bear significant amounts of organic material, notably off-channel deposits (Fig. 8.12). Cross-bedding is absent from the sedimentary record, presumably because of the lack of dune bedforms on the delta surface.

Massive beds range in thickness from 5cm to >100cm and are associated with poorly sorted coarse sediment. Massive beds also appear intensely bioturbated, though biogenic structures are not clear. Graded beds range in thickness between 5cm and >100cm and are only slightly bioturbated (Fig. 8.12)

An additional structural feature of the fluvial delta deposit is mud and sand interbedding. This feature consists of sharply defined 1-2cm thick lenses of silty organic muds within a silty sand host bed. The best examples of interbedding are found within the fine upper beds of off-channel sequences. X-ray radiographs clearly reveal the interbedding in core VC2 (Fig. 8.12). The significance of this style of bedding is discussed in section 8.5.

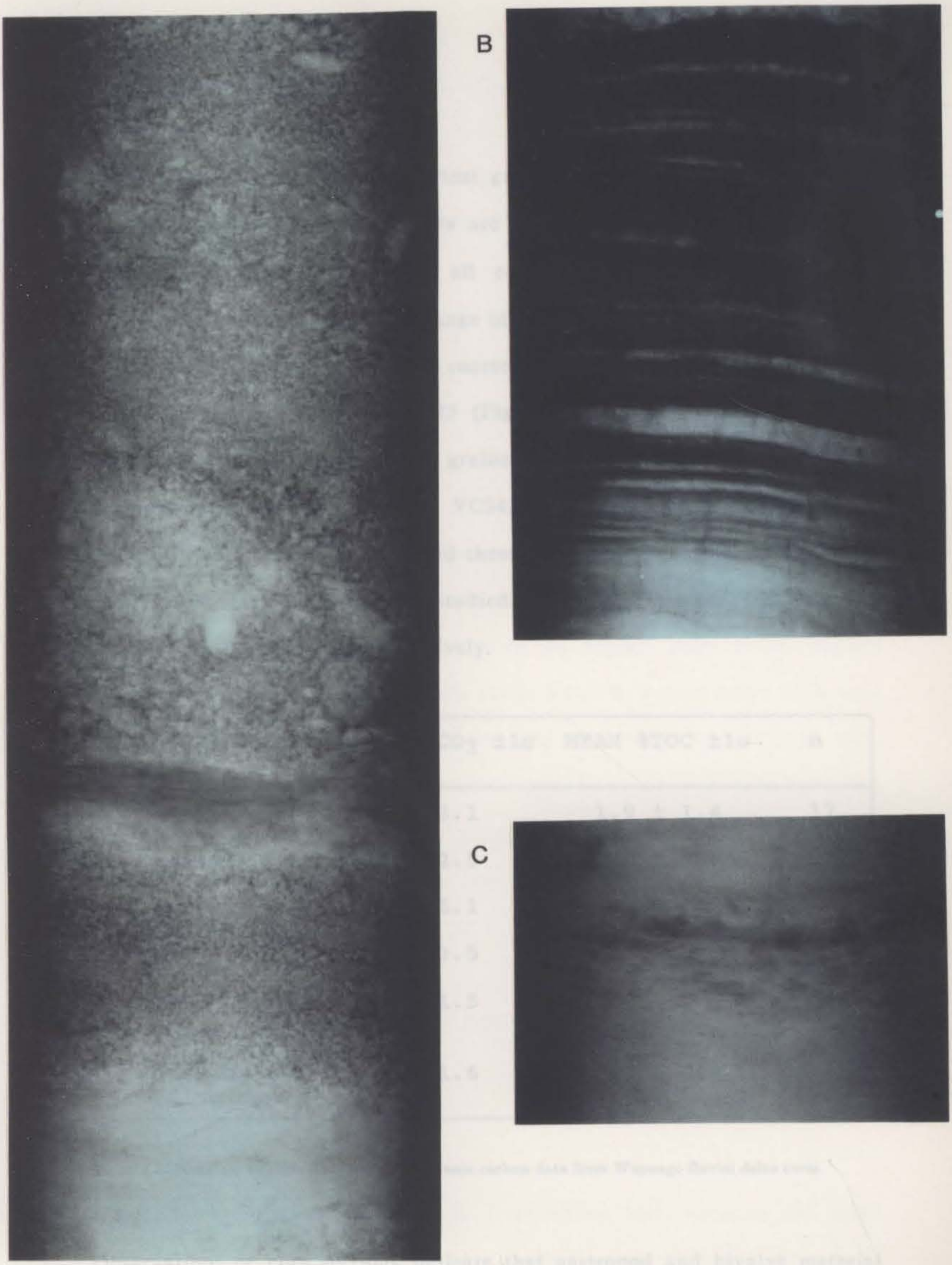


Figure 8.12: Prints of core x-ray radiographs: (a) core VC345 showing massive and graded beds; (b) core VC2 showing mud and sand interbeds in off-channel deposits); (c) concentration of horizontal burrows in organic rich (TOC= 11%) sediment in VC2.

8.3.4 Carbonate content

Carbonate values are plotted against graphic logs for all Wapengo fluvial delta cores (Figs. 8.5-8.10) and the data are summarised in Table 8.3. With the exception of the off-channel cores, all cores display a relatively uniform carbonate profile with values in the range of 1-10%. Lower carbonate values are associated with massive gravel bearing coarse sandy beds. A good example exists at 90cm from the top of core VC345 (Fig. 8.5). Conversely, peak carbonate concentrations occur within the finer grained beds located toward the base of coarsening upward sequences in cores VC345 and VC1. Fine grained beds are thickest within off-channel deposits and these beds possess the highest carbonate content of all fluvial delta sediments studied. Samples from cores VC2 and VC7 yielded values of 22% and 36%, respectively.

CORE	LOCATION	MEAN %$CaCO_3$ ±1σ	MEAN %TOC ±1σ	n
VC345	Landward	5.5 ± 3.1	1.9 ± 1.4	17
VC1	Medial	5.8 ± 2.5	2.0 ± 1.7	10
VC11	Medial	7.2 ± 5.1	1.3 ± 0.6	7
VC12	Seaward	5.5 ± 3.5	0.8 ± 0.9	5
VC7	Off-channel (fine cap)	5.0 ± 1.5 (21.6)	0.9 ± 0.6 (11.1)	4
VC2	Off-channel (fine cap)	4.7 ± 1.6 (36.2)	0.7 ± 0.4 (10.7)	4

Table 8.3: Summary of carbonate and total organic carbon data from Wapengo fluvial delta cores.

Observations of core sections indicate that gastropod and bivalve material deposited within off-channel sediments is typically in an intact condition, suggesting preservation in situ. Indeed, x-ray images show some individuals (e.g. *Tellina albinella, Nassauris sp., Notospisula sp.*) positioned within feeding burrows. By contrast, shell material within coarser deposits close to the present channel are often broken and rarely associated with burrow traces. It is therefore assumed that the channel proximal shell deposits are reworked.

8.3.5 Total organic carbon content

Variations in the concentration of total organic carbon within Wapengo fluvial delta sediments display similar relationships to gross sediment texture as those described for carbonate content. Summary TOC data are presented in Table 8.3 and specific values are plotted in Figures 8.5-8.10. Massive beds of homogeneous sediment texture, found within all fluvial delta cores, contain uniform amounts of TOC, typically in the range 0.5-2.5%. Values below 0.5% were measured within the coarse sandy beds, with good examples in cores VC345, VC1, VC2 and VC7. Peak TOC values (>2.5%) were measured in finer grained sediments and the highest concentrations were yielded by the thick silty muds that constitute the upper beds of off-channel deposits. For example, the upper beds in cores VC2 and VC7 both contain 11% TOC.

8.4 SEDIMENTOLOGY OF THE FLOODPLAIN UNIT

8.4.1 Morphology

The floodplain unit of Zone C in Narrawallee Inlet occupies the great majority of the modern depositional surface. Approximately 9.2km^2, or 85 percent of the palaeovalley area, is floodplain. The entire floodplain is above the level of supratidal inundation and is therefore vegetated by grassland, pasture and uncleared casuarina swamp. The Narrawallee floodplain displays considerable topographic variation. Figure 8.13 presents a plot of the gradient of the floodplain along a central axis defined by drill site elevations, illustrating a clear seaward trending slope. The elevation of drillhole N2, the most landward drill site, is 6.3m above sea level. At site N3, 750 metres down-valley the floodplain is 3.7m above sea level, representing a gradient of 0.2 degrees. The slope is less steep along the remainder of the transect. Between N3 and N7, a distance of 1950 metres, the surface elevation decreases from 3.7m to 3.2m. This is equivalent to a gradient of 0.01 degrees.

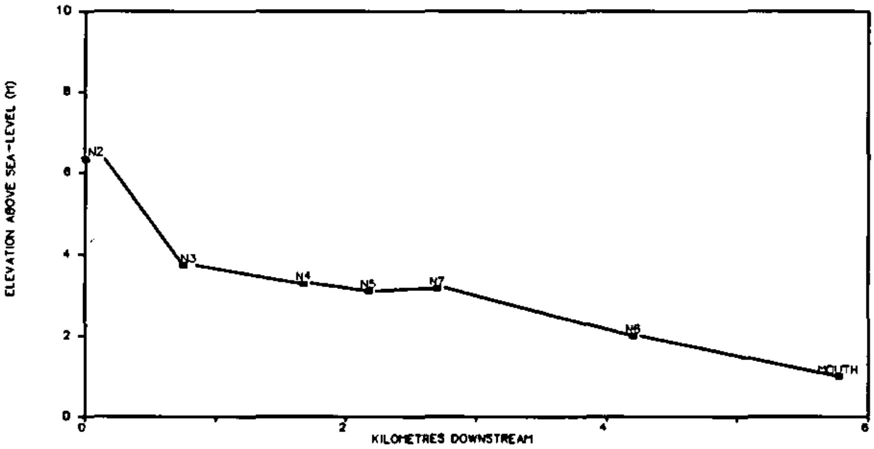


Figure 8.13: Generalised longitudinal profile of the Narrawallee Inlet floodplain. The profile represents straight line segments between drill hole sites and therefore approximates an axial transect.

The floodplain surface also displays topographic variation in a lateral direction. Specifically, levee banks flanking the main fluvial channel are elevated up to one metre above the overbank depositional surface. The Narrawallee floodplain was not surveyed laterally, but field observations indicated that the floodplain slopes downward from the channel toward the edge of the palaeovalley. Similar down-valley and cross-valley floodplain characteristics were observed by Nanson and Young (1981) for the Minnamurra River and American Creek systems, located in the vicinity of Lake Illawarra.

8.4.2 Sediment texture and mineralogy

The most complete core recovery of deposits representing the Narrawallee floodplain was yielded by cores N2 and N3. Detailed descriptions of sediment properties is, therefore, restricted to those two sites.

The upper six metres of sediment in core N2 is interpreted to represent the complete Holocene floodplain sequence in the landward portion of Narrawallee valley. Figure 8.14 presents a graphic log and summary textural plot of the N2 deposit. Summary statistics are listed in Table 8.4. Massive beds of moderately to poorly sorted silty fine sands dominate the deposit. As in the Wapengo delta, the supratidal sands in core N2 do not display evidence of oxidation. Sand content varies between and 43% and 84%. Bed thickness ranges from one to two metres. In some cases, the coarse beds display a subtle fining upward trend represented by an increase in silt content and a decrease in sand size (e.g. 2.5-3.0m) (Fig. 8.14). Interspersed between the massive beds are thin (<10cm) massive beds of moderately sorted silty coarse sands. Frequency histograms of the sand fraction record the contrast in grain size as relatively narrow distributions for fine sands and broad distributions for coarse sands.

Core N3 yielded an eight metre thick deposit of floodplain sediment (Fig 8.15). Recovery between 4.5 and 7.5 metres was poor in silty fine to very coarse sands. The upper 4.5m is characterised by fining upward beds and massive beds of silty fine sands. Occasional beds of moderately to poorly sorted silty coarse sands and gravels are also present. Gravel content in some coarse beds is particularly high (e.g. 47% at 7.5m). Bed thickness varies between 0.1m and two metres, though the coarser sands are always within the thin beds (Fig. 8.15). Texture contrasts are most evident in the sand, silt and clay ratios. For example, the fining upward bed that occupies the upper two metres of the core diplays a decrease in sand content from 93% to 4% and a concomitant increase in silt (2%-53%) and clay (2%-43%) (Fig. 8.15). Variations in the grain size of the sand fraction are less distinct, as illustrated by the slight rightward shift in position of the mode in frequency histograms between the samples from 2m and 0m.

CORE	LOCATION	VERTICAL TREND PHI RANGE	MEAN SIZE (PHI ±1σ)	MEAN SORTING (PHI ±1σ)	N
N2	Landward	Massive 2.45-2.56φ Coarse beds 1.6φ	2.46 ± 0.28	0.71 ± 0.15	23
N3	Landward	Fining 2.00-3.07φ Coarse beds 0.2φ	2.62 ± 0.31	0.58 ± 0.14	19
N5	Medial	Fining 2.11-3.06φ Massive 2.07-2.16φ Coarse beds 0.36φ	2.38 ± 0.33	0.61 ± 0.09	15

Table 8.4: Summary of textural data from Narrawallee three floodplain cores.

Although core recovery in sandy sediment from N5 was poor, a brief description of the samples recovered is included for completeness. The upper 12.4m of N5 consists of an overall fining upward sequence similar in character to that observed in N3. Massive beds of silty fine sands and occasional deposits of poorly sorted coarse to very coarse sands and gravels were observed. An example

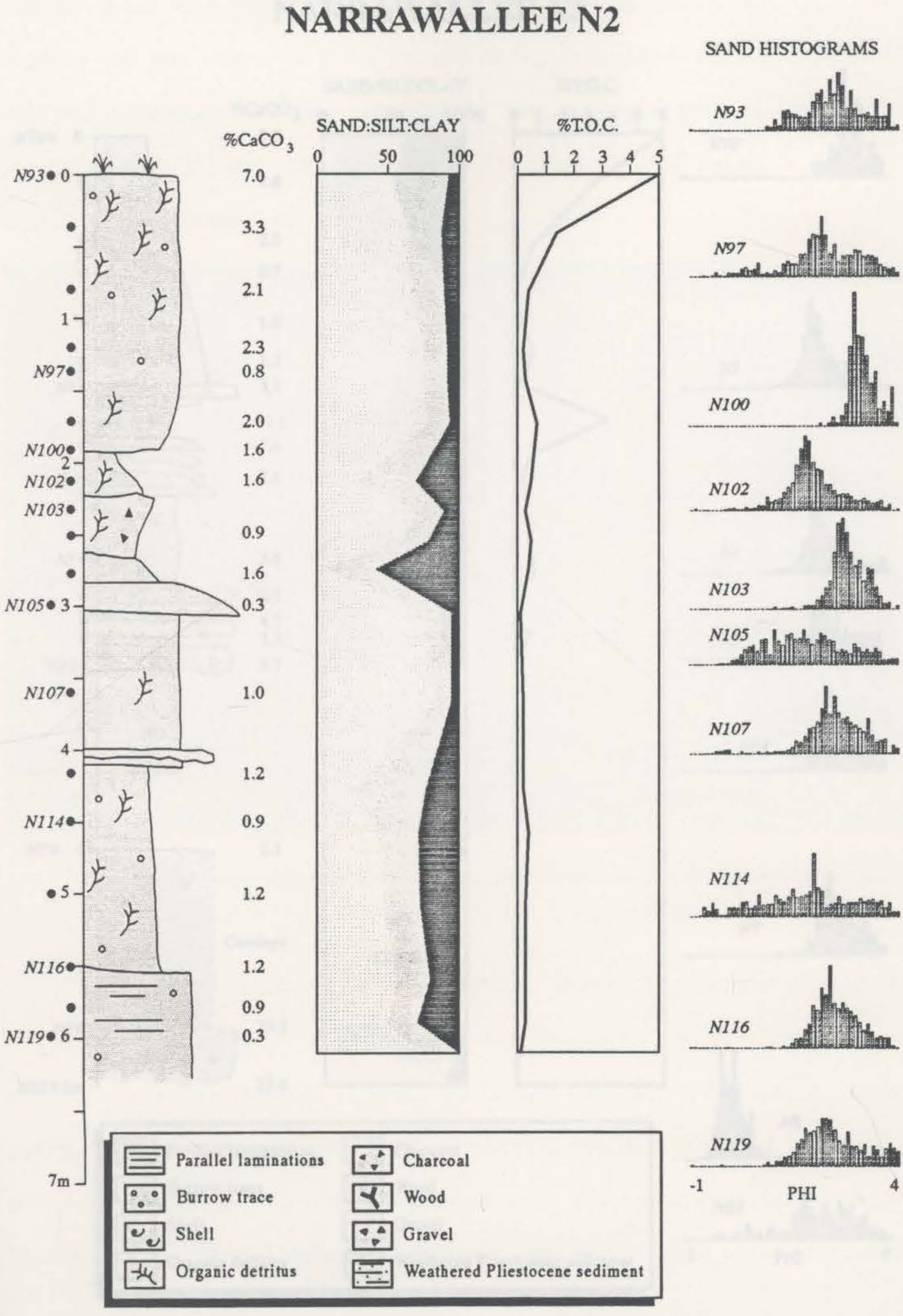


Figure 8.14: Narrawallee core N2 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic content; and, frequency distribution histograms for the sand fraction.

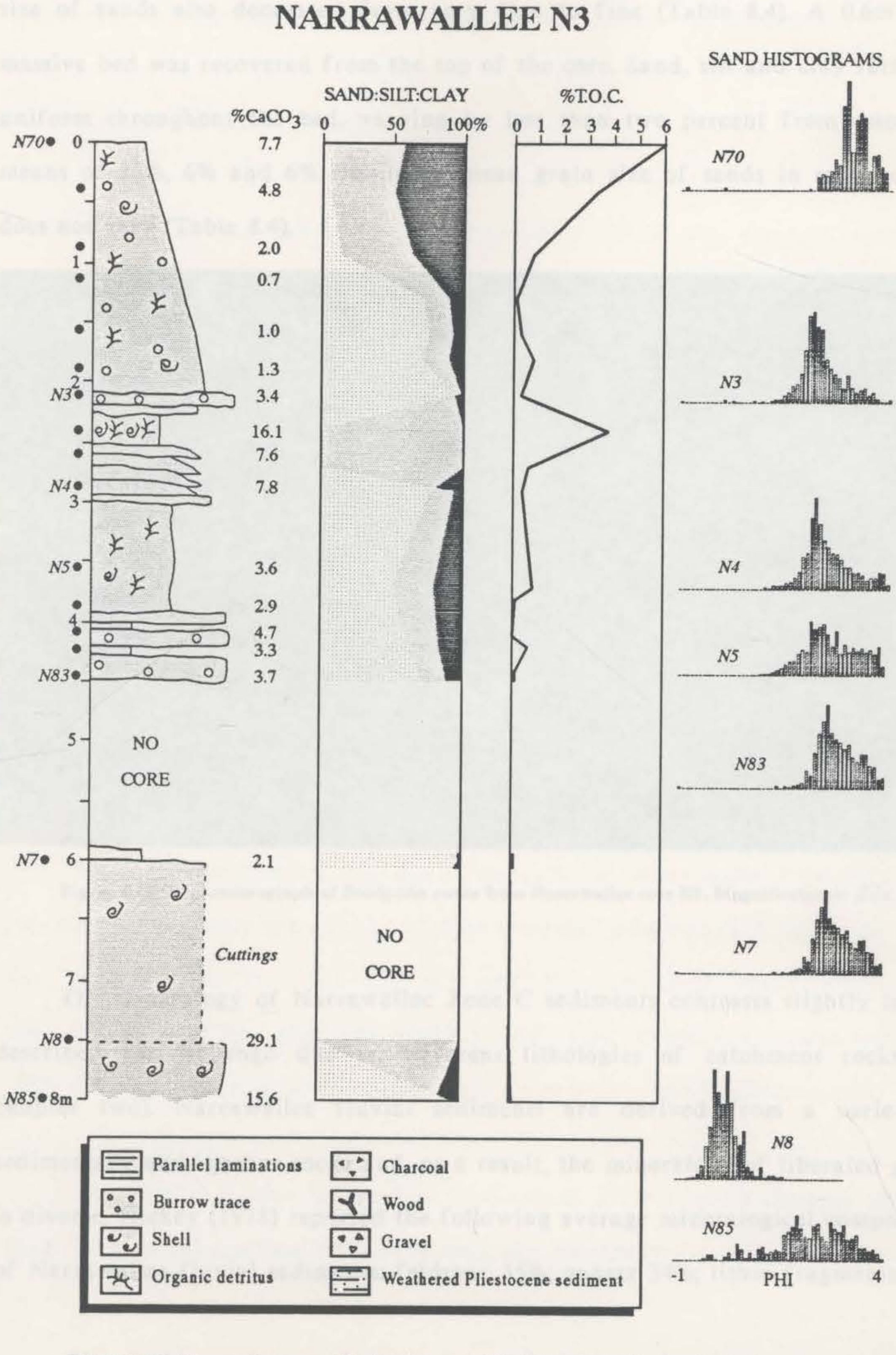


Figure 8.15: Narrawallee core N3 showing: graphic log; subsample depths; carbonate content; sand-silt-clay ratios; total organic content; and, frequency distribution histograms for the sand fraction.

of a fining upward bed exists at 12.0-12.4m, wherein sand content decreases from 78% to 41%, silt increases from 11% to 36% and clay from 11% to 23%. The mean size of sands also decreased from very fine to fine (Table 8.4). A 0.6m thick massive bed was recovered from the top of the core. Sand, silt and clay ratios are uniform throughout the bed, varying by less than two percent from respective means of 88%, 6% and 6%. Similarly, mean grain size of sands in massive beds does not vary (Table 8.4).

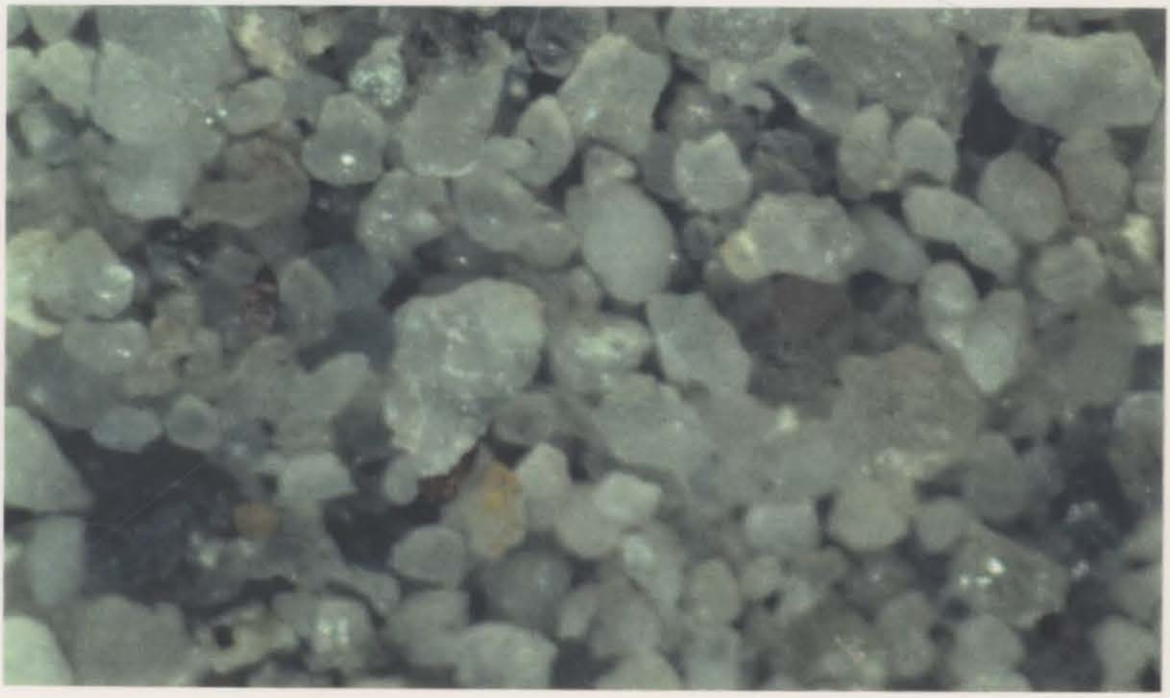


Figure 8.16: Photomicrograph of floodplain sands from Narrawallee core N3. Magnification= 22x

The mineralogy of Narrawallee Zone C sediments contrasts slightly to that described for Wapengo due to different lithologies of catchment rocks (see chapter two). Narrawallee fluvial sediments are derived from a variety of sedimentary and igneous rocks and, as a result, the mineralogy of liberated grains is diverse. Hickey (1978) reported the following average mineralogical composition of Narrawallee fluvial sediments: feldspar 35%; quartz 34%; lithic fragments 17%;

pyroxene 6%; magnetite 6%; and other 2%. Figure 8.16 shows a photomicrograph of a sample of fluvial sediment from core N3, from which it is clear that fluvial sediments are characterised by a first generation mineralogical suite.

8.4.3 Sedimentary structures

The structural character of Narrawallee floodplain deposits that were sampled in an undisturbed condition is relatively simple. That is, beds that are characterised by uniform sediment texture appear devoid of physical structures, an observation that is consistent with massive deposits. Biogenic structures in massive beds are poorly preserved, usually represented by indistinct horizontal burrows. Bioturbation caused by rooting activity is common in the upper metre of the floodplain deposit. Graded beds are evident where fining upward textural trends exist. Bioturbation is minimal in graded beds, hence biogenic structures are absent.

8.4.4 Total organic carbon content

The concentration of organic carbon within Narrawallee Inlet floodplain deposits is uniformly low. Table 8.5 lists the mean and standard deviation values for TOC content in cores N2, N3 and N5. All three cores possess TOC concentrations of less than one percent. Low TOC measurements are consistent with the relatively high sand content that characterises the floodplain unit.

The only exception to the low TOC result are surface sediments analysed from N2 and N3 (surface sediments were not recovered for N5). TOC content in surface sediment is high, between five and six percent, because of the presence of decaying vegetation within the upper 0.20m of the deposit.

CORE	LOCATION	MEAN %$CaCO_3$ ±1σ	MEAN %TOC ±1σ	N
N2	Landward (surface)	1.2 ± 0.7 (7.0)	0.3 ± 0.2 (5.0)	28
N3	Landward (surface)	7.4 ± 6.9 (7.7)	0.8 ± 1.0 (6.0)	30
N5	Medial	4.2 ± 2.0	0.6 ± 0.4	20

Table 8.5: Summary of carbonate and total organic carbon data from Narrawallee floodplain cores.

8.4.5 Carbonate content

Carbonate content is more variable than TOC concentrations (Table 8.5). Select carbonate values are plotted against graphic core logs in Figures 8.14-8.15. In the most landward core, (N2) carbonate content is comparatively low, less than two percent for much of the unit, but increases to seven percent within the upper 0.2m. The increase near the floodplain surface in core N2 is consistent with the observed presence of minor amounts of fine shell fragments within the sediment. The comminuted condition of the shell precludes species identification.

Further downstream, the floodplain deposits in cores N3 and N5 display higher carbonate contents. Peak values in N3 of 29% were recorded in a sample extracted from the base of the floodplain unit that contained large numbers of reworked gastropods in association with poorly sorted coarse sands and gravels. Beds of silty fine to medium sands are also host to reworked shell, but in fewer numbers than in the coarse beds. Carbonate content in the finer beds of N3 and N5 ranges between 0.7% and 9% (Fig. 8.15).

8.5 SUMMARY: REVIEW OF ZONE C PROPERTIES IN RELATION TO DEPOSITIONAL PROCESSES

The morphology and sedimentological character of fluvial delta, floodplain and associated channel units as observed in Wapengo and Narrawallee are interpreted to represent deposition dominated by overbank processes and in situ aggradation of channel bedload. There appears negligible evidence for lateral migration of the channel. The evidence is most comprehensive for Wapengo Lagoon, where core recovery was complete and off-channel sampling was carried out. Therefore, the following summary of the data concentrates upon Wapengo and uses Narrawallee data to demonstrate the general uniformity of Zone C facies character.

(a) Morphology: The finger-like morphology of the Wapengo Lagoon fluvial delta is consistent for Type I deltas that prograde into a shallow basin with low wave energy, low tidal range and negligible littoral drift (Coleman and Wright, 1975; van Heerden, 1983). Because it possesses only one channel, the Wapengo delta is a simple example of a Type I delta. More complex examples occur within the Mississippi River delta, where multiple distributary channels and delta levees have formed (Coleman and Prior, 1980).

(b) Sediment texture: The portion of the Wapengo fluvial delta, sampled for this study, has developed as the result of the filling and eventual abandonment of a prior channel. The lower unit that mantles the pre-Holocene surface, and

characterised by massive beds of silty sand is interpreted to represent aggradation of the bedload in a shallow (c.2m) channel. The coarse beds overlying the channel fill constitute the basal deposits of the levee that flanks the present channel. It is likely that these coarse sands and gravels were deposited as bedload when the levee was a mid-channel bar. The coarse sands are in turn overlain by fining upward silts and fine sands that represent low energy overbank deposition.

The development of the landward section of the fluvial delta has bought about a 50% reduction in size of the middle reaches of Wapengo Creek. Nanson and Young (1981a) also note a downstream reduction in channel size within the floodplains of the Illawarra area (see section 8.2.2). Additional similarities exist between Wapengo and Narrawallee deposits and those studied by Nanson and Young (1981), as detailed below.

Downstream of the channel fill portion of the delta, the fluvial channel appears not to have changed position from the current course. Consequently, the delta has developed initially via deposition of channel bedload as subtidal and intertidal delta lobes, and later as overbank deposition of fines. The resultant vertical sequence displays fining upward trends and massive beds. Fining upward beds are best developed at sites adjacent to the channel. Cores VC1 and VC11 are examples. The trend from silty medium sands and gravels to silty fine sands records the transition from channel margin deposition of bedload to overbank deposition of suspended load.

At off-channel locations, the vertical sequence consists of a basal bed of massive to coarsening upward beds that are interpreted to represent off-channel deposition of the bedload when the delta was regularly inundated by tides prior to the establishment of the supratidal delta levee. Off-channel sites possess thicker fine-grained beds than channel margin sites, suggesting that off-channel sites have experienced low energy overbank depositional conditions for a longer period than channel margin sites. Furthermore, the absence of coarse sediment beds from the upper portion of the off-channel sequence indicates that channel migration has not occurred at Wapengo.

The massive unit of coarse sands and gravels in VC12 was deposited as bedload in the intertidal environment at the present river mouth. This deposit is considered to be the modern equivalent to coarse beds preserved at depth further upstream. It is important to note that the modern deposit is thicker than the buried deposits upstream. Upstream, the bed is 1.1m thick and decreases downstream to 0.20m. The difference in bed thickness suggests that the buried deposit is only a partial record of the original bed. Assuming the original thickness of the buried bed was comparable to that of modern beds, the upper 0.85-0.90m of the original deposit was planed off and presumably redeposited downstream. This process contributes to the general downstream fining of mean sand size within the bedload deposits.

The final comment with regard to the texture of fluvial deposits concerns the thin interbeds and lenses of coarse sands that occur in channel margin cores. These beds are interpreted to represent episodes of high energy deposition. River floods are considered the most probable mechanism for generation of high flow velocities and deposition of relatively coarse bedload. Further, it is highly likely that fine sands are flushed into the barrier basin during these flood events.

The Narrawallee deposits display textural trends that are considered to be consistent with those observed in Wapengo, although the total thickness of Zone C deposits is greater in Narrawallee. Thus, Narrawallee floodplain material consists of massive beds of silty medium sands and fining upward beds that grade from coarse sands and gravels to silty medium sands. Occasional coarse sandy interbeds are also present.

Narrawallee lacks a modern fluvial delta of the type observed in Wapengo Lagoon. However, it is likely that a delta did exist in Narrawallee earlier in the Holocene (see chapter nine). Yet, from the available data, it is not possible to isolate a fluvial delta deposit from the floodplain deposit in Narrawallee. The implication is, therefore, that despite contrasting morphological characteristics the delta and floodplain units are equivalent in terms of their gross sedimentological properties.

(c) Sedimentary structures: Where present, physical structures provide important indications regarding depositional conditions in the fluvial delta and floodplain environment. The majority of Zone C deposits were observed to display a massive structure. The lack of cross-bedding is attributed to the absence of dune bedforms, particularly in delta levee and overbank environments. The channel fill deposit described from the middle reaches of Wapengo Creek also lacks crossbeds, suggesting that dune bedforms are not represented in the channel environment either. The massive appearance of many beds may also be attributed, in part, to bioturbation. Burrowing activities are particularly evident in off-channel locations, where conditions are favourable for colonisation by large populations of infauna (see section 8.5d).

Graded beds are considered an important structural signature that is well developed in Zone C deposits of both Wapengo and Narrawallee. Graded beds exist where there is sufficient variation within the grain size population of the suspended load for waning currents to deposit progressively finer grains (Reineck and Singh, 1986). A graded bed, therefore, may be produced from either a waning river flood or waning tidal currents. In an ideal situation, the distinction between fluvial flood deposits and tidal deposits may be made by identifying structures that have a tidal origin only. For example, the presence of tidal couplets would indicate a tidal genesis (Nio and Yang, 1989). The graded beds in Wapengo cores do not display any structures that are diagnostic of tide influenced deposition. Therefore, the origin of graded beds is described as probably waning fluvial flow with possible but not demonstrable influences from tidal currents.

Mud and sand interbeds were described from cores sampled from the off-channel portion of the Wapengo fluvial delta. Interbedding of fine-grained sediment with coarser material may, in some instances, have a tidal origin. That is, fines settle out onto coarser bed materials at low tide and during slack high water. In section 8.2 it was stated that inundation of the supratidal area of the fluvial delta occurs only during river floods and/or when the high tide is elevated above mean spring level by processes such as seiching, set-up, and/or storm surge. The interbeds preserved within the off-channel deposit are, therefore, interpreted simply as slack water deposits that may be of purely fluvial, purely tidal or mixed fluvial-tidal origin. It is not possible to distinguish between river flood slack water and tidal flood slack water from the sedimentary record.

(d) Carbonate and total organic carbon content: The concentration of carbonate and organic material in fluvial delta and floodplain deposits exhibit a

consistent relationship with sediment texture and in turn, depositional location. That is, low $CaCO_3$ and low TOC values were measured in samples rich with sand and gravel sized particles. Conversely, fine grained sediment yielded high $CaCO_3$ and TOC concentrations. Therefore, peak concentrations of shell and organic detritus are associated with off-channel deposits. X-rays of off-channel cores revealed many shells to be in situ within the upper two metres, whereas channel margin cores typically display a broken and reworked assemblage of shells. The general conclusion to be drawn from these observations is that the off-channel environment provides habitat conditions suited to benthic organisms in terms of the low energy conditions, infrequent reworking of sediments and an abundance of organic material that provides a valuable food source for infauna. Indeed, concentrations of burrow traces are observed in organic rich beds. In contrast, the channel margin and channel fill depositional sites are characterised by more variable, hence stressful, habitat conditions including flash flooding, fluctuating salinity levels and a substrate that is relatively deficient supply of consumable organics.

It is not likely, however, that the organic content of off-channel sediments will remain high because a proportion of the material will eventually be consumed by burrowing infauna. In addition, the supratidal elevation of the upper portion of Zone C sediments suggests that they should become oxidised, involving destruction of a significant proportion of organic material. Nevertheless, the current TOC content of fluvial delta sediments is comparable to that for Zone B deposits and substantially greater than in Zone A sediments of Wapengo. It is pertinent to note that TOC values of the order described are considered sufficient for hydrocarbon source rocks (Bjorlykke, 1989). Further discussion of the economic significance of Zone C deposits is presented in chapter 10.

In conclusion, it is apparent from the observed characteristics of Zone C deposits in Wapengo and Narrawallee that, despite the regular fluctuations in water levels and reversal of currents associated with tidal processes, the tidal signature is by no means clear. Certainly, the only characteristic that may be used to recognise tidal influences is the presence of in situ estuarine shell species, and their long term preservation is not guaranteed. In terms of sediment texture and structures, the fluvial facies does not display any consistent characteristics that may be related unequivocally to tidal processes. Interbedding of silty sands with coarse sands may be a product of irregular tidal inundation of the supratidal fluvial delta, but similar bedding can occur in purely fluvial deposits (Reineck and Singh, 1986).

It is argued, therefore, that Zone C deposits are more strongly influenced by processes that operate at a low frequency but high magnitude. Specifically, sudden and shortlived fluctuations in river discharge that recur on a seasonal to aperiodic basis are considered the primary process at work in Zone C. This conclusion is supported by fluvial studies elsewhere on the south coast. For example, Nanson and Erskine (1988) conclude from an analysis of the morphology and behaviour of several N.S.W. coastal rivers that, in general, southeast Australian coastal rivers are in a deficient sediment supply state. The lack of morphological responses (e.g. bar mobilisation, bank erosion and point bar accretion) to the frequent low magnitude events is cited as evidence for a fluvial regime characterised by long term storage of sediment. Appreciable quantities of floodplain materials are liberated only during large storm and river flood events.

It is these events that are most recognisable in the sedimentary record and it appears that everyday tidal processes are not capable of erasing the signature left by the high energy fluvial events.

CHAPTER 9: LATE QUATERNARY EVOLUTION OF STUDY SITES

9.1 INTRODUCTION

The Late Quaternary history of the two study sites, Wapengo Lagoon and Narrawallee Inlet, are described in this chapter. The discussion is divided into three sections. The first section deals with the evolution of the barrier/inlet facies (Zone A) with an emphasis upon the barrier/ beach-ridge and flood-tidal delta units of both sites. Problems related to radiocarbon dating material in Zone A deposits are identified at the outset. The evolution of Zone A facies in Wapengo and Narrawallee are described and placed in the context previous studies of N.S.W. barrier/inlet deposits.

The evolution of Zones B and C are discussed together in the second section because they are intrinsically linked via a common sediment source . The focus is upon the barrier basin and fluvial delta/floodplain units since they constitute the greater part of Zone B and C deposits. Radiocarbon dating and amino acid racemization dating provide the data for chronologic reconstructions of Zones B and C. The limitations of the respective dating techniques are also discussed. Particular attention is given to the apparent differences in sedimentation rates in Zones B and C between the study sites. Geochronologic data are combined with lithostratigraphic information to provide estimates of sedimentation rates and to formulate explanations for variations in the nature and extent of valley filling. Dating results from Lake Conjola are used to supplement the analysis of barrier basin sedimentation rates and as a basis for comparison of sedimentation rates between estuaries at different stages of evolution along the N.S.W. south coast.

In the final section of the chapter, estuarine morphometric data are assessed in terms of their validity as an evolutionary indicator. The conclusions drawn in chapter five from the morphometric properties of facies are compared to the interpretation of the evolutionary histories of Wapengo and Narrawallee estuaries.

9.2 AGE AND EVOLUTION OF ZONE A FACIES

9.2.1 Dating problems

The difficulty in establishing accurate radiocarbon based chronologic profiles for barrier and tidal inlet deposits along the N.S.W. coast is well recognised (Shepherd, 1974; Thom et al., 1978; Thom et al., 1981; Roy, 1984b). Further, the problem is not confined to the southeast Australian coast, having been encountered in a variety of coastal settings (e.g. U.S. Atlantic coast, Kraft, 1971; Kraft et al., 1973). Problems arise largely from noise introduced to a chronology by lateral and vertical reworking of shell and organic detritus as a result of bedform migration and bioturbative mixing. A common result is for the age of a deposit to be overestimated when relatively old organic material is incoporated into the sediment (Roy, in press). The problem appears to be most acute for landward Zone A deposits. For example, Thom et al. (1981) report that the inner beach ridge at the mouth of the Wonboyn River yielded comminuted shell dated at 8650 ± 150 C-14 yrs b.p. The beach ridge could only have formed at present sea-level, so it is presumed that the shell has been reworked from older transgressive sediment (Thom et al., 1981). Radiocarbon dates of material from the barrier, beach-ridge, backbarrier flat and flood-tidal delta units must, therefore, be treated with caution and taken as maximum age estimates for sediment deposition.

9.2.2 Wapengo barrier evolution

Subsurface investigations in the Wapengo barrier have not been undertaken for this study. The following discussion is, therefore, based upon observations of barrier morphology and evolutionary studies of other N.S.W. barriers displaying analogous form to Wapengo. The Wapengo barrier is a low foredune stationary (Type 2a) barrier (Thom et al., 1978). The barrier is recessed into the inlet with only the backbarrier flat separating it from the northwestern side of the valley (see Fig. 6.9), which is in contrast to the seaward position of other south coast barriers. In addition, the barrier is comparatively small and narrow, occupying an area of only 0.23km^2 (3% of valley area).

The recessed position of the Wapengo barrier is not considered evidence for landward barrier migration, as befits the receded barrier (Type 3) of Thom et al. (1978). Nor is the small size of the barrier a function of a limited supply of marine sediment during the Holocene. Rather, the morphology of the Wapengo barrier is attributed to the inlet throat being directly exposed to the powerful southeast ocean swell, and the lack of a protective headland upon which the barrier may anchor. In Wapengo, most of the marine sands appear to have been deposited during and after the PMT as an extensive flood-tidal delta and backbarrier flat instead of as a large subaerial barrier.

Unfortunately, radiocarbon dating of stationary barrier deposits is less detailed than dating of prograded barriers (see below). Nevertheless, the stratigraphy and morphology of stationary barriers indicates that the transgressive unit and backbarrier sands were deposited between about 8000 and 6500 radiocarbon years ago as sea-level rose and that the regressive unit and capping dune/beach units accumulated once sea-level stabilised (Thom et al., 1978). The stationary condition of the Wapengo barrier suggests that it also formed during the mid-Holocene and has remained essentially unmodified since then.

9.2.3 Wapengo flood-tidal delta evolution

The chronology of flood-tidal delta growth is well documented for select N.S.W. sites. Dating studies have been confined to the larger estuaries of Port Hacking, Broken Bay, Lake Macquarie and the Shoalhaven River (Roy et al., 1980; Roy and Crawford, 1981; Nielson and Roy, 1982; Roy, 1984b). These studies serve to reinforce models of rapid landward transport of marine sand during and following the PMT. However, like prograded barrier growth, rates of tidal delta growth are variable and probably related to estuary type.

Time lines constructed from radiocarbon dates on comminuted shell in the Port Hacking tidal delta by Roy (1984b) suggest continual sedimentation throughout the Holocene at an annual rate of $16000m^3$. Roy (1984b) also cites modern bed measurements which record a 2.8m advance of the delta toe in one year. Port Hacking is a drowned river valley type of estuary with an open mouth that promotes tidal delta growth. The source of sediment for continued progradation is presumed to be reworked surface sands from the estuary mouth (Roy, 1984b).

In contrast to Port Hacking, the flood-tidal delta in the Hawkesbury River estuary appears to be a relict feature. Landward delta growth was very rapid during the PMT, ceasing shortly after stillstand was achieved. A rate of two to four metres per year during the period 10000-7000 yrs BP is suggested by Roy

(1984b). Evidence that tidal delta growth was confined to the early to mid Holocene is provided by the presence of fluvial delta sediments onlapping the inner edge of the tidal delta. A radiocarbon date of 3385 yrs b.p. from near the contact between the fluvial delta and tidal delta points to a mid Holocene termination of tidal delta deposition (Roy, 1984b). The Hawkesbury estuary is also the drowned valley type but the early dominance of fluvial deposition near the estuary mouth prevented further tidal delta formation. Marine sands continue to move into the mouth of the Hawkesbury River, but they are deposited on the Woy Woy beach-ridge barrier located on the northern side of the embayment, rather than the flood-tidal delta (Thom et al., 1981).

Radiocarbon dating of material from the Wapengo tidal delta has been somewhat limited, with only one date obtained. Consequently, it is not possible to calculate sedimentation rates. A large wood fragment was recovered from a vibracore located approximately 100m from the landward limit of the tidal delta at a depth of 1.70m, some 16cm above an erosional contact with weathered Pleistocene clays. It yielded an age of 6230 ± 200 yrs b.p. (SUA 2759). It is highly likely that the wood sample was reworked prior to deposition at the core site, and that the tidal delta sediment was deposited some time after 6000 yrs b.p. Even so, this date and the stationary condition of the delta in historical times provide some indication of the relict nature of tidal delta deposits in Wapengo Lagoon.

Radiocarbon dates from the landward end of two other barrier estuary tidal deltas support the above conclusion. Two shells sampled toward the base of the landward portion of the Lake Macquarie tidal delta returned dates of 4590 ± 210 and 5850 ± 220 yrs BP (Roy, 1984b). In Narrabeen Lagoon a shell sample, also from the distal portion of the tidal delta and 0.1m above the Pleistocene-Holocene contact was dated at 5910 ± 90 yrs BP (Hudson, 1989).

Tidal delta deposition in barrier type estuaries appears to be closely linked to barrier emplacement. That is, once estuary mouths were blocked by barrier and tidal delta deposits, there remained little scope for continued landward migration of marine sand (Roy, 1984b). Exceptions occur where beach-ridge barriers continue to prograde, such as in Broken Bay (Thom et al., 1981). Given that most barrier estuaries of the N.S.W. coast have a stationary barrier and that the sediment surplus required for barrier formation seems to have become depleted in most cases by the stillstand, it is reasonable to conclude that the present form of flood-tidal delta and backbarrier flats has remained largely unaltered since the mid-Holocene.

9.2.4 Narrawallee barrier evolution

The barrier deposit in Narrawallee is a prograded barrier (Type 1) (Thom et al., 1978) that consists of a series of ten beach ridges located behind a relatively large vegetated foredune. The most complete published chronostratigraphic reconstructions of prograded barrier deposits on the N.S.W. coast remain those of Thom et al. (1978, 1981) for select barrier and beach-ridge plains along the central and south coasts (e.g. Fens Embayment, Woy Woy, Shoalhaven, Moruya, Wonboyn). Despite problems with radiocarbon dating, these studies have been able to formulate comprehensive chronostratigraphic sequences for prograded barrier deposits.

In a review of studies undertaken at a number of localities in N.S.W., Thom et al. (1981) demonstrate considerable variability in rates of barrier progradation. For example, at Moruya, Broulee, Woy Woy and the Fens, between 80 and 100 percent of the barrier width was deposited by approximately 4000 years ago, indicating that rapid progradation preceeded a much slower rate of barrier growth. Furthermore, there are significant variations, both between and within sites, in the timing of changes to growth rates. Broulee slowed down by about 6000 yrs BP, Woy Woy by 4000 yrs BP and south Fens by 4500 yrs BP. Progradation at south Moruya slowed by 5000 yrs ago, at central Moruya by 6000 yrs BP, yet at north Moruya the rate has remained constant since before the stillstand (Thom et al., 1981). To add to the complexity, accelerated growth rates are evident at Wonboyn and north Shoalhaven beach-ridge plains, where over half the barrier deposit is less than 4000 years old (Thom et al., 1981).

It was postulated by Thom et al. (1981) that variable growth rates are an expression of local differences in sediment supply related to the process of adjustment of the nearshore profile to present sea-level. Barriers that ceased prograding by the mid-Holocene are recognised as having a steep nearshore profile that is in equilibrium with present sea-level. In contrast, beach-ridge plains with younger late Holocene deposits are associated with a flatter (disequilibrium) nearshore gradient, suggesting an external sediment source such as river input or longshore transport. Attainment of equilibrium following the PMT appears to a occupy a lag period of some 3000 years and longer if external sand sources exist (Thom et al., 1981).

Due to problems of poor core recovery, Zone A sediments from Narrawallee have not been dated for this study. However, several radiocarbon dates are reported by Hann (1985) from shallow auger holes located near the mouth of Narrawallee Inlet (Table 9.1). All dates confirm the Holocene age of the beach-ridge barrier deposit. For example, two shell samples buried 3-4m below sea-level in two beach-ridges situated north of the entrance channel yielded radiocarbon ages of 5290 ± 130 b.p. (SUA-2486) and 3930 ± 75 b.p. (SUA-2485) (Hann, 1985). The younger date corresponds to the most seaward ridge and indicates that the Narrawallee beach-ridge barrier was largely deposited during the mid-Holocene, as suggested by the aforementioned N.S.W. barrier models. In addition, the nearshore profile seaward of the Narrawallee barrier is described by Hann (1985) as relatively steep and concave up, indicating a shoreface that is in apparent equilibrium with present sea-level.

UNIT	DEPTH	MATERIAL	C-14 AGE (yrs bp)	LAB CODE
Inner Beach-ridge	3-4m	shell	5290 ± 130	SUA-2486
Outer Beach-ridge	3-4m	shell	3930 ± 75	SUA-2485
Flood-tidal delta (seaward shoal)	4-5m	shell	1940 ± 55	SUA-2479
Flood-tidal delta (landward shoal)	4-5m	shell	7070 ± 75	SUA-2477

Table 9.1: Conventional radiocarbon dates from Narrawallee Zone A deposits (source: Hann, 1985).

An additional feature of the Zone A deposits in Narrawallee Inlet is the preservation below sea-level of barrier/inlet sands and gravels that are inferred by Hann (1985) to be Pleistocene in age. The thickest barrier deposits were recovered from auger holes located south of the present estuary mouth. Here seven metre thick units of mature podzolised marine sands overlie bedrock and basal fluvial sands. Similar podzolised inlet sands were recovered below sea-level by the author further landward from drillhole N6 (see section 10.2). The weathered condition of the sands suggests lowering of the water table during the Pleistocene glacial low sea-level period. In the vicinity of the estuary mouth a 10m thick deposit of estuarine marine sand with a significant fluvial component occurs at six metres below sea-level (Fig. 9.1) (Hann, 1985). This deposit is interpreted as a Last Interglacial tidal delta unit, assuming that this was the last time sea level reached near the present position along this coast (Roy and Thom, 1981). At both locations the Pleistocene sediments are overlain by Holocene estuarine inlet sands (mixed fluvial & marine) and barrier/dune deposits (Hann, 1985).

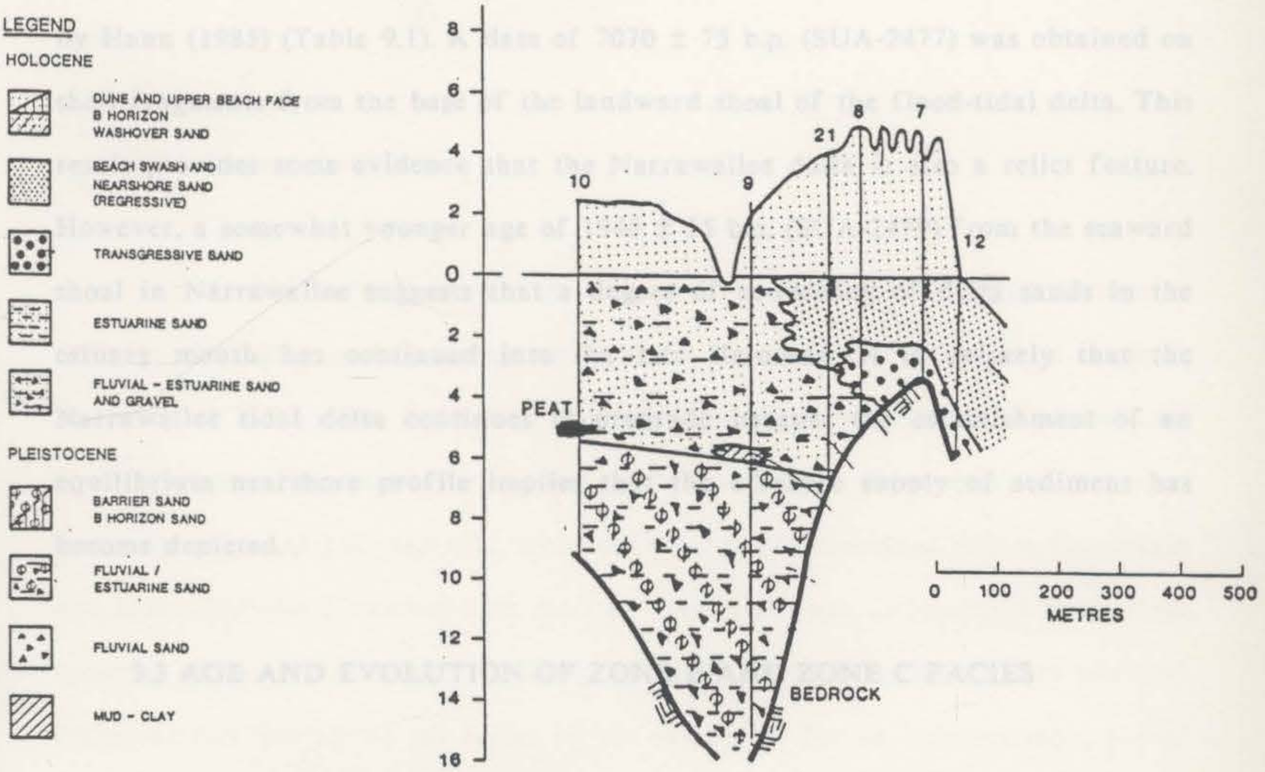


Figure 9.1: Stratigraphic cross-section from the mouth of Narrawallee Inlet, showing basal Pleistocene tidal delta sand unit (reproduced from Hann, 1985).

It is evident, therefore, from the limited subsurface data available from Narrawallee that the valley has experienced a history of barrier and tidal inlet deposition that most likely extends from the Last Interglacial to the present (Hann, 1985). In addition, the presence of fluvial sands in subsurface deposits near the present estuary mouth suggests that Narrawallee Creek has supplied terrestrial sediment to the coast during the Last Interglacial and may continue to do so (Hann, 1985). Further evidence for Late Pleistocene sedimentation in Narrawallee is presented in section 9.3.4.

9.2.5 Narrawallee flood-tidal delta evolution

Two radiocarbon dates from the Narrawallee flood-tidal delta are reported by Hann (1985) (Table 9.1). A date of 7070 ± 75 b.p. (SUA-2477) was obtained on shell fragments from the base of the landward shoal of the flood-tidal delta. This result provides some evidence that the Narrawallee delta is also a relict feature. However, a somewhat younger age of 1940 ± 55 b.p. (SUA-2479) from the seaward shoal in Narrawallee suggests that a degree of reworking of delta sands in the estuary mouth has continued into the late Holocene. It is unlikely that the Narrawallee tidal delta continues to prograde because the establishment of an equilibrium nearshore profile implies that the offshore supply of sediment has become depleted.

9.3 AGE AND EVOLUTION OF ZONE B AND ZONE C FACIES

Previous studies of the age and evolution of barrier basin and fluvial delta/floodplain portions of N.S.W. estuaries have concentrated on sites along the central coast (e.g. Lake Macquarie, Narrabeen Lake, the lower Hawkesbury River and Port Hacking) (Thom and Roy, 1983). There are few published studies of barrier basin and fluvial delta/floodplain evolution in south coast estuaries. The only examples are studies in several Illawarra coastal streams (Neller, 1980; Nanson and Young, 1981a,b) and in the Shoalhaven River valley (Walker, 1962; Wright 1970; Wright et al. 1980; Thom et al., 1981; Wearne, 1984). Of the few radiocarbon dates reported from N.S.W. basin deposits, most relate to the base of the basin deposit allowing gross calculations of Holocene sedimentation rates only (Thom and Roy, 1983). Detailed evolutionary models for Zones B and C incorporating rates of Holocene deposition are yet to be constructed. The results presented here are significant for they add to our understanding of the evolution of N.S.W. estuaries and because they represent a preliminary attempt at quantifying sedimentation rates in the river deltas and basins of south coast estuaries.

9.3.1 Dating problems

Two dating methods have been employed to determine the age of Zone B deposits and assist in the reconstruction of the evolutionary history of Zone B. Radiocarbon dating has been used to obtain numeric ages of samples recovered from Wapengo Lagoon, Lake Conjola and Narrawallee Inlet cores. Substantial fragments of wood and charcoal, ideal for dating, are abundant within floodplain and basin deposits. However, care must be exercised when interpreting dates from material of terrestrial origin because it is highly likely that the wood or charcoal fragment was 'stored' on the slopes of the catchment for an indeterminate period before deposition in the estuary (Blong and Gillespie, 1978). Mixing by burrowing fauna and high energy events (e.g. floods) also occurs in barrier basin and floodplain sediments. Radiocarbon dates from wood and charcoal must, therefore, be treated with caution and taken as a maximum age for the host sediment. In some instances, it is possible to recover shell material that is in situ. Greater confidence may be placed upon the accuracy of a date derived from material in this condition, provided appropriate corrections are made to allow for the marine reservoir effect (Gillespie and Polach, 1979; Gillespie, 1990).

The second dating method employed for Zone B and C samples is amino acid racemization dating. The technique was used to date fossil shell only from Narrawallee sediments. Because amino acid racemization provides relative ages only, it is necessary to calibrate results against a technique that yields radiometric ages. Previous studies in Australia have employed uranium-series and radiocarbon dating to satisfy this need (Schwebel, 1978, 1984; Murray-Wallace et al., 1988; Murray-Wallace and Bourman, 1990; Murray-Wallace et al., 1991). In this study, radiocarbon dates provide the basis for calibration of amino acid racemization results and the derivation of approximate radiometric ages for the shell and associated sediment.

Several assumptions are made with regard to the extent of racemization measured in a fossil shell (Murray-Wallace and Kimber, 1990). The primary concern here relates to the burial history of the shell. In this regard, it is presumed that temperature and moisture conditions have remained more or less stable since deposition of the shell, and that no significant diagenetic changes have occurred. If it is evident that reworking or subaerial weathering of the deposit has occurred, thereby exposing shell to fluctuating environmental conditions, contamination may occur and amino acid D/L ratios must be interpreted with caution. The majority of samples analysed from Narrawallee sediments were extracted from well buried clays that are interpreted to have experienced only minor post-depositional variations in temperature and moisture levels. An additional limitation of amino acid dating is the variation in the extent of racemization that is known to exist between shell of different genera (Murray-Wallace and Kimber, 1990). The problem can be minimised if samples from the one genera are analysed. Unfortunately, due to the paucity of shell material in Narrawallee cores, it was necessary to analyse fossils from a variety of genera.

Amino acid racemization dating has been applied to very few coastal deposits in southeast Australia. The only published results are those from Largs on the central coast and these relate to deposits of presumed Last Interglacial age (Thom and Murray-Wallace, 1988). In terms of allowing for environmental conditions prevailing along the N.S.W. coast during the Late Quaternary, the method is currently in a stage of relative infancy. The results presented in this chapter represent a necessary contribution to the further understanding of the racemization process in fossil shell within the coastal deposits of southeast Australia.

9.3.2 Wapengo basin and delta evolution

Barrier basin and fluvial delta deposits in Wapengo Lagoon disconformably overlie a unit of weathered, compact clay of unknown thickness (Fig. 9.2). The unit was not recovered in all cores and, where observed, occurs at different depths below sea-level (3 to >4m), indicating that the erosional surface is not without topographic variation (see ch.7). The specific age of the unit is not known, however, an analogy may be made between the Wapengo unit and similar deposits elsewhere on the N.S.W. coast that have been assigned an approximate age.

Previous workers have employed the Late Quaternary sea-level curve of Chappell (1983) to ascribe a Last Interglacial age (140-120 Ka) to weathered estuarine clays that are buried beneath Holocene material (e.g. Fullerton Cove in Newcastle Bight, Roy, 1980; Botany Bay, Albani, 1981; Hann, 1986; and, Lake Illawarra, Thom et al., 1986). It is probable, therefore, that the Wapengo unit is also a partially preserved estuarine basin deposit of Last Interglacial age. Results from amino acid racemization analysis of shell from the barrier basin unit in Narrawallee, presented later in this section, support this interpretation of the Wapengo unit.

Figure 9.2: Photograph of section of core W2 from Wapengo Lagoon, (depth: 1.80m to 2.0m) showing erosional surface that marks the disconformity between Pleistocene estuarine clays and Holocene tidal delta sands.

Sample details and results for radiocarbon analyses of Wapengo Lagoon Zone B deposits are presented in Table 9.2. The deepest sample recovered for dating from the Wapengo deposit was a wood fragment from core VC2 at a depth of 4.2m below the surface of the fluvial delta. Core VC2 was located 750 metres seaward of the inferred position of the mid-Holocene basin shoreline (Fig. 9.3). A radiocarbon age of 6390 ± 80 yrs b.p. (SUA-2905) was yielded by the wood. That the wood submitted for dating was reworked and pre-dates the time of deposition of the host sediment is undoubted. However, the degree to which the sample had decomposed was minimal, suggesting that it had not long deceased before being transported to the basin of Wapengo. Therefore, the radiocarbon date on the wood fragment is interpreted to represent a maximum age for the early stages of Holocene barrier basin sedimentation in Wapengo Lagoon.

In terms of the stratigraphy of the Wapengo valley fill, the date of 6390 ± 80 years b.p. makes sense. That is, although not encountered in core VC2, the depth from which the wood sample was recovered is considered close to the contact between Holocene barrier basin deposits and underlying Pleistocene sediments. Furthermore, in the context of the revised Late Quaternary sea-level curve for eastern Australia constructed by Thom and Roy (1983), the date is in excellent agreement with the arrival of sea-level at its current position and the commencement of basin sedimentation by about 6500 yrs BP.

The combined wood and charcoal sample taken from VC11 at a depth of 3.5m provides an additional age estimate for the commencement of Holocene barrier basin sedimentation in Wapengo. The sample was taken from immediately above the Pleistocene-Holocene erosional contact at a location now occupied by an intertidal levee of the fluvial delta, but was once the centre of the basin. A radiocarbon age of 6050 ± 190 yrs b.p. (SUA-2906) was yielded by the sample. The reported age is again taken as a maximum age for deposition of the host sediment because the dated material was not in situ. This result is also considered valid in terms of the Thom and Roy (1983) sea-level curve. Moreover, it is consistent with the date from VC2 in that it indicates that initial deposition at the basin centre site represented by VC11 took place at approximately the same time as the near palaeo-shoreline site, represented by VC2 (Fig. 9.3).

CORE	SAMPLE DEPTH	MATERIAL	LAB CODE	C-14 AGE (YRSb.p.)
Wapengo VC9	1.40-1.42m	Peat	SUA-2758	1590 ±120
Wapengo VC11	3.49-3.53m	Wood and charcoal	SUA-2906	6050 ±190
Wapengo VC2	4.20-4.25m	Wood	SUA-2905	6390 ± 80
Conjola LC2	0.21-0.29m	Organic mud	BETA-33198	790 ± 60
Conjola LC2	3.00-3.01m	Wood	SUA-2859	4160 ± 80
Conjola LC4	0.21-0.29m	Organic mud	BETA-33199	620 ± 80
Conjola LC4	3.71-3.78m	Organic mud	BETA-33200	3570 ± 90

Table 9.2: Sample details for conventional radiocarbon dates from Wapengo Lagoon and Lake Conjola barrier basin and fluvial delta deposits. (Source of Conjola data: Hunter, 1989).

The final radiocarbon date obtained from Wapengo Lagoon barrier basin sediments provides an indication of basin sedimentation rates, and the timing of the important transition from basin to fluvial delta depositional conditions. Core VC9, taken toward the seaward end of the supratidal fluvial delta displays a sharp erosional contact between basin sediments and delta sediments at 1.4m below sea-level (Fig. 9.3). Organic debris sampled immediately above this contact, yielded a radiocarbon age of 1590 ± 120 yrs b.p. (SUA-2758). Although the result has a relatively large error term, the in situ condition of the material allows the date to be accepted as a reasonable estimate of the timing of the start of fluvial delta deposition at the site.

Extrapolating from core VC11, the thickness of basin sediments overlying the Pleistocene unit at the seaward end of the supratidal delta is approximately 2.1m. Based on the two radiocarbon dates from VC11 and VC9 the rate of accretion at the seaward end of the delta is in the range 4.4cm to 5.0cm per century. This sedimentation rate does not take into account natural compaction of basin muds resulting from loading by the fluvial delta. Mud compaction via dewatering and degassing can be significant. Coleman and Prior (1980) cite an extreme compaction rate of 200cm per year for the mouth of the Mississippi River. The sedimentation rate for Wapengo must, therefore, be taken as an approximate minimum rate. Furthermore, it should not be applied to the whole basin because, as shown below, rates will vary according to location relative to the sediment source and depth of the pre-Holocene surface which is not uniform.

At the near palaeo-shoreline site represented by core VC2, the contact between Pleistocene and Holocene sediments is deeper than 4.2m. The minimum thickness, therefore, of the barrier basin deposit at this site is 2.9m. Based on the faster sedimentation rate of 5.0 cm/century from the VC11 site, a period of 5800 years would have been required to accumulate the 2.9m of mud. If correct, this suggests that basin deposition ceased at the VC2 site sometime between 670 and 510 years ago. Since basin deposition at the more remote VC11 site ended 1590 years ago, the sedimentation rate at the VC2 site must have been greater. It is possible to estimate that rate by indirect means using the radiocarbon date from VC11 to infer rates of fluvial delta progradation hence the termination of barrier basin depositional conditions at VC2. The VC11 date suggests that the fluvial delta took 4910 years to prograde 1375m from the inferred palaeo-shoreline. This equates to an approximate rate of 10m growth every 36 years. Assuming a constant rate of delta deposition since 6500 yrs BP, it follows that the delta took 2700 years to reach the VC2 core site. Therefore, the transition from basin to delta depositional conditions at the VC2 site occurred at about 3800 years BP, and the accumulation of the 2.9m of sediment in VC2 was achieved at a rate between 10.8cm and 11.5cm per century, twice that of the central basin site (Fig. 9.2).

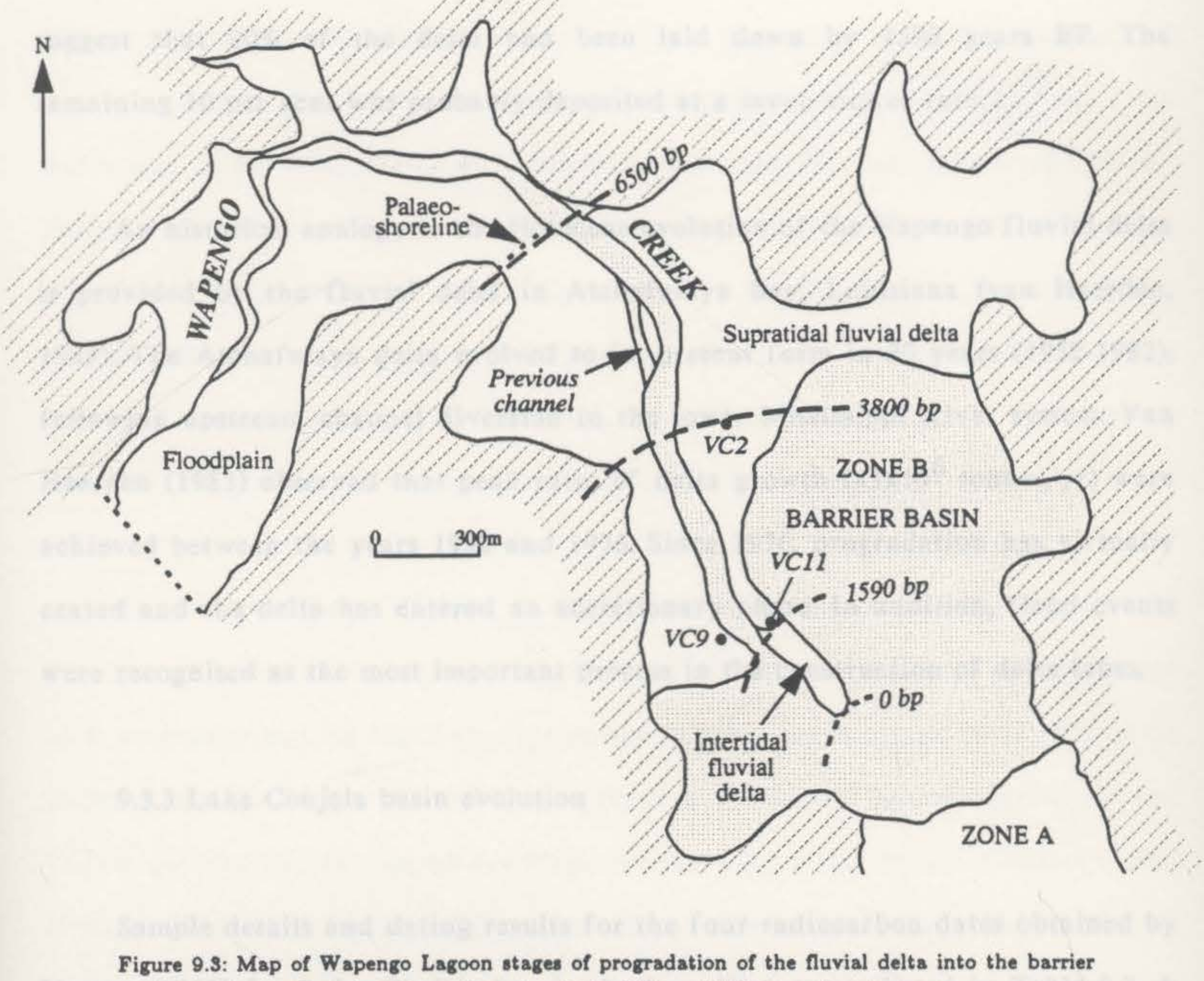


Figure 9.3: Map of Wapengo Lagoon stages of progradation of the fluvial delta into the barrier basin based on radiocarbon dates. Core sites VC2, VC9 and VC11 are also shown.

The assumption that the fluvial delta prograded at a constant rate may not be valid given the apparent spatial variation in basin sedimentation rates. Indeed, it is logical and probable that delta growth rates also decrease with increasing distance from the source. Furthermore, in the context of models of floodplain evolution and channel behaviour of N.S.W. coastal rivers, sediment is probably delivered to estuary deltas in discrete pulses associated with river flood events and/or during an FDR (Erskine and Warner, 1988). Without additional radiocarbon dates from the delta, it is not practical at this point to attempt to quantify rates of delta progradation. However, gross volumetric approximations suggest that 90% of the delta had been laid down by 1590 years BP. The remaining 10 per cent was probably deposited at a much slower rate.

An historical analogy to the Holocene evolution of the Wapengo fluvial delta is provided by the fluvial delta in Atchafalaya Bay, Louisiana (van Heerden, 1983). The Atchafalaya delta evolved to its present form in 30 years (1952-1982), following upstream channel diversion in the lower Mississippi River system. Van Heerden (1983) observed that peak rates of delta growth (43×10^6 tonnes/yr) were achieved between the years 1952 and 1976. Since 1976, progradation has virtually ceased and the delta has entered an accretionary phase. In addition, flood events were recognised as the most important process in the construction of delta lobes.

9.3.3 Lake Conjola basin evolution

Sample details and dating results for the four radiocarbon dates obtained by Hunter (1989) for Lake Conjola barrier basin sediments are listed in Table 9.2. A wood fragment and an organic mud sample, separated by 2.75m of sediment, were dated from core VC2. The core was taken in four metres of water, 800m from the mouth of Conjola Creek. The ages of 4160 ± 80 years b.p. (SUA-2859) and 790 ± 60 years b.p. (BETA-33198) suggest a sedimentation rate of 8.2cm per century. The older wood sample is reworked and provides a maximum age for the sediment only, hence the sedimentation rate is taken as a minimum estimate. The core did not penetrate the full thickness of the basin deposit, but based on this rate and assuming deposition started 6500 years ago, the basin deposit at this site should be at least five metres thick.

The second Conjola core for which radiocarbon dates are available is LC4. This core was taken in basin waters some 9.5m deep at a site 2.8km seaward of the the mouth of Conjola Creek. Radiocarbon ages yielded by organic muds from 0.25m and 3.75m were 620 ± 80 years b.p. (BETA-33199) and 3570 ± 90 (BETA-33200), respectively (Hunter, 1989). Both results are considered reliable because the organic mud consists of weed that is decaying in situ. The two dates suggest a sedimentation rate of 11.9cm per century. However, the complete Holocene sequence was not sampled in core LC4; the estimated thickness of the deposit, based on the above rate, is approximately 7.25m.

Greater confidence is held in the dates and sedimentation rates from LC4 than the LC2 results. As noted above, the basal date from LC2 must be interpreted as a maximum age on the deposit, thereby causing the sedimentation rate to be underestimated. A rate of 11.9cm per century is akin to the maximum rate of 11.5cm per century calculated for Wapengo shoreline sites, yet the Conjola valley is less infilled than Wapengo. The contrast in infill states is explained in part by the deeper palaeovalley of Conjola, reported by Hunter (1989) to be 20-30m. The bedrock depth in Wapengo is not known, but the pre-Holocene surface is known to lie some two to five metres below sea-level. The accommodation space for

Holocene sediment in Conjola is, therefore, much greater than in Wapengo, and is recognised as a primary causal factor of different infill states. The significance of the presence of pre-Holocene deposits as an influential factor on estuary evolution will become more apparent in the following section on Narrawallee Inlet.

9.3.4 Narrawallee basin and delta evolution

Chronostratigraphic data incorporating radiocarbon and amino acid racemization dates from the Narrawallee delta provide a very different set of results to Wapengo and Conjola in terms of the apparent numeric age of the respective barrier basin deposits. Yet the results have important implications to the problem of explaining the variety of estuary infill states among south coast estuaries.

A summary of the results of analyses on the extent of amino acid racemization for eight mollusc fossils from the Narrawallee valley fill are presented in Table 9.3. The relative extent of racemization as indicated by D/L ratios of different amino acids is broadly in agreement with that previously observed for molluscan fossils from southern Australia. That is, D/L ratios are typically arranged in the order Alanine (ALA) >> Phenylalanine (PHE) >> Leucine (LEU) > Glutamic acid (GLU) > Valine (VAL) (Murray-Wallace and Kimber, 1987, 1989). Grandmeans calculated for these amino acids for Narrawallee samples of the same expected geologic age follow the above order, with the exception of alanine and phenylalanine which are very similar. Thus, ALA= 0.37±0.05; PHE= 0.38±0.12; LEU= 0.32±0.05; GLU= 0.28±0.07, and; VAL= 0.23±0.06 (Table 9.3).

Table 9.3: Extent of amino acid racemization ('total acid hydrolsate') for mollusca from the Narrawallee valley fill, N.S.W.

			AMINO ACID D/L RATIOS*					
FAMILY	SPECIES	CORE & DEPTH	ALA	GLU	LEU	PHE	VAL	EXPECTED GEOLOGIC AGE
VENERIDAE	*Eumarcia fumigata*	N1/2 8.99m	0.35 ±0.002	0.22 ±0.0003	0.34 ±0.14	0.28 ±0.005	0.15 ±0.004	late- Pleistocene
TURRITELLIDAE	*Gazameda subsquamosa*	N3 7.50m	---- ----	0.40 ±0.01	---- ----	0.55 ±0.03	0.28 ±0.001	late- Pleistocene
PECTINIDAE	*Chlamys (Chlamys) asperrima*	N3 8.10m	0.36 ±0.01	0.23 ±0.006	0.26 ±0.006	0.24 ±0.008	0.23 ±0.002	late- Pleistocene
PECTINIDAE	*Chlamys (Chlamys) asperrima*	N3 10.15m	0.32 ±0.03	0.24 ±0.006	0.29 ±0.04	0.36 ±0.02	0.22 ±0.04	late- Pleistocene
TELLINIDAE	*Tellina albinella*	N5 3.48m	---- ----	0.18 ±0.06	0.21 ±0.02	0.16 ±0.004	0.08 ±0.00	Holocene
OSTREIDAE	*Ostrea sp.*	N5 23.08m	0.36 ±0.004	---- ----	0.29 ±0.02	0.29 ±0.005	---- ----	late- Pleistocene
PECTINIDAE	*Chlamys (Chlamys) asperrima*	N5 24.52m	0.47 ±0.002	0.31 ±0.001	0.35 ±0.02	0.52 ±0.008	0.30 ±0.004	late- Pleistocene
CARDIIDAE	*Fulvia tenuicostata*	N7 19.40m	0.36 ±0.00	0.25 ±0.01	0.40 ±0.08	0.43 ±0.02	0.18 ±0.008	late- Pleistocene
		GRAND MEAN#	0.37 ±0.0 5	0.28 ±0.07	0.32 ±0.05	0.38 ±0.12	0.23 ±0.06	
		COEFFICIENT OF VARIATION	13.5%	25.0%	15.6%	31.6%	26.1%	

ALA- Alanine; GLU- Glutamic acid; LEU- Leucine; PHE- Phenylalanine; VAL- Valine.

* Data represent mean value ± one standard deviation calculated for replicate analyses.

Grand (arithmetic) mean of D/L ratios for Pleistocene fossils.

The extent of racemization for the mollusca from Narrawallee Inlet compare favourably with Last Interglacial uranium-series calibrated fossils from the Woakwine Range barrier complex (Schwebel, 1978, 1984; Murray-Wallace et al., 1991). Numerical ages of 100,000 ± 30,000 and 125,000 ± 20,000 years respectively, were obtained on aragonitic muds and molluscs from backbarrier lagoon facies of the Woakwine Range (Schwebel, 1978). The extent of racemization of the amino acids, valine (D/L= 0.20±0.01) and leucine (D/L= 0.35±0.01) in *Anadara trapezia* from the Woakwine Range barrier, compare well with the grandmeans of 0.23±0.06 (valine) and 0.32±0.05 (leucine) for the Narrawallee data set (Table 9.3). An assumption in this aminostratigraphic correlation is that present mean annual temperature (MAT) differences between the two sites (Narrawallee MAT: 18^{o}C; Woakwine MAT: 15^{o}C) reflect temperature differences, hence racemization conditions, during the diagenetic history of fossils (Wehmiller, 1984).

Coefficients of variation indicated that alanine (CV= 13.5%) and leucine (CV= 15.6%) provided the most concordant results. Larger scatter was evident, however, for valine (CV= 26.1%), glutamic acid (CV= 25.0%) and phenylalanine (CV= 31.6%). These data contrast with coefficients of variation of less than 12%, typically obtained for within-genus intershell amino acid D/L ratio variation (Murray-Wallace, 1987). The larger variation in the data set presented here is likely to be due to the fact that samples from different families were selected for dating (Table 9.3). Despite the larger D/L ratio variation the data set points to a common Pleistocene age for the taxa sampled from the weathered barrier basin deposit in cores N2, N3 and N5.

The Narrawallee data also plots marginally below the envelope for the extent of valine racemization in Last Interglacial fossils against MAT (latitude) for southern Australia (Murray-Wallace et al., 1991). The standard deviation (±0.06) associated with the grandmean (0.23) indicates that the data are not significantly different at the 2 sigma level. From these data it is concluded that the barrier basin clays recovered in N2, N3 and N5 from Narrawallee were deposited during the Last Interglacial maximum, approximately 120,000 years ago (oxygen isotope substage 5e).

The comparatively limited extent of racemization for several amino acids (GLU: 0.18±0.06; PHE: 0.16±0.004; VAL: 0.08±0.00) in the specimen of *Tellina albinella* from 3.48m in core N5 is consistent with the Holocene age ascribed to the host facies. The Holocene age is based on a lithostratigraphic correlation with facies from the closely related core N7 where subfossil wood has been radiocarbon dated at 6320 ± 100 bp (SUA-2907). These data are also consistent with other radiocarbon calibrated Holocene mollusca in southern Australia (Murray-Wallace et al., 1988; Murray-Wallace & Bourman, 1990). In contrast, the extent of racemization of a range of amino acids (ALA: 0.36±0.00; LEU: 0.40±0.08; PHE: 0.43±0.02) in a specimen of *Fulvia tenuicostata* from 19.4m in core N7 points to a late Pleistocene age for this individual and suggests that it has been locally reworked into the overlying basal Holocene tidal inlet sediments during the PMT.

Radiocarbon dating was undertaken on wood, charcoal and shell from cores N3, N5 and N7 to assist in the calibration of the amino acid data (Table 9.4). With the exception of the wood sample from N7, all samples are likely to be beyond the practical limits of radiocarbon dating. Minor contamination (c.1%) by radiocarbon with a modern activity may have been incorporated in these samples resulting in the apparent ages reported. Gupta & Polach (1985, Table 6.3a) report that contamination by modern carbon at the one per cent level can artificially reduce the age of a 100,000 year old sample to approximately 37,000 years. In this context, the 'finite' radiocarbon age of 33450 ± 800 BP (SUA-2863) for specimens of the gastropod *Gazameda subsquamosa*, from 7.5m in N3, indirectly validates the Last Interglacial age ascribed to the shells based on the extent of amino acid racemization. Indeed, contamination of the sample is highly probable given the weathered condition of the associated barrier basin sediments.

The radiocarbon age of 39200 ± 2100 (NZA-578) yielded by wood and charcoal collected at 21.93m from the barrier basin deposit in core N5 is not credible. Contamination by modern carbon is less likely in this core given the burial depth and lack of weathering of the sediment. The second radiocarbon date of >40000 (NZA-582) from 28.2m in core N5 suggests that the barrier basin deposit is considerably older than 40 Ka BP and does not represent an interstadial age of 30-40 Ka BP.

Support for this interpretation is provided by the oxygen isotope record from planktonic foraminifera (Shackleton and Opdyke, 1973) and models of glacio-eustatic sea level change from Barbados (Matthews, 1973), the Huon Peninsula (Chappell, 1983) and southern Australia (Cann et al., 1988). These studies indicate that sea-levels were too low during oxygen isotope substages 5a (c.82Ka: -16m) and 5c (c.105Ka: -12m to -16m) to account for the barrier basin clays located upvalley in Narrawallee Inlet. Similarly, biostratigraphic studies of benthic foraminifera in southern Australia suggest that sea-level was between 22.5m and 22m below present during oxygen isotope substage 3 (c.45-30 Ka) (Cann et al., 1988). The most recent period before the Holocene during which sea-level was at or above present level, thereby providing estuarine depositional conditions in Narrawallee Inlet, was during the maximum of the Last Interglaciation.

CORE & ELEVATION	SAMPLE DEPTH	MATERIAL	LAB CODE	C-14 AGE (yrs b.p.)
N7 3.2m	6.45m	Wood	SUA-2907	6320 ± 100
N3 3.7m	7.50m	Shell	SUA-2863	33450 ± 800
N5 3.1m	21.93m	Wood	NZA-578	39200 ±2100
N5 3.1m	28.23m	Charcoal	NZA-582	>40 000

Table 9.4: Conventional radiocarbon age for four samples from the Narrawallee valley fill.

The radiocarbon age of 6320 ± 100 (SUA-2907) on a reworked wood sample taken 1.15m from the base of barrier basin muds in auger hole N7 is accepted as a maximum age for the enclosing muds (Table 9.4). The result is consistent with the Holocene sea-level envelope of Thom and Roy (1983) in so far that it suggests that Holocene barrier basin sedimentation at Narrawallee began during the mid-Holocene near the time when sea-level reached the present position.

Unfortunately, the N7 drill hole did not yield any dateable material from the top of the basin muds so sedimentation rates cannot be calculated. However, utilising the barrier basin sedimentation rate of 5.0cm/century from Wapengo central basin sites, the 2.05m of sediment above the dated wood sample in N7 would have taken 4100 years to accrete. This implies a date of 2220 b.p. for the transition at the site from barrier basin to fluvial delta/floodplain depositional conditions. The Narrawallee transition time pre-dates that for Wapengo (1590 b.p) which is to be expected given the advanced infill state of Narrawallee. Unweathered barrier basin deposits at the relatively shallow depth interval of 4.4m to 7.6m were encountered only at the N7 drill site, suggesting that the

Holocene barrier basin in Narrawallee was considerably smaller in area and depth than its late Pleistocene counterpart.

In summary, the Narrawallee Zone B and C deposits represent a product of two successive sea-level highstands. The episodes are each represented by a transgressive-to-highstand barrier basin unit bound by regressive fluvial deposits that interfinger with barrier/inlet facies at the seaward end of the valley. A generalised lithostratigraphic valley profile for Narrawallee is presented in Figure 9.4. Amino acid racemization dating suggests that the lower lagoon facies represents a period of at least partial valley filling during the Last Interglacial (oxygen isotope substage 5e). The diagenetic properties of the sediments also indicate a protracted period of subaerial exposure consistent with the Late Quaternary sea-level record (Chappell, 1983). Unweathered clays, preserved in core N5 from the deeper central area of the valley, are interpreted as a basal remnant of a much thicker estuarine lagoon facies that has been eroded during the last glacial period and ensuing PMT, but not subject to a fluctuating water table (Fig. 9.5). The wedge of fluvial sediment underlying the lower estuarine clays at the head of the valley is interpreted as a low stand regressive deposit. Based on stratigraphic relationships, an age older than 120,000 years is inferred for this fluvial wedge. The thin bed of fluvial sediments overlying the lower clay unit in the central portion of the sequence are interpreted to be a sea-level lowstand deposit of Last Glacial age.

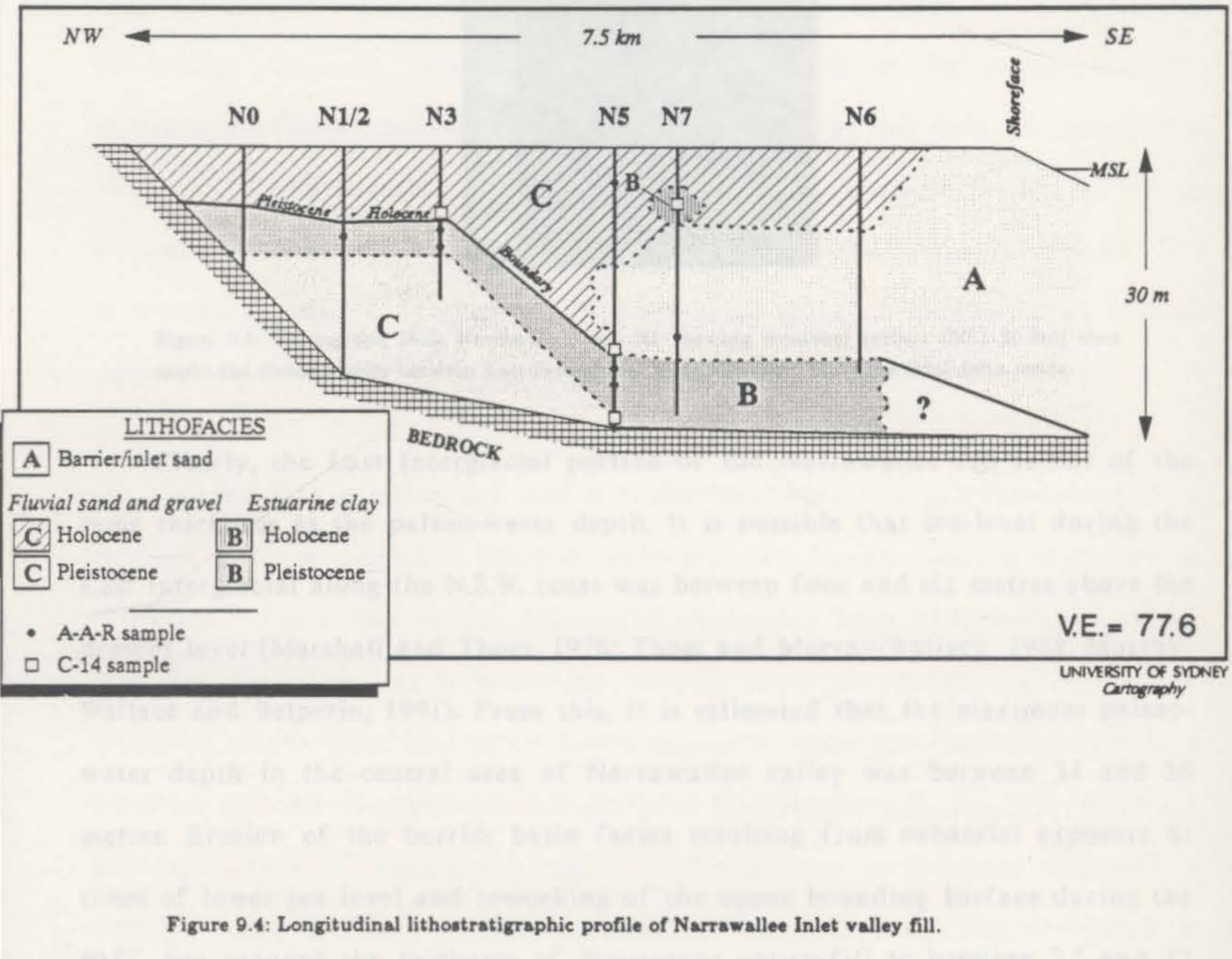


Figure 9.4: Longitudinal lithostratigraphic profile of Narrawallee Inlet valley fill.

Figure 9.5: Photograph from Narrawallee core N5 showing erosional surface (20.1-20.3m) that marks the disconformity between Last Interglacial basin clays and Holocene tidal delta sands.

Clearly, the Last Interglacial portion of the Narrawallee fill is not of the same thickness as the palaeo-water depth. It is possible that sea-level during the Last Interglacial along the N.S.W. coast was between four and six metres above the present level (Marshall and Thom, 1976; Thom and Murray-Wallace, 1988; Murray-Wallace and Belperio, 1991). From this, it is estimated that the maximum palaeo-water depth in the central area of Narrawallee valley was between 34 and 36 metres. Erosion of the barrier basin facies resulting from subaerial exposure at times of lower sea level and reworking of the upper bounding surface during the PMT, has reduced the thickness of Pleistocene valley-fill to between 7.5 and 17 metres at different sections. Lowstand scouring of Last Interglacial deposits is also likely to have occurred in Wapengo Lagoon. Limited information from cores suggests that the scour depth in Wapengo is spatially variable and is probably greatest (up to 7m) toward the valley axis.

The upper lagoon muddy facies at Narrawallee records the second highstand episode, associated with Holocene sea-level. Lowstand scouring of sediments laid down during the first highstand period appears to have been concentrated at the seaward end of the valley, resulting in variable accommodation space for Holocene sedimentation. At the landward end of the valley, where accommodation space is minimal, Holocene deposition has taken the form of a regressive fluvial facies. It appears that conditions suitable for deposition of estuarine muds, during the present highstand, were shortlived and limited to the central valley area. The barrier/inlet facies (discussed in chapter 10) located at the seaward end of the valley is assumed to be largely Holocene, though there is evidence for a Pleistocene component (Hann, 1985). The Holocene portion of the Narrawallee fill is thus an example of a complete progradational sequence dominated by fluvial deposits.

Amino acid racemization and radiocarbon dating also provide information relevant to the dynamics of estuarine environments. The radiocarbon shell sample (SUA-2863) from core N3 is interpreted as having been reworked into basal Holocene sandy gravels (channel lag deposit) from the underlying Pleistocene estuarine clays. These data point to the degree of sediment reworking that may occur in response to glacio-eustatic sea-level fluctuations and serves to illustrate the importance of reliable stratigraphic frameworks to evaluate Quaternary dating methods. Clearly, there is an active layer, the thickness of which is dependent on the dynamics of different environments, from which material may be reworked into younger sediments. Furthermore, the depth of reworking has a direct bearing on the preservation potential of different facies, to be discussed at greater length in chapter ten.

The preservation of estuarine sediments of Last Interglacial age in Narrawallee valley is significant at the regional scale for two reasons. Firstly, it adds to the limited body of geochronologic evidence for late-Pleistocene marine deposits in southeast Australia and extends the known distribution of such deposits. Secondly, the sequence presents a key piece of information that will assist in explaining the wide variety of valley infill states along the New South Wales south coast. That is, it demonstrates how the present extent of valley sedimentation depends not only on contemporary sedimentation rates but also on the degree to which Pleistocene deposits are preserved. Following Davies (1980), the term 'Pleistocene inheritance' is adopted to describe the role played by pre-Holocene deposits in determining the present character of south coast estuaries.

The question arises, why do some estuaries possess significant volumes of Pleistocene sediment and others do not? Two factors must be considered when addressing this question. First, the erosive capacity of fluvial systems during periods of low sea-level. Hunter (1989) compared the bedrock profiles of Narrawallee Inlet and Lake Conjola. Both valleys were found to be incised to approximately 35m below sea-level at their present mouths, and 45m a further 3.5km seaward. However, the dimensions of the two valleys differs in their upstream reaches. Specifically, the Conjola valley is narrow and V-shaped with valley side gradients between 0.02 and 0.07 degrees, whereas the Narrawallee valley is comparatively broad with valley side gradients of 0.01 to 0.03 degrees (Hunter, 1989). It would appear, therefore, that fluvial scouring during periods of low sea-level has been far more effective in the narrow confines of the Lake Conjola valley than in the broader Narrawallee valley.

The second factor to consider with regard to the degree of preservation of Pleistocene deposits is the initial volume of Pleistocene sediment. Obviously, the volume of the original Last Interglacial fill deposit cannot be accurately determined beyond calculating the maximum accommodation space at a time of higher sea level (see above). Given the varied degree of valley filling that exists among south coast estuaries at present sea levels, it is probable that similar variations prevailed during prior sea-level highstands. Indeed, considering the low denudation rates that have characterised southeast Australia throughout the Cainozoic (see chapter two) and in view of the few episodes of sea-level highstand equal to Holocene levels, it is possible that some estuaries (e.g. Lake Conjola) have never reached maturity in Quaternary times.

9.4 FACIES MORPHOMETRY AS AN EVOLUTIONARY INDICATOR

A comparison between the morphometric properties of estuarine facies and the geological evolution of estuaries is presented in this section as a means for assessing the accuracy of a technique of morphometric analysis as an indicator of the evolutionary stage of an estuary.

One of the main characteristics of the ENTROPY generated classes presented in chapter five was the lack of variation in the relative proportion of estuary area occupied by Zone A deposits. For example, ENTROPY classes 1, 2A and 2B all possess a mean Zone A area of between 19 and 25 per cent (standard deviation: 8 to 11%) (see section 5.4.1). The relative uniformity of Zone A area among the 49 estuaries within these three classes is interpreted to be consistent with the observation that barrier/inlet deposits are relict features of early to mid-Holocene age. If barriers and tidal deltas deposition continued until the late

Holocene, a greater degree of inter-estuary variation in present Zone A area would be expected. In the case of the barrier and tidal delta units of Wapengo and Narrawallee, the greater part of deposition took place during and soon after the PMT. Since the mid- to late-Holocene these deposits have remained stationary, with negligible additions of sediment from the shoreface, suggesting establishment of an equilibrium shoreface profile.

With regard to the morphometric properties of Zone B and Zone C, the ENTROPY classification identified considerable variation among the south coast estuary population. Thus, for classes 1, 2A and 2B the mean Zone B area ranged from 1% to 54% (standard deviation: 2 to 8%) and the mean Zone C area from 21% to 80% (standard deviation: 10 to 11%) Further, C.A.R.T. identified the barrier basin and floodplain units as the most important variables in determining the membership of the ENTROPY classes. The ENTROPY classes are interpreted to represent estuaries at different stages of floodplain development. Thus, immature estuaries (class 1) are those with a dominance of Zone B surface deposits. Mature estuaries (classes 2A and 2B) display an areal dominance of Zone C deposits. The identification of considerable variance of Zone B and C development among south coast estuaries is interpreted to be consistent with the observation that deposition within barrier basins and floodplains/deltas has continued throughout the Holocene at varying rates, and in most cases remains active.

While the morphometric analysis identified the relict status of Zone A deposits and the active condition of Zone B and C facies, it was not able to recognise the significance of the Pleistocene inheritance factor. It may be possible, however, to use morphometric data to identify estuaries with a strong Pleistocene inheritance. For example, estuaries that are characterised by a relatively large Zone C area may possess Pleistocene deposits of Last Interglacial age in the shallow sub-surface. Clearly, sub-surface investigations are required to confirm this prediction. Nevertheless, it is argued that a morphometric analysis is valuable in as much that it synthesises a significant quantity of data into a scheme with distinct physical properties, thereby contributing toward our understanding of the character and evolution of south coast estuaries.

9.5 SUMMARY

The Late Quaternary evolution of Wapengo Lagoon and Narrawallee Inlet may be summarised in three main points:

(a) Zone A facies units are relict features that formed relatively rapidly during the PMT and the early stages of the stillstand. Since about 4000 BP deposition on the Wapengo stationary barrier, the Narrawallee prograded barrier, and associated flood-tidal deltas and backbarrier flats has been negligible. In Narrawallee, there appears to be partial preservation of Pleistocene barrier/inlet deposits at depth. The age of these deposits is uncertain, but a Last Interglacial age is probable.

(b) Facies Zones B and C in Wapengo Lagoon display evidence of deposition during the PMT and throughout the late Holocene. Partial preservation of pre-Holocene basin deposits is also evident in Wapengo in the sub-surface. Both Zones B and C remain the most active portions of Wapengo, as evidenced by ongoing basin filling and floodplain growth. In Narrawallee, fluvial sediments that pre-date the Last Interglacial lie at the base of the valley fill. They are overlain by relatively thick, truncated Last Interglacial barrier basin deposits. Holocene basin deposition was relatively short-lived and confined to a small area of the valley. The upper 6 to 20m of the Narrawallee valley fill is dominated by regressive fluvial sediments and overbank deposition now prevails. It is probable that during floods, fluvial sands and silts are transported to the lower reaches of Narrawallee Creek and possibly to the beach and nearshore.

(c) An important control over the stage of estuary filling appears to be the extent of Pleistocene inheritance. Estuaries such as Narrawallee, that have retained a significant volume of Pleistocene fill are currently at an advanced stage of infill. In contrast, estuaries that do not display an appreciable volume of Pleistocene sediments, such as Wapengo and Conjola, appear today as immature to semi-mature estuaries. Contemporary controls on estuary evolution, such as temporal variations in yields of sediment from catchments, should not be totally discounted as significant factors in estuary evolution during the Holocene. It is clear that the process of sediment delivery from the catchment is not fully understood. Further work in this regard is required.

That some estuaries have a relatively strong Pleistocene inheritance has important implications with regard to the long term preservation potential of incised valley fills. An assessment of the preservation potential of each of the three facies zones is presented in the following chapter.

CHAPTER 10: GEOLOGICAL AND ENVIRONMENTAL APPLICATIONS OF MODERN ESTUARINE STUDIES

10.1 INTRODUCTION

The value of geomorphic and sedimentologic studies of estuaries to two related areas of research are investigated in this chapter. The first area concerns the application of modern estuarine studies to the interpretation of ancient estuarine deposits. Initially, an assessment of the preservation potential of modern facies is made, using the Late Quaternary record of south coast estuaries as an indicator. The economic significance of ancient estuarine deposits is also assessed. Particular attention is paid, in this regard, to the potential for ancient deposits to act as reservoirs and sources for hydrocarbons. Several case studies of hydrocarbon bearing ancient estuarine deposits are presented and analogies drawn between the sedimentologic characteristics of those deposits and modern wave-dominated complexes.

The second area of research for which geomorphic estuarine studies may be important is environmental management. The focus of the discussion will be upon evaluating estuarine models as a tool to assist in the prediction of possible responses to greenhouse induced climate change, in particular sea-level rise. Geomorphic, biological and hydrological responses are all considered. An additional environmental application of estuarine studies concerns the impact of human disturbance. Accurate prediction of responses to disturbance, either within the estuary proper or in the catchment, require site specific studies. However, it is argued that knowledge of the general character of estuaries is sufficient to identify facies and morphostratigraphic units that are most sensitive to human activity. In this way, estuarine studies have the potential to contribute to improved environmental management strategies.

10.2 PRESERVATION POTENTIAL AND ECONOMIC SIGNIFICANCE OF ESTUARINE DEPOSITS

Descriptions and analysis of the character of modern estuarine facies can provide very valuable information that may assist the interpretation of ancient deposits (Elliot, 1986; Reineck and Singh, 1986; Ebanks, 1987). In the first instance, the gross textural properties observed in modern facies may be used to invoke an estuarine origin for ancient deposits with similar properties. At a more sophisticated level, an understanding of facies organisation, geometry and internal structure may prove a powerful interpretive tool because it incorporates variation in the spatial and vertical dimensions. For example, knowledge of spatial and stratigraphic relationships between facies may permit one to distinguish between wave-dominated and tide-dominated deposits, and to orient oneself within an incompletely preserved ancient deposit (Reinson et al., 1988; Zaitlin and Shultz, 1990).

An additional application of modern estuarine studies involves identifying facies as possible analogies to ancient deposits that have evolved into petroleum reservoirs and hydrocarbon source rocks. In particular, the textural and structural properties of modern sediments can be used to gauge the primary porosity and permeability of the deposit, and hence assess the reservoir potential of the facies. With regard to source rocks, Bjorlykke (1989:271) states that, "since petroleum is derived from organic matter, it is important to understand how and where sediments with a high organic content are deposited." Therefore, measurements of organic carbon concentrations in modern sediments can provide a useful first-order indication of the potential for hydrocarbon formation in different facies.

Long term survival of estuarine deposits is dependent on a range of factors, including: (i) the rate of post-depositional fluctuations in relative sea-level; (ii) the erosive power of rivers and streams during sea-level lowstand; (iii) wave and tidal energy during sea-level highstand; and, (iv) local tectonic activity (Davis and Clifton, 1987). The rate of sea-level change is considered by Davis and Clifton (1987) to be the paramount control over the preservation of estuarine deposits. The following discussion considers the preservation potential of the three estuarine facies zones separately in the context of variable rates of sea-level rise.

10.2.1 Zone A

10.2.1.1 Preservation potential: Hypothetical responses of Zone A facies to variable rates of sea-level rise were formulated by Sanders and Kumar (1975) and Rampino and Sanders (1980) from the transgressive New York coast. During relatively slow sea-level rise, deposits in the coastal zone are almost completely reworked and redeposited along the retreating coast. A potential example, detailed in chapter three, is the coast of southern Ireland where transgression is slow and decelerating (Carter et al., 1989a). It is anticipated that preservation of the barrier, flood-tidal delta, associated channels and barrier flats will be minimal following a slow transgression (Reinson, 1984). Where sea-level rise is fast, such as along the coast of Nova Scotia, conditions are such that drowned and partially reworked barrier and inlet deposits are stranded on the continental shelf (Boyd and Penland, 1984; Boyd et al., 1987; Carter et al., 1989b).

Among the Zone A morphostratigraphic units recognised in N.S.W. estuaries, those occupying the lower (subtidal) and landward portions of the valley fill are considered to have a greater preservation potential than the upper (supratidal) and seaward units, because during sea-level rise the upper seaward deposits are directly exposed to the erosive forces of the advancing surf zone (Reinson, 1984). Therefore, the regressive portions of barriers (dunes/beaches), beachridge plains and the seaward shoals of flood-tidal deltas are not likely to be preserved under transgressive conditions. The record of Zone A will most probably consist of the basal transgressive portion of barriers, backbarrier flats and the landward shoals of flood-tidal deltas, capped by a nearshore and inner shelf facies.

Whether coastal deposits are more or less likely to survive a sea-level regression than a transgression remains a contentious issue (Kraft, 1971; Klein, 1974; Reinson, 1984). In general terms, however, the preservation of Zone A sediments is considered less probable under regressive conditions, particularly if the lowstand episode is protracted. Lowering of sea level, hence river base level, results in a steepening of river channel gradients and rejuvenation of river downcutting. Consequently, scouring of a barrier and inlet fill may be very extensive due to the seaward (down-valley) location of the Zone A deposits. Fluvial scouring is likely to be more extensive for tidal delta sediments than barrier and beach-ridge units because of the lower vertical position of inlet fill. The presence of a Pleistocene core (Inner Barrier) of Last Interglacial age in many central and north coast barrier complexes and in several south coast barriers (e.g. Bhewerre barrier in St Georges Basin estuary (Thom et al., 1978; Bradshaw, 1987) provides evidence of partial barrier survival during a regression.

An example of extensive lowstand scouring of tidal inlet deposits, hence their lower preservation potential, is provided by the Narrawallee Inlet fill. Drill holes N5 and N6 and N7 (Fig. 4.6) provide the only available record of preserved Zone A sediments for the Narrawallee valley fill. The majority of Zone A sediments observed in the Narrawallee valley fill are Holocene tidal delta deposits that occupy the space created by low-stand scouring of Pleistocene material (Fig. 9.4). It is acknowledged that core recovery was not complete, especially in sandy sediment. Recovery was particularly poor from hole N6 and data from that core and from auger hole N7 are used to assist in stratigraphic reconstructions only. A brief description of the Narrawallee Zone A deposit from core N5 follows:

* Between 14m and 21m core N5 yielded a relatively thick unit of very well to well sorted, well rounded, quartz dominant fine sands. Lithic and feldspar content is slightly greater (up to 5%) in the lower metre;

* The silt and clay fractions of the sediments are low to negligible (<2%) for much of the unit, though the fine fraction is as high as 15% in occasional thin (10cm) beds and rip-up clasts enclosed within the lower three metres of the unit;

* Carbonate content within the upper six metres of the unit varies between 1% and 5% but increases dramatically in the lower metre (20-21m) to between 20% and 50%. All shell is comminuted and presumably reworked;

* TOC content is very low, less than 0.2%, with most samples recording values within the limits of analytical error (+/- 0.1%).

* Facies architecture is difficult to discern due to poor core recovery in sands. Small to medium scale planar cross-bedding and flaser bedding is occasionally evident in resin peels. The majority of core recovered from this facies, however, exhibits a massive structure. Burrow traces are rare and, where present, are poorly defined.

The mature mineralogy and overall textural properties observed from core N5 subsamples are consistent with those documented for the intertidal environments of Zone A in Wapengo Lagoon. Clean medium to fine sands are associated with flood-tidal delta shoals. Cross-bedding in association with flaser bedding is also suggestive of tidally influenced deposition. The presence of comminuted shell, lithics and feldspars in the lower portion of the Zone A unit is likely to reflect reworking and mixing of fluvial with marine sediments during the PMT. While no single attribute of the deposit provides conclusive evidence of tidal inlet depositional conditions, it is argued that collectively these traits are similar to those described for the medial to inner portion of the Wapengo tidal delta.

Lithostratigraphic and chronostratigraphic evidence support the interpretation that tidal delta deposits sampled from core N5 are of Holocene age and not Pleistocene remnants. Pleistocene Zone A sediments were recovered, however, by Hann (1985) near the mouth of Narrawallee Inlet, but they appear limited to isolated pockets of unknown spatial extent. In the lithostratigraphic context, the Zone A deposit in N5 disconformably overlies the basal unit of oxidised barrier basin clays of Pleistocene age. The disconformity is marked by an erosional surface, which was presumably formed by the advancing flood-tidal delta during and following the PMT.

10.2.1.2 Reservoir Potential: The viability of a sedimentary body as a petroleum reservoir is assessed primarily in terms of the porosity and permeability properties of the rock. Additional factors associated with recovery and production of oil and gas are also important, but are not included in this discussion (see Ebanks (1987) for a review of enhanced oil recovery methods).

Porosity is defined as the ratio of the volume of pore space to the volume of sediment and, depending on the manner in which grains are packed, the intergranular porosity of most well sorted sandstones ranges between 26% and 48% (Bjorlykke, 1989). Intragranular and secondary porosity are additional properties that can determine whether a rock is sufficiently porous. The former requires the presence of minerals with the capacity to absorb fluid (e.g. pumice) and the latter results from dissolution of unstable minerals or carbonate, thereby increasing pore space (Ebanks, 1987; Bjorlykke, 1989).

Permeability relates to the mobility of fluids within the sediment body and is dependent upon the size of pore spaces and existence of adequate connections between the spaces (Ebanks, 1987). For example, the presence of bedding planes and fractures within the rock will improve permeablity. Permeability, expressed in millidarcy's (md), is calculated by measuring the rate of flow of a liquid of known viscosity through a rock of known volume. Values for petroleum producing deposits in the range 100md to 1000md are considered very good. In general, high porosity and permeability most commonly occurs in well sorted sandstones that have a high percentage of grains larger than 63 microns and low silt and clay content (Bjorlykke, 1989).

Because the present study is concerned with modern, unconsolidated sediments it is not possible to directly measure the effective porosity and permeability of the deposit since these properties will obviously change during burial and diagenesis. Nevertheless, it is possible to offer general comments regarding the reservoir potential of the Zone A sediment body and to relate the sedimentologic properties of modern deposits to examples of ancient deposits with similar properties and proven reservoir value.

The textural character and mature mineralogical composition of Zone A sediments described for the Wapengo and Narrawallee estuaries are such that the intergranular porosity is considered high. In contrast, intragranular porosity is low due to the poor absorption properties of quartzose sands. The likelihood of clastic Zone A deposits developing secondary porosity, via dissolution of unstable minerals such as micas, feldspars and lithic fragments is also low, given the mineralogical maturity of the original deposit. Secondary porosity may develop through removal of fossil shell but this requires that the carbonate is not leached out prior to burial and consolidation of the deposit.

Assessing the permeability of Zone A deposits is even more speculative task than predicting relative porosity, since permeability is largely dependent upon post-burial conditions. That is, fractures and faults, which greatly improve permeability, only form once the deposit is buried (Ebanks, 1987; Bjorlykke, 1989). The presence, however, of bidirectional crossbedding, reactivation surfaces and other physical sedimentary structures in the modern deposits provide an indication that potentially suitable oil migration paths exist from the time of deposition (Ebanks, 1987).

As shown by the Wapengo study, structural properties of the sedimentary body can vary spatially, in a manner that may not be beneficial to oil migration. Specifically, the absence of bedding planes from the inner portion of the deposit (corresponding to the landward tidal flat shoal and backbarrier flat in Wapengo) could limit the reservoir quality of the rock (Bjorlykke, 1989). Nevertheless, the lateral continuity and textural homogeneity of Zone A facies assemblage, the flood-tidal delta and inlet channel in particular, are attributes that allow one to assign them a high reservoir potential (Zaitlin and Shultz, 1990). This is in contrast to the view of Israel et al. (1987) who suggest that the modern microtidal flood-tidal delta in San Luis Pass would be a low quality reservoir. Their assessment is based on the prediction of low intergranular porosity due to high interstitial clay content, numerous clay filled burrows and intense bioturbation. It would appear, therefore, that not all tidal inlet deposits possess as mature a mineralogical suite as the N.S.W. examples.

Case studies: From the literature examined pertaining to ancient estuarine deposits, three examples from Canada are selected because they provide sufficient data for comparisons between the sedimentologic properties of the ancient deposits and those observed in modern N.S.W. estuaries.

(a) McMurray Formation: The Lower Cretaceous McMurray Formation in northern Alberta includes a tidal channel sand facies characterised by fine to very fine, well sorted quartz rich (95-98%) sands that display small-scale bidirectional cross beds (Fig. 10.1). The combined silt and clay fraction is less than 12%, although higher fines content is recorded in isolated mud clasts. Porosity is high, ranging between 30% and 36% (Rennie, 1987). Because the McMurray Formation is an unconsolidated deposit, a measure of permeability is not relevant for the reservoir assessment and oil recovery from the McMurray sands. (Rennie, 1987).

From the description of the McMurray reservoir sands offered by Rennie (1987), it is possible to equate them with the seaward shoal of the flood-tidal delta and entrance channel in modern deposits on the basis of gross textural properties and the presence of cross-beds. In volumetric terms, the prime production sands of the McMurray Formation are one to two orders of magnitude larger than the volume of Zone A sands in Wapengo and Narrawallee. The volume of the McMurray tidal sand body is approximately 3.87×10^8 m^3. (Rennie, 1987), whereas the Wapengo and Narrawallee volumes are 13.5×10^6 m^3 and 60×10^6 m^3, respectively. Despite their relatively small size there is no discounting the importance of the flood-tidal delta/ entrance channel depositional environments for petroleum exploration.

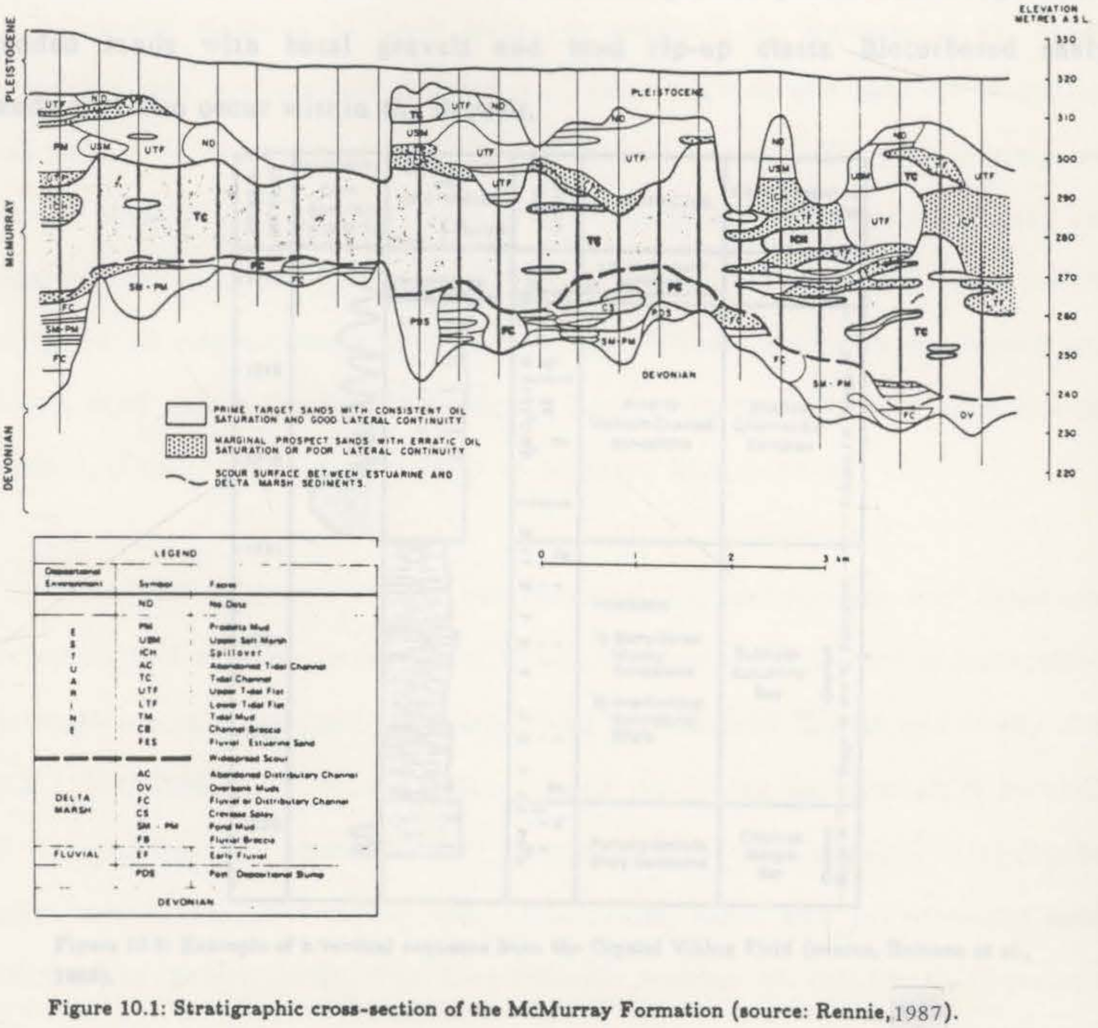


Figure 10.1: Stratigraphic cross-section of the McMurray Formation (source: Rennie, 1987).

(b) Crystal Field: The Crystal Viking Field is a dual oil pool in the Lower Cretaceous Viking Formation, south-central Alberta. Four depositional settings are inferred from the Viking Formation: shelf-shoreface; tidal channel; estuary bay-fill, and; upper transgressive (Fig. 10.2) (Reinson, et al., 1988). The oil bearing reservoir is characterised by a multiple tidal channel lithofacies up to 30m thick (Fig. 10.2) (Reinson et al., 1988). In the regional context, the tidal channel is associated with shelf-shoreface, estuary bay and upper transgressive facies. The tidal channel deposit consists of fine to medium grained planar and trough cross-bedded sands with basal gravels and mud rip-up clasts. Bioturbated shaly sandstones also occur within the deposit.

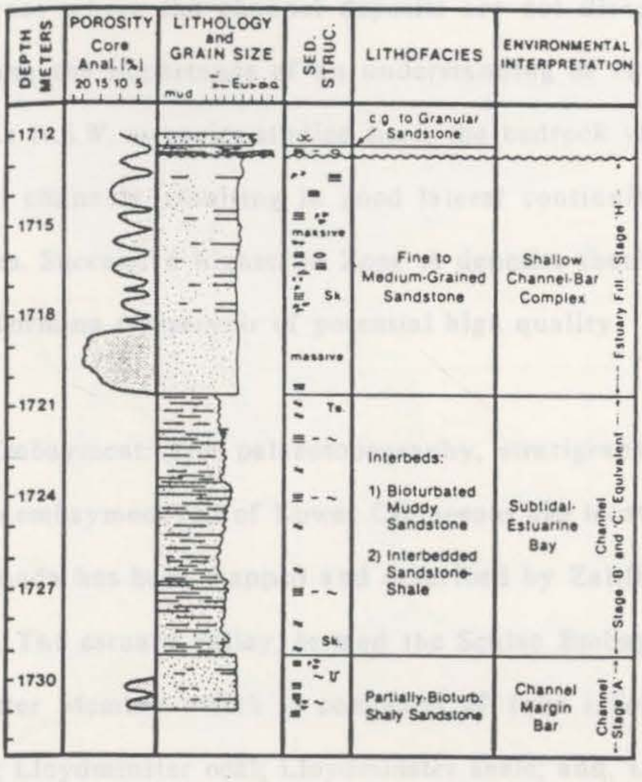


Figure 10.2: Example of a vertical sequence from the Crystal Viking Field (source, Reinson et al., 1988).

The reservoir properties of the channel facies in this case are marginal, with an average porosity of 11% and permeability value of 100md (Reinson et al., 1988). The multiple channel fill sequences that complicate the Viking reservoir are interpreted to represent three successive stillstand depositional episodes during an overall transgressive event lasting $2x10^5$-$3x10^5$ years. Despite the stratigraphic complexity of the Viking deposit, it is considered by Reinson et al. (1988) to be an excellent analogy of modern mesotidal and microtidal tidal inlet deposits. Furthermore, the preservation of three channel fill units of different age attests to the high preservation potential of inlet deposits.

Detailed mapping of each inlet fill sequence by Reinson et al., (1988) illustrated that the reservoir properties of each differed and that oil production was poorest in areas where the channel deposits are not directly superimposed, thereby highlighting the importance of an understanding of facies geometry and distribution. In the N.S.W. estuaries studied here, the bedrock valley sides restrict migration of tidal channels, resulting in good lateral continuity of channel and deltaic sand bodies. Successive highstand Zone A deposits should overlie existing deposits, thereby forming a reservoir of potential high quality.

(c) Senlac Embayment: The palaeotopography, stratigraphy and lithofacies architecture of an embayment fill of Lower Cretaceous age located in west-central Saskatchewan, Canada has been mapped and described by Zaitlin and Shultz (Fig. 10.3) (1984, 1990). The estuary valley, termed the Senlac Embayment, is occupied by the Lloydminster Member which is composed of four informal stratigraphic units: basal sands; Lloydminster coal; Lloydminster shale; and, Lloydminster sands (Zaitlin and Shultz, 1990). The Lloydminster member of the Lower Cretaceous Mannville Group has been interpreted by Zaitlin and Shultz (1984, 1990) as a wave dominated estuarine embayment fill. As such, it is considered an ancient analogue to modern estuaries along the N.S.W. coast.

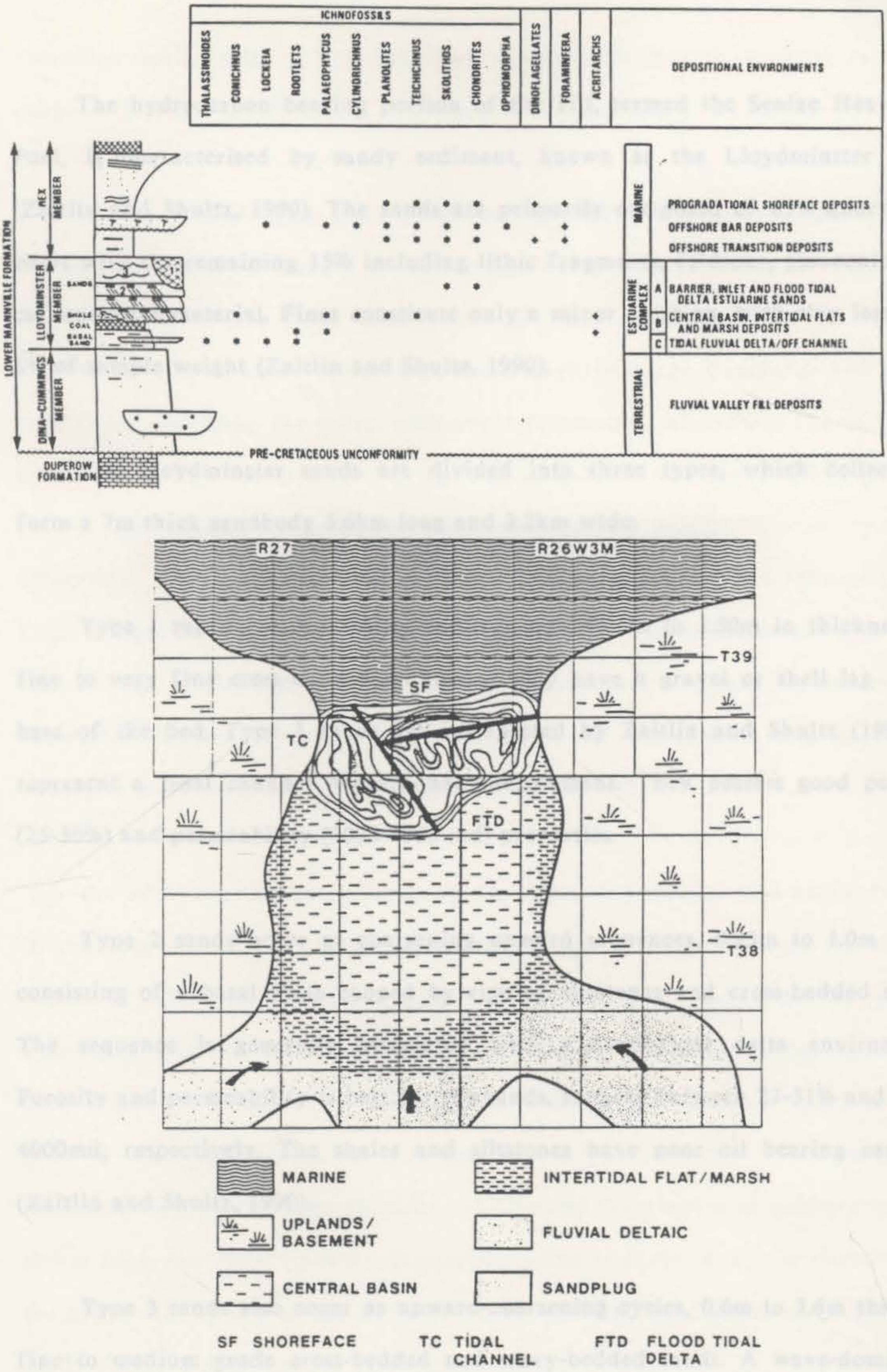


Figure 10.3: Idealised vertical section and spatial organisation of facies in the Senlac Embayment (source: Zaitlin and Shultz, 1990).

The hydrocarbon bearing portion of the fill, termed the Senlac Heavy Oil Pool, is characterised by sandy sediment, known as the Lloydminster sands (Zaitlin and Shultz, 1990). The sands are primarily composed of 85% quartz and chert with the remaining 15% including lithic fragments, feldspar, glauconite and carbonaceous material. Fines constitute only a minor fraction, with clay less than 8% of sample weight (Zaitlin and Shultz, 1990).

The Lloydminster sands are divided into three types, which collectively form a 7m thick sandbody 5.6km long and 3.2km wide:

Type 1 sands feature fining upward beds, 0.05m to 1.50m in thickness, of fine to very fine cross-bedded sands that may have a gravel or shell lag base of the bed. Type 1 sands are interpreted by Zaitlin and Shultz (1990) to represent a tidal channel depositional environment. They possess good porosity (25-30%) and permeability (3000-4000 md) properties.

Type 2 sands occur as coarsening upward sequences, 0.25m to 1.0m thick, consisting of a basal shale capped by rippled siltstones and cross-bedded shales. The sequence is generally associated with a flood-tidal delta environment. Porosity and permeability is best for the sands, ranging between 27-31% and 1000-4000md, respectively. The shales and siltstones have poor oil bearing capacity (Zaitlin and Shultz, 1990).

Type 3 sands also occur as upward-coarsening cycles, 0.6m to 7.6m thick, of fine to medium grade cross-bedded and wavy-bedded sands. A wave-dominated shoreface environment is inferred from these characteristics. Porosity is in the range 29-31% and permeability, 2000-3500md (Zaitlin and Shultz, 1990).

All three sand types have produced significant quantities of oil. Specific production data are presented by Zaitlin and Shultz (1990, figs. 20, 21), suffice to say here that of the three sand facies, the tidal channel facies is the most valuable due to textural uniformity, primary sedimentary structures and lateral continuity providing for more effective hydrocarbon migration. The shoreface facies has the poorest production capacity because of variations in porosity and permeability related to the upward-coarsening texture profile. The ability of the flood-tidal delta facies to produce oil is also restricted by the relatively high fines content and shales that act as obstacles to fluid movement. In the case of the Senlac Pool, knowledge of the distribution and specific properties of reservoir sub-facies enabled more effective and efficient exploration and production strategies to be implemented (Zaitlin and Shultz, 1990).

An additional factor influencing the reservoir potential of a sediment body is the location of the deposit with respect to the hydrocarbon source. The sediments with the greatest source rock potential in the estuarine systems considered here are the organic rich lagoon and interdistributary bay deposits of Zone B and C (see below). The juxtaposition of Zone A reservoir deposits to the Zone B hydrocarbon source sediments is an ideal spatial relationship. Oil migration may, however, be partially inhibited by the absence of primary bedding planes from the distal (landward) portion of the reservoir body. As stated above, the lateral continuity of the tidal delta and barrier flat deposits outweighs such limitations and enhances the reservoir potential.

From this brief assessment of the preservation potential of the various morphostratigraphic units of Zone A and of the petroleum reservoir potential of the sediments as a whole, it is apparent that it is the intertidal and subtidal units that have the greater potential of being incorporated in the geologic record and of becoming repositories for hydrocarbons.

10.2.2 Zone B and Zone C facies

10.2.2.1 Preservation potential: The partial preservation of the highstand estuary fill of Last Interglacial age in Narrawallee Inlet points to the higher potential for incorporation of such deposits in the geologic record than has previously been recognised (Davis and Clifton, 1987). This potential is not, however, uniform for all estuarine facies. The greatest preservation potential is afforded to deposits located in the deepest and landward portion of the valley. Predictably, these deposits include barrier basin and fluvial facies. Long-term preservation of the seaward facies is considered less likely, though this depends on the rate of post-depositional sea level fluctuations.

Preservation of Zone B deposits is also influenced by local conditions such as valley configuration and stream gradients. Thus, estuaries that are infilled only to a limited extent such as Lake Conjola and Burrill Lake and which have narrower valleys and steeper stream gradients, appear to lack Pleistocene deposits (Hunter 1989). Subsurface investigations carried out in Wapengo and Narrawallee suggest that those south coast estuaries that are partially to fully infilled have a strong Pleistocene inheritance. Moreover, the Zone B barrier basin component of the Pleistocene deposit is always part of that inheritance. Pleistocene estuarine deposits are not confined to the N.S.W. south coast. Thick (30-50m) deposits of partly oxidised estuarine clays, that probably relate to the Last Interglacial, have been recovered from the sub-surface in Botany Bay (Albani, 1981; Hann, 1986) and Newcastle Bight (Roy, 1980) on the south-central coast, and in the Richmond River valley on the north coast (Roy and Thom, 1981).

In summary, the preservation potential of fine-grained Zone B deposits, particularly the barrier basin unit, is considered high. The identification of ancient deposits ascribed an estuarine basin origin is further confirmation of this.

10.2.2.2. Source rock potential: In addition to being represented in the geologic record Zone B deposits evolve into high grade hydrocarbon source rocks (e.g. shale and coal). Moreover, they are often located within close proximity, or in direct contact with, reservoir rocks. The characteristic fine-grained texture of the Zone B rock acts as an ideal lateral seal and where multiple fill sequences are preserved, as top and bottom capping rocks (Zaitlin and Shultz, 1990).

The potential for sediments preserved within Zone B and C deposits of south coast estuaries to develop into hydrocarbon rich source rocks may be assessed on the basis of the TOC analysis. It is not intended that this assessment be an absolute measure of hydrocarbon potential, rather an evaluation of the relative potential of facies units comprising a valley fill.

Ultimately, the presence of hydrocarbons in a sedimentary deposit is dependent upon a range of factors relating to the diagenetic history of that particular deposit. These factors include burial depth, pressure, temperature, chemistry of the consituent minerals and of interstitial waters. (Bjorlykke, 1989; Gautier, et al. 1985). Though these factors are important in determining the final hydrocarbon content of a deposit, they are considered secondary to the initial concentration of organic matter since organics are recognised as the primary source of hydrocarbons for petroleum bearing rocks (Bjorlykke, 1989). The examination of TOC concentrations in modern and relict sediments presented in this chapter can therefore assist in detailing the manner in which organic material is incorporated into the sediment and to test for spatial and vertical variability within component facies.

As noted in chapter seven, there exists a fine balance between sedimentation rates and biological destruction of organic material to arrive at optimal TOC concentrations. Bjorlykke (1989) cites TOC values of between two and three percent as ideal concentrations for source rocks. In terms of the morphostratigraphic units of Zones B and C, it appears that this optimum is achieved within the finer grained beds of the barrier basin and upper floodplain units (TOC: 1-10%). Reinson (1973; 1977) reported similarly high TOC values (>5%) from the clay rich basin of Mallacoota Inlet, Victoria. TOC data presented for modern Holocene (Wapengo) and relict Pleistocene (Narrawallee) Zone B deposits indicate that the initial organic content of the sediment is well within accepted limits for potential hydrocarbon source rocks. However, diagenetic alteration of the deposit may in some cases greatly reduce or even totally remove the TOC contained within the deposit, thereby minimising the hydrocarbon source potential of the rock. Notwithstanding, the potential economic merit of ancient estuarine Zone B deposits cannot be overlooked. Three examples are presented below to illustrate the significance of Zone B and Zone C deposits when preserved in economically valuable ancient valley fills.

Case Studies:

(a) McMurray Formation: The Cretaceous McMurray Formation of northern Alberta display a broad suite of facies that may be considered ancient equivalents to modern Zone B and C deposits. These include: fluvial estuarine sands; abandoned fluvial channel silts and sands; overbank muds; fluvial distributary channel sands; crevasse splay sands; pond muds; and, fluvial gravelly sands (Fig. 10.1) (Rennie, 1987). In terms of economic value, only two of the facies are considered prime targets for oil recovery: the fluvial estuarine sand and the distributary fluvial channel sands.

The fluvial estuarine sand facies is characterised by very coarse, poorly sorted gravelly sands that occur as discrete bodies scoured into fine grained estuarine deposits. The fines content is low, typically less than seven per cent. Physical structures include large scale crossbedding and massive beds. A river flood origin is ascribed to this facies by Rennie (1987) and a modern analogy may be the intertidal fluvial delta unit in south coast estuaries. The facies has a porosity of between 29 and 32% and yields 5 to 15% bitumen by weight.

The second productive facies, the distributary fluvial channel, is a moderate to well sorted fine to medium grained sand with occasional coarse sand interbeds. Carbonaceous debris occur throughout. Graded beds and large scale crossbeds are the dominant structures. The fines content is described by Rennie (1987) as erratic and this is interpreted to indicate a depositional environment similar to the channel fill and channel margin deposits of Wapengo Lagoon. The porosity of the distributary channel deposit is in the range 27% to 34% and bitumen yield 4% to 16% (Rennie, 1987).

Zone B deposits are not recognised as constituting a major volumetric component of the McMurray valley fill. Stratigraphic sections indicate that pond muds and prodelta muds occur as small isolated lenses, not unlike the Holocene barrier basin deposit in Narrawallee (Fig 10.1). The McMurray fill is dominated by tidal channel and fluvial channel deposits that record multiple scour and fill cycles associated with an overall transgression punctuated by short regressive periods (Rennie, 1987).

(b) Crystal Field: The Crystal Viking Formation in south-central Alberta includes an estuarine embayment fill of Early Cretaceous age that incorporates Zone B deposits in close association with hydrocarbon bearing reservoir rocks (Reinson et al., 1988). The primary reservoir deposit, described above, is interpreted to be represented by the tidal channel facies at the seaward end of the embayment.

The estuary bay-fill facies is divided by Reinson et al. (1988) into a subtidal estuarine muddy and shallow channel-bar sandy subfacies. The former subfacies is characterised by finely laminated shales with distinct interbeds of bioturbated muddy fine-grained sandstones. Average thickness of the bay-fill subfacies is eight metres and gamma-ray log cross-sections indicate the basin is approximately eight kilometres long and between three and five kilometres wide (Reinson et al., 1988). The subfacies is considered to be an excellent ancient example of modern barrier basin deposits in terms of both sedimentologic character and absolute scale of the deposit.

The estuary bay-fill subfacies is directly overlain by the shallow channel-bar sub-facies. The channel deposit features massive and thinly bedded fine to medium grained sandstone and a high content of carbonaceous material (Reinson et al., 1988). Because of the relatively coarse grained nature of this sub-facies it acts as a low grade secondary reservoir body. The unit is of variable thickness, ranging from 3.5 to 9m, and appears to be preserved only toward the margins of the bay-fill deposit. It is, therefore, a likely analogue of modern intertidal and supratidal barrier basin shoreline deposits.

Fluvial floodplain and off-channel deposits are not recognised in the Crystal Viking Formation. Reinson et al. (1988) argue that their absence is indication for erosion of the uppermost valley deposits during a slow and lengthy transgression. As a result, the estuary fill consists of barrier basin shales capped by inlet sandstone and shelf mudstone (Fig. 10.2).

In the lateral context, the two sub-facies of the bay-fill grade into the tidal channel deposit in the estuary inlet. The hydrocarbon source for the Viking reservoir is not specified by Reinson et al. (1988), however, it is inferred from their stratigraphic reconstruction that oil and gas has migrated up-dip from the bay-fill. Indeed, it is possible that the sandy channel-bar subfacies acted as a conduit for hydrocarbon migration. The lateral association of the bay-fill with the main reservoir body clearly establishes the Viking Formation as an estuarine complex and again emphasises the importance of an understanding of facies organisation and stratigraphic relationships for efficient petroleum exploration (Reinson et al., 1988).

(c) Senlac Embayment: The lower portion of the Lloydminster Member, in the Senlac Embayment fill, comprises three facies: a basal sand; the Lloydminster lignite coal; and, the Lloydminster shale (Fig. 10.3). The basal sands are preserved toward the headward area of Senlac Embayment as calcareous sandstones that display numerous upward fining beds. Bed thickness ranges from 0.1m to 1m and the maximum thickness of bedsets is five metres (Zaitlin and Shultz, 1990). Fining upward trends are gradational from medium massive and cross-bedded sands to rooted siltstones. Zaitlin and Shultz (1990) report that the porosity (<5%) and permeability (<0.01md) of the sands is poor. The location and sedimentologic properties of the basal sand are interpreted by Zaitlin and Shultz (1990) to represent a tide influenced fluvial delta and off-channel environment. A modern analogy would be the supratidal fluvial delta in Zone C of Wapengo Lagoon. In terms of the economic value of the Senlac deposit, the low porosity and permeability indicate that the reservoir potential is very limited. The presence of carbonaceous material in the siltstones may provide a hydrocarbon source.

The Lloydminster coal overlies the basal sands and is interbedded with shale and siltstone and ranges in thickness from one to five metres (Zaitlin and Shultz, 1984) (Fig. 10.3). The shale and siltstone is finely laminated with flaser and lenticular beds and is rich in carbonaceous material, including rootlets. Zaitlin and Shultz (1990) interpret the deposit to derive from what they term a 'fringing upper intertidal to supratidal facies' found within tidal-fluvial and central basin estuarine environments.

In the context of the suite of morphostratigraphic units defined in this study, the Lloydminster coal is interpreted to represent the intertidal and supratidal shoreline units of Zone B. The ancient deposit described by Zaitlin and Shultz (1990) lacks the coarse texture observed in modern deposits. This is attributed to contrasts in the lithology of source rocks for the respective deposits.

The Lloydminster shale overlies the coal unit and is relatively thin and discontinuous being between 0-80cm thick (Fig. 10.3). Sedimentary structures include laminated, flaser and lenticular tidal bedding and burrow traces typical of shallow subtidal to intertidal environments (Zaitlin and Shultz, 1984, 1990). The shale is interpreted by Zaitlin and Shultz (1990) to be the product of deposition in tidal flat and subtidal lagoon environments of the central area of the Senlac Embayment. The modern equivalent, therefore, of the Lloydminster shale are the silty muds of the barrier basin unit of Zone B.

The contact between the coal and shale units and the overlying Lloydminster sands marks an erosional surface along the axis of Senlac Embayment. The sand deposit is in turn overlain by nearshore and shoreface marine siltstones and sandstones (Fig. 10.3). This stratigraphic arrangment of the major facies in the Senlac fill is interpreted as a record of continued marine transgression into the embayment following the flooding during early Albian times (Zaitlin and Shultz, 1984). It is assumed from the limited thickness of the Lloydminster coal and shale that the original deposit was truncated by erosion associated with the rise in relative sea-level, in a manner similar to that described from the seaward end of Narrawallee.

Zaitlin and Shultz (1990) note that the oil held within the Senlac reservoir was sourced not from the Lloydminster coal and shale units but externally from the Mississippian Exshaw Formation to the south-west. Notwithstanding, the coal and shale deposits have played an important role in the development of the Senlac oil pool. That is, the coal provides a lateral seal to the east and west of the reservoir sandstone and the shale provides the seal to the south. The topseal and up-dip seal are provided by offshore and open marine fine grained deposits, respectively. As a result, the Lloydminster sands of the Senlac Embayment are an ideal stratigraphic trap for hydrocarbons (Zaitlin and Shultz, 1990).

With regard to the estuaries of the N.S.W. south coast, the morphostratigraphic units with the greatest source rock potential are the fine grained barrier basin and upper beds of the floodplain and supratidal fluvial delta. The juxtaposition of the basin and flood-tidal delta is an important stratigraphic relationship because it implies a short migration path for hydrocarbons from source to reservoir. The basin shoreline is of marginal potential value. Deposits in the fluvial channel are generally too coarse for the accumulation of significant amounts of organic material. The fluvial channel fill may, however, be a reservoir of moderate quality. Diagenesis of basin muds and floodplain silts may reduce their TOC content, as observed in Narrawallee cores. Post-depositional alteration of TOC appears to be greatest within the upper beds of the basin fill. Despite this limitation, it is apparent that the facies in modern incised valley estuaries have ancient equivalents that today yield hydrocarbons. Ancient estuarine deposits should, therefore, be a prime exploration target.

10.3 APPLICATION OF ESTUARINE STUDIES TO ENVIRONMENTAL MANAGEMENT

Geomorphic studies can contribute in two ways to the management of estuaries that are under stress, either directly or indirectly, from human activity. According to Walker (1984), one of the requirements of a true facies model is that it can act as a predictor in new situations. Disturbance from human activity may produce new situations by altering the natural state of estuaries. With regard to indirect human disturbances, the most immediate threat to estuaries is probably that of sea-level rise and increased storm activity resulting from greenhouse induced climate change (Bird, 1988; Chappell, 1990). In the context of sea-level rise, therefore, an estuarine facies model should provide for prediction of likely geomorphic responses to a change in depositional processes. The aim here is to predict possible geomorphic, hydrological and biological responses in estuaries to a change from a sea-level stillstand regime to a transgressive setting. Integral to predictions is the concept that estuaries lie along a process-controlled spectrum. The bio-physical characteristics of estuaries that are currently experiencing sea-level rise (e.g. Delaware, Maine, Nova Scotia) may therefore be used to predict likely changes in N.S.W estuaries.

Direct human interference to estuarine systems can come from activities within an estuary and in the catchment. An additional requirement of a true facies model is that it provides a guide from which to obtain further data (Walker, 1984). Therefore, while the estuarine facies studies presented here may not be able to directly predict the impact of internal and external human activities, it does provide a framework for future research. In particular, the study identifies areas of an estuary that are most susceptible to disturbance and in need of monitoring. Those areas are highlighted in section 10.3.2.

10.3.1 Predicting responses to climate change

Climate change induced by phenomena such as the greenhouse effect has the potential to severely affect estuarine environments in a number of ways. Estuaries are particularly sensitive to changes in climatic conditions because the climate influences a range of estuarine processes, including: freshwater input; wave activity; mixing and circulation; and, biological activity. If predictions of a global warming trend are correct then significant changes may occur to mean sea-level, wave climate, tidal regime and behaviour of coastal river systems.

The following summary of predictions related to greenhouse induced climate change for Australia are presented to provide a base for discussion of responses from estuarine systems.

Temperature: Mean annual air temperature in southern Australia is estimated to increase by up to four degrees celsius, with the maximum increase during winter months. Increased ocean and estuarine water temperatures are expected 10 to 20 years after the air temperature increase (CSIRO, 1988).

Sea-level: It has been estimated that the extent of global sea-level rise by the year 2050 will range between 0.24 and 1.17m (Hoffman, 1984). For the coast of Australia, conservative estimates predict a rise of 0.20m above present by 2030, whereas extreme estimates put the increase as high as 1.40m by 2030 (CSIRO, 1988). For the purposes of this study, a rise of one metre during the next century is assumed.

Waves and Tides: A rise in sea-level will increase the incidence of wave inundation of beaches and coastal lowlands (Short, 1988). Along the southern N.S.W. coast, waves have their greatest impact on the beach and foredune portion of barriers when wave uprush coincides with sea-level set-up. Set-up is generally caused by infragravity waves reaching the shoreline in the form of standing waves (Short, 1988). If sea-level rises, the impact of these high energy waves could extend to the vegetated foredune of barriers. In addition, the height of breaking waves may increase marginally due to greater shelf and nearshore water depths.

Finally, the incidence of wave penetration into estuary inlets is also likely to increase.

Absolute tidal range along the open coast of southern N.S.W. is not likely to change significantly if sea-level rises. The steep gradient of the southeast Australian shelf and shoreface does not favour tidal amplification. It is probable, however, that an elevation of all tidal stages will occur with increased sea level. Consequently, spring tides will inundate existing supratidal flats in estuaries, tidal range at the landward reaches of estuaries will increase and the tidal limit in rivers will migrate upstream (Short, 1988).

Rainfall and river discharge: The N.S.W. south coast may experience as much as a 50% increase in late summer and autumn rainfall due to an extension of the southern limit of tropical and subtropical maritime air (CSIRO, 1988). The intensity and frequency of storm events may also increase if the predicted southward shift in east coast cyclones occurs. The summer/autumn increase may be partially compensated for by a 20% decrease in winter rainfall due to fewer storm fronts developing from eastward-moving mid latitude high and low pressure cells. Overall, the south coast rainfall pattern is probably going to increase by up to 30% and seasonal differences will become more pronounced (CSIRO, 1988; Pittock, 1988).

The rainfall increase should be mirrored by a similar increase in river discharge into estuaries. In particular, an increase in the number of intense storms could cause an increase in the gradient of the flood-frequency curve for coastal streams and rivers. That is, the return period of catastrophic floods will shorten and the magnitude of floods with a specific recurrence interval will increase. The implications of increased discharge to sediment transport and delivery to estuaries are discussed in section 10.3.1.1.

The following discussion outlines likely responses of south coast estuaries to the aforementioned changes. The focus is upon geomorphic responses. Brief comments regarding likely hydrological and biological responses are also offered.

10.3.1.1 Geomorphic responses: In an assessment of areas of the Australian coast most susceptible to sea-level rise Short (1988), makes an important distinction between vertical inundation and horizontal inundation. That is, permanent flooding in the vertical dimension will be equal to sea-level rise for the entire Australian coast. However, the extent of horizontal inundation will vary depending on the cross-shore gradient of a particular section of coast. In other words, horizontal flooding will be most severe along coasts with a low gradient. The N.S.W south coast lies within a high gradient zone (1:10-1:100) (Short, 1988). The south coast also possesses a second category of low gradient deposits defined in general terms by Short (1988) as coastal wetlands. The wetlands include all estuaries and coastal lagoons and they are considered prone to extensive horizontal flooding.

The response of estuarine geomorphic components to vertical and horizontal inundation will be most evident in facies morphology. In general, estuaries will experience a landward shift in their respective depocentres, although seaward progradation of fluvial deltas may counter this. The possible changes that may occur in each facies zone are as follows:

Zone A: At the seaward side of the barrier/spit complex an increased incidence of beach and foredune erosion and a reduction in barrier width should be the initial change (Short, 1988). In addition, complete recovery of the beach profile to its original form will probably not occur. Consequently, barriers that were previously of the stationary type could well adopt a morphology that is characteristic of receded type barriers.

The general response of flood-tidal deltas will be for deltas to prograde landward into the barrier basin area of the estuary. Progradation requires an adequate external sediment supply. Three possible sources exist. The first source is the present seaward shoal. An encroaching sea will erode the seaward deposits of the pre-existing delta and tidal currents transport them landward. The second source is material eroded from the seaward face of barriers. Efficient delivery of sand from the barrier to the delta requires minimal losses offshore and longshore. Losses of this type are expected to be small due to the compartmentalised nature of the south coast. Indeed, coastal compartments will become more pronounced during a 'mini transgression'. The rate of sea-level rise will also influence the efficiency of sand recycling. The slower the rise, the more complete the reworking of existing deposits. The third source of material for flood-tidal delta growth is the backbarrier flat and relict (Pleistocene) fringing deposits that are currently supratidal. During sea-level rise these deposits will be inundated and the sediments reworked by tidal currents and wind waves.

In estuaries where the supply of sediment for flood-tidal delta growth is insufficient to compensate for inundation, it is possible that the present delta will become a permanent subtidal feature. Estuaries with a narrow bedrock walled entrance and comparatively small barrier (e.g. Pambula Lake) are candidates for tidal delta drowning. One consequence of the tidal delta becoming subtidal is the destruction of prior intertidal shoals and dispersion of marine sands in a landward direction by tidal currents.

Zone B: The barrier basin unit of Zone B will deepen by an amount equal to the magnitude of vertical sea-level rise. The surface area of basins will also increase. However, the extent of areal enlargement will be directly related to the current degree of basin infill. That is, immature estuaries (e.g. Lake Conjola) will record only a small increase (<5%) in basin surface area, whereas mature estuaries (e.g. Narrawallee Inlet) will most likely experience a reversal in their evolutionary condition with the formation of a potentially broad, albeit shallow, basin.

Estuaries that are currently at an intermediate stage of evolution (e.g. Wapengo Lagoon) that are characterised by a basin floor that is within the depth of effective wave base and display significant basin shoreline deposits may also suffer a setback in their evolution. The basin floor will return to a depth greater than the depth of effective wave reworking. This may be partially compensated for by an increase in basin wave power, consequent upon increased storm activity and a greater basin fetch. Supratidal and intertidal shoreline deposits will become subtidal if sea-level rises by one metre and their characteristic coarse sediments partially reworked to form new intertidal and supratidal units.

Zone C: Changes to conditions in the catchment resulting from climate change need also to be considered in relation to Zone C responses. Stream behaviour and sediment delivery are paramount in this regard. Wasson et al. (1988) calculated that average annual hillslope erosion rates in eastern Australia will increase by between 12% and 26% if predictions of increased frequency of intense summer rainfall events under a warmer climate are correct. The delivery of eroded material to the transport reaches of streams may decline, however, due to greater vegetation cover on the lower slopes (Wasson et al., 1988). To counter this effect, it is possible that a warmer, wetter climate across southeast Australia will initiate a permanent flood-dominated regime (FDR). A direct consequence of the onset of a FDR is channel enlargement and the attendant release of sediment for transport to estuaries (Wasson et al., 1988).

Given the above, one likely response of Zone C morphostratigraphic units to sea-level inundation involves the drowning of the present intertidal and supratidal fluvial delta units and the tidal limit will be translated upstream. Inundation of the delta is not likely to result in major reworking of the deposit because it is anticipated that tidal currents will remain relatively weak in Zone C. The widening of the fluvial channel and release of sediment into the channel under FDR conditions, will probably result in renewed delta progradation and floodplain accretion to counter the drowning of the original delta. In addition, flooding and overbank deposition is likely to become more common under a FDR regime (Wasson et al., 1988).

10.3.1.2 Hydrologic responses: Changes to the hydrological regime of south coast estuaries following a sea-level rise are considered here with reference to tidal range, salinity and turbidity. In general terms, the hydrological condition of an estuary will depend largely on two interrelated factors: (a) the condition of the estuary entrance because it influences the efficiency of tidal exchange; and, (b) river discharge because it can affect the condition of the entrance.

The condition of the estuary entrance will be determined in part by the response of the flood-tidal delta to sea-level rise. Three possible responses are envisaged. First, if a flood-tidal delta is drowned and the estuary entrance becomes deeper, as predicted for a rock walled inlet, the tidal range will increase throughout the estuary and tidal waters will penetrate further landward. Second, if the tidal delta surface accretes at a rate equivalent to sea-level rise through the addition of sediment from the barrier and seaward delta shoals then tidal range in the estuary may not change significantly. The third response involves a decrease in tidal range due to deposition of a large volume of marine sand in the estuary mouth. In extreme cases the estuary mouth may close.

Given the variety of entrance conditions among south coast estuaries at present sea-level, it is likely that all three responses will occur if sea-level rises. However, it is predicted that there will be more closed estuaries than at present because a 'mini transgression' will further compartmentalise the coast and promote retention of barrier/inlet sands within present embayments. Further, inlet closure will be favoured if sea-level rise is slow, allowing for efficient reworking of seaward barrier and tidal delta sediments.

Changes to the salinity regime in estuaries following sea-level rise will depend upon the condition of the estuary entrance and river discharge (Sherwood, 1988). In estuaries with a permanently open mouth, the wedge of saline waters will penetrate further landward, possibly into the present non-tidal reaches of the fluvial channel. Increased salinity will be most noticable in estuaries where the flood-tidal delta is drowned and attenuation of the tidal prism is minimal. At the other extreme, where estuary mouths become closed a trend toward brackish and fresh conditions may develop.

The salinity structure may be complicated by changes in river discharge. For example, if the frequency of river flooding increases in association with a FDR, the influence of the saline wedge may be significantly reduced. However, the flood discharge required to achieve flushing of an estuary will be greater than at present due to the increased estuary volume following sea-level rise. Further, a warmer climate and larger estuary surface area could result in higher evaporation rates, adding to the uncertainty regarding estuarine salinity structure after sea-level rise.

Turbid waters tend to be confined to estuarine barrier basins and near river mouths, where the fines content in sediments is greatest (see chapter seven). An increase in basin depth following sea-level rise will favour a reduction in suspended sediment load because some areas of the basin floor will be beyond the depth of wave reworking. However, this effect may be compensated for by the introduction of suspended sediment from eroding shoreline, fluvial delta and floodplain deposits (see section 10.3.1.3). Turbidity levels, therefore, may not change appreciably (Sherwood, 1988).

The hydrological changes outlined here are of a qualitative nature only and no attempt has been made to predict quantitative change. Notwithstanding, it is evident that the current feedback relationship between geomorphic and hydrologic regimes will continue to operate under a new sea-level and climatic setting and that an understanding of those relationships allows for improved prediction of possible responses to environmental change. In the following section, relationships between geomorphic and hydrologic regimes are utilised to assess possible biological responses to environmental change.

10.3.1.3 Biological responses: Possible changes to the biota of south coast estuaries are considered here in the context of responses of their habitat environments to sea-level rise and climate change. Particular attention is given to those biotic elements for which most information is available: (a) saltmarsh communities that occupy the fluvial delta and backbarrier flats; (b) and, molluscan fauna of intertidal and subtidal areas.

(a) Saltmarsh communities display a sharply defined zonation pattern that is the result of different tolerance levels of individual species to tidal inundation (Clark and Hannon, 1969, 1970; Frey and Basan, 1978; Vanderzee, 1988). The marshes of southeastern Australian estuaries occupy low gradient, low energy depositional surfaces and consist of three general zones: (i) a seaward mangrove zone that lies approximately between midtide and high tide levels; (ii) a *Sarcocornia* zone that extends up to the level of maximum spring tides; and, (iii) a zone of grasses, sedges and saltbush that occupy supratidal areas (Clark and Hannon, 1967; Vanderzee, 1988).

The ability of each species to withstand salinity and waterlogging decreases with increasing elevation. The elevation differences between zones in south coast marshes is typically one to two metres, which is equal to the magnitude of predicted sea-level rise. The small differences in elevation between saltmarsh zones renders them sensitive to variations in relative sea-level. In addition, the location of estuarine saltmarsh on the fluvial delta and backbarrier units provides for protection against ocean wave attack that, on an exposed shore, may obscure the effects of sea-level rise. Estuarine marsh communities are, therefore, likely to be very responsive to sea-level rise (Vanderzee, 1988).

Responses of saltmarsh vegetation to sea-level rise have been modelled by Orson et al. (1985) for the Atlantic and Gulf coasts of North America. Vanderzee (1988) recognised similar responses to increased tidal inundation in the saltmarsh communities along the subsiding coast of Corner Inlet in southeast Victoria. From the premise that the primary controls on marsh survival are the rate of marsh sedimentation and the rate of sea-level rise, three vegetative responses are thus postulated (Fig. 10.4) (Orson et al., 1988).

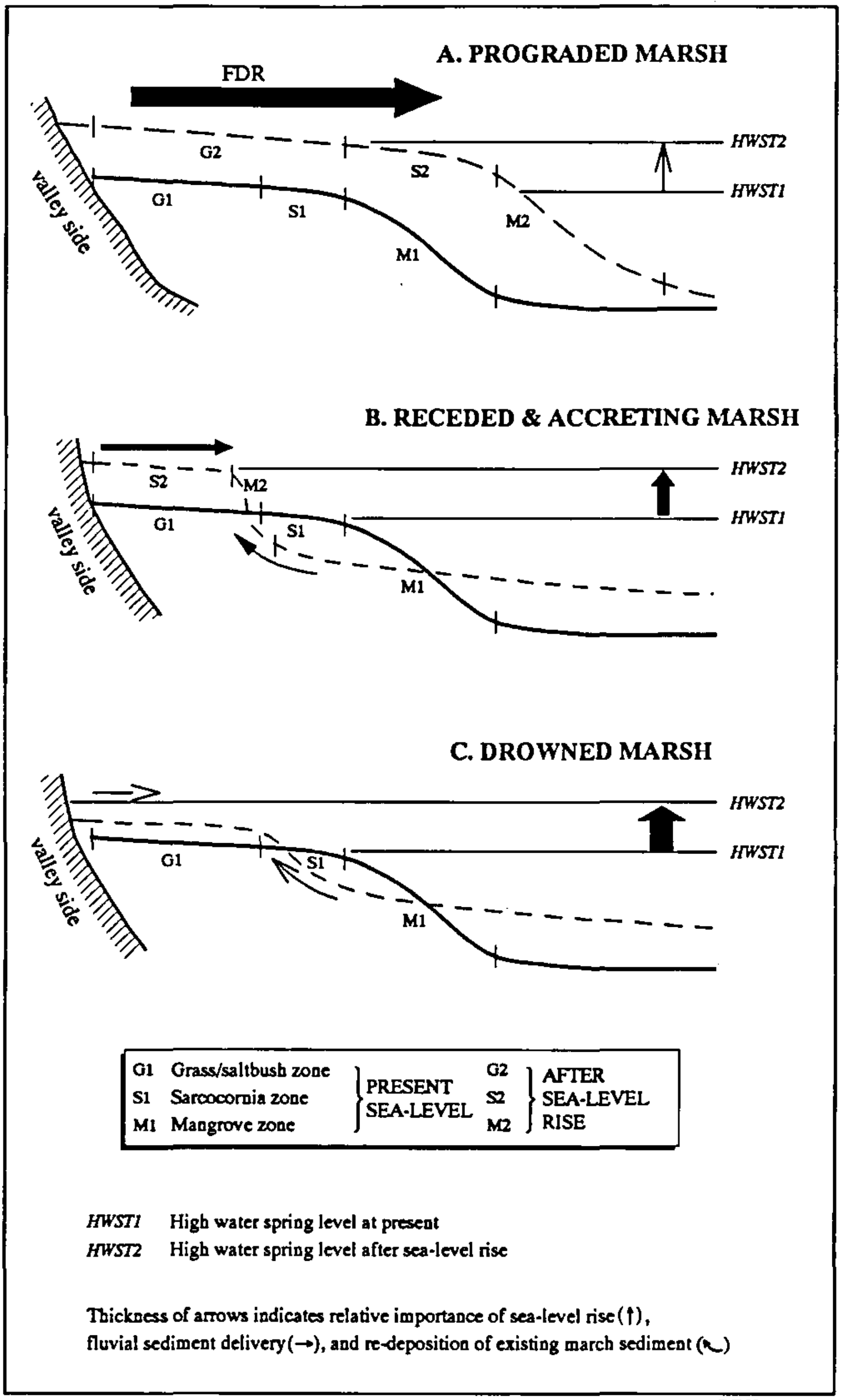
The first response involves progradation of the marsh and accompanying expansion of the marsh area as pioneer species (i.e. mangroves) colonise new deposits (Fig. 10.4a). This model requires that sediment supply rates exceed the rate of relative sea-level rise (Orson et al., 1988). Vanderzee (1988) notes that sufficiently high sedimentation rates may occur on marshes located near a river mouth that is debouching large volumes of sediment. In south coast estuaries, the required rate of sediment supply for marsh progradation may occur if a FDR is initiated by climate change. During a FDR, river channels widen and become erosional, mobilising large quantities of sediment some of which is ultimately deposited on the fluvial delta. If the fluvial deltas and marsh communities of south coast estuaries were to prograde and the flood-tidal deltas were to migrate landward with the rising sea, an overall trend toward accelerated valley filling, rather than estuary deepening, would ensue.

The second response of saltmarshes to sea-level rise is characterised by marsh recession and accretion (Fig. 10.4b). That is, the seaward margin of the marsh is eroded as sea-level rises but the surviving marsh continues to accrete due to redeposition of eroded marsh sediment (Vanderzee, 1988). Sediment supplied by a river may also contribute to continued marsh accretion. Marsh recession would cause the landward migration of floral associations. Plants at the seaward margin of the marsh would die first due to increased salinity levels, longer periods of inundation and erosion of the substrate. Plants in the landward saltmarsh zone would then be forced to migrate further landward as their habitat is altered by more frequent tidal flooding.

In south coast estuaries, the area available for marsh retreat and landward shifts of vegetation zones is limited by the bedrock valley sides. Therefore, survival of south coast saltmarsh via recession and redeposition requires that sea-level rise be of a magnitude that provides accomodation space for the marsh. If not, then this response mode may be transient only and marshes may disappear altogether.

The third response, marsh drowning, will occur if sediment supply rates from both autochthonous and allochthonous sources cannot keep pace with the rate of sea-level rise (Fig. 10.4c) (Orson et al., 1985; Vanderzee, 1988). Under this scenario, all zones of marsh vegetation die together and substrate erosion is accelerated to the extent that not even recolonisation by pioneer plants is possible.

If south coast rivers and streams do not enter a FDR phase and deliver sediment to deltas and estuarine marshes then the drowning marsh model is probable, especially in estuaries where a physical barrier to landward migration of the marsh exists (e.g. steep valley sides).



G1	Grass/saltbush zone	PRESENT SEA-LEVEL	G2	AFTER SEA-LEVEL RISE
S1	Sarcocornia zone		S2	
M1	Mangrove zone		M2	

HWST1 High water spring level at present
HWST2 High water spring level after sea-level rise

Thickness of arrows indicates relative importance of sea-level rise (↑), fluvial sediment delivery (→), and re-deposition of existing march sediment (↖)

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Figure 10.4: Response models of saltmarsh communities to sea-level rise. Adapted from Orson et al. (1988) for fluvial deltas in south coast estuaries.

(b) The response of estuarine fauna to changes associated with a rise in sea-level are briefly reviewed here with an emphasis on the resident molluscan fauna. It is assumed that molluscan responses are representative of the response of migrant estuarine animals (e.g. fish) in general (Hodgkin and Kendrick, 1984; Sherwood, 1988).

Estuarine molluscs are not likely to be greatly affected by a one to two metre rise in sea-level. Most species occupy substrates that range from intertidal to shallow subtidal and, therefore, should tolerate a slight increase in water depths. Molluscs should, however, be responsive to other habitat changes, notably salinity, turbidity and temperature conditions, that may change in association with sea-level rise (Hodgkin and Kendrick, 1984).

Molluscs that survive in estuarine waters are termed euryhaline in recognition of their high tolerance of fluctuating salinity levels. If sea-level rises and the saline wedge penetrates further landward, thereby increasing mean salinity and reducing the magnitude of temporal salinity variations, it is possible that conditions may become better suited to open marine species. Fossil evidence from estuaries in western Victoria (Sherwood, 1988) and southern Western Australia (Hodgkin and Kendrick, 1984) suggest marked changes in the species composition of estuarine molluscs during the Holocene. For example, in the Victorian estuaries, open marine and euryhaline-marine molluscs (e.g. *Katelysia rhytiphora, Ostrea angasi, Velacumantus australis*) occur in fossil beds within the present fluvial reaches of estuaries. Euryhaline species now prevail within the fluvial reaches. Similar species changes are reported for the West Australian estuaries (Hodgkin and Kendrick, 1984). Here the euryhaline-marine molluscs, *Katelysia scalarina* and *Ostrea angasi*, dominate mid-Holocene deposits 40km upstream from the mouth of the Swan River.

Radiocarbon dating of open marine fossil shells from the landward beds suggests that high (near-marine) salinity levels persisted throughout Western Australian estuaries from 7000 to 4000 years bp, and from 6000 to 2500 bp in western Victoria (Sherwood, 1988). Fossil shell beds from the late Holocene period are dominated by euryhaline species (e.g *Nassarius burchardii, Solatellina donacioides, Tellina deltoidalis*) reflecting the increased influence of fluvial discharge as estuaries infilled and tidal range was reduced (Hesp, 1984; Hodgkin and Kendrick, 1984; Sherwood, 1988). Similar changes to shell species during the Holcene are described for the Gippsland Lakes in eastern Victoria by Thom et al. (1986). A rise in sea-level during the next century may, therefore, cause a return to salinity conditions similar to those postulated for the mid Holocene and the reappearance of stenohaline and marine molluscs in the fluvial reaches of estuaries.

It is plausible that conditions suitable for euryhaline species could persist following sea-level rise. For this to occur the increased salinity will have to be partially negated by a simultaneous increase in freshwater discharge. A warmer, wetter climate over southeast Australia could provide the necessary conditions for increased runoff and the initiation of a FDR. Indeed, it is conceivable that salinity conditions could become more variable than at present if catastrophic floods occur with increased frequency and the saline wedge migrates landward.

In summary, it is likely that both the floral and faunal components of estuarine biota of the south coast will undergo significant changes if the predicted rise in sea-level and changes to the regional climate occur during the next 50 to 100 years. The exact nature and magnitude of the response remains unclear. A variety of possible changes to the distribution of marsh vegetation and of molluscs have been presented here. It is also possible that climate change may cause changes to the species composition of saltmarshes and faunal populations. For example, an increase in mean annual temperature and in precipitation would probably lead to an increase in species diversity hence increased competition for limited habitat space. In the case of saltmarshes, if low-lying areas are reduced in size by rising sea-level dramatic floristic changes to saltmarsh associations may occur as some species (e.g. mangroves) adjust more readily to change than others. It is evident, therefore, that monitoring of estuarine biota is an important adjunct to geomorphic studies for successfully detecting rising sea-level and climate change. The importance of environmental monitoring is expanded upon in the following section.

10.3.2 Assessing the sensitivity of estuarine systems to human disturbance

Human disturbance activities may be divided into internal and external types. Internal disturbances derive from activity within the estuary proper and might include dredging of shoals, construction of entrance training walls, channel straightening, wetland reclamation, aquaculture, and introduction of pollutants (e.g. heavy metals) from ships. For the geomorphologist and sedimentologist, internal stresses result in alterations to tidal circulation patterns, sediment transport pathways and the chemical properties of sediments.

External activities result from activity outside the estuary but within the catchment and include removal of terrestrial vegetation, road construction, drainage modifications, agriculture, and urban construction. External disturbances are manifest in estuaries by increased sedimentation in some areas, accelerated erosion of channel margin deposits, increased river discharge, and introduction of solid and dissolved pollutants to estuarine sediments and waters.

It is not intended to provide a detailed account of the range of estuarine responses to the various disturbance activities. Such a discussion may be unfounded in the absence of site specific studies. Rather, the aim here is to identify areas of estuaries that are most likely to display evidence of disturbance and, subsequently, to nominate sites that should be targeted for monitoring.

From a sedimentological perspective, estuarine responses to internal and external disturbances may be reduced to two broad options: deposition and erosion. Both options are repsonses to the existence of disequilibrium conditions in an estuary. Deposition will occur when the sediment supply rate overwhelms the capacity of waves and currents to transport the sediment. These conditions may be observed on the intertidal fluvial delta unit in N.S.W. estuaries. Erosion results when the energy of transport processes is sufficient to remove pre-existing deposits and any incoming sediment from a site. For example, the lower reaches of fluvial channels exhibit an erosional response during a FDR.

Between the extremes of deposition and erosion, a state of non-deposition prevails when a dynamic equilibrium between sediment supply and processes exists. A potential example of non-deposition is the flood-tidal delta in N.S.W. estuaries. Neither long term deposition nor erosion is evident for tidal deltas (chapter nine). Short term erosion may occur if river flooding occurs but the sediment is quickly returned to the inlet by wave and tidal currents, indicating the existence of a dynamic equilibrium between inlet processes and the inlet sediment body.

Table 10.1 presents an assessment of the potential for the detection of human induced deposition and erosion at sites represented by estuarine morphostratigraphic units. With regard to deposition, the most sensitive units are interpreted to be the intertidal fluvial delta, supratidal fluvial delta and floodplain units. The latter two units are likely to record increased sediment yield from catchments in off-channel (slack water) deposits. Bioturbation of these fine grained sediments may, however, obscure the resolution of the post-settlement record. Bioturbation is not expected to be as great a problem for intertidal delta deposits. This unit is typically coarse grained and if catchment erosion is accelerated by human activity may respond by prograding at a rate sufficient to prevent thorough bioturbation.

The entrance channel and flood-tidal delta units may also be sensitive to increased fluvial sediment yield to estuaries. The primary indicator for disturbance to the present condition of the tidal delta and associated channel is expected to be the deposition of fluvial sediment in areas previously dominated by marine sands. It is improbable that the barrier and beachridge units will readily display evidence of increased fluvial sediment delivery. Both units are essentially remote from the fluvial and tidal processes that transport fluvial material. It is conceivable, however, for fluvial sediment to bypass the estuary and be deposited on the beach and/or foredune. To achieve this, an exceptionally high energy river flood would be required and, in any case, the increased fluvial sediment flux would be detected well before reaching the barrier.

UNIT	DETECTION POTENTIAL AND GEOMORPHIC INDICATOR	
	DEPOSITION	EROSION
Barrier/ beachridge	Poor: none	Moderate: dune activity
Entrance channel	Good: fluvial & marine sand mixing	Good: channel widening
Flood-tidal delta	Good: as above	Good: mobilisation of shoals
Backbarrier flat	Moderate: as above	Moderate: wave erosion
Barrier basin	Poor: none (bioturb.)	Poor: none
Supratidal shoreline	Poor: none (wave reworking)	Moderate: wave erosion
Intertidal shoreline	Poor: none (wave reworking)	Moderate: wave erosion
Supratidal fluvial delta	Excellent: off-channel deposition	Poor: none
Intertidal fluvial delta	Excellent: delta progradation	Moderate: wave erosion
Floodplain	Excellent: off-channel deposition	Poor: none
Fluvial channel	Good: point bar accretion	Excellent: channel downcutting

Table 10.1: Assessment of the potential for detecting deposition and erosion of estuarine morphostratigraphic units and likely geomorphic changes.

The barrier basin and shoreline units of Zone B are not likely to be particularly sensitive to human induced sedimentation. Certainly, sediment will settle out on the basin floor and along the shore, and lead or caesium isotope dating of the fine fraction can be utilised as a means for recognising recent deposits. In the majority of cases bioturbation and wave activity will rework new deposits into pre-existing material, thereby destroying the isotope profile (Oldfield and Appleby, 1984; Loughran et al., 1988).

The most sensitive areas to human induced erosion are considered to be the fluvial channel, entrance channel, intertidal fluvial delta, flood-tidal delta, shoreline, backbarrier flat and barrier/beachridge morphostratigraphic units. Activities such as dredging, training wall construction and channel straightening can cause dramatic changes to estuary circulation, and in turn induce erosion of pre-existing deposits (Williams, 1983). A good example is provided by the inlet to Wallis Lake on the central coast.

In 1966 a breakwater was constructed along the northern bank of the Wallis entrance to complement the training wall on the opposite bank, built in 1913. Since 1966, extensive scouring of sand (6×10^4 m^3 yr^{-1}) from the initially large flood-tidal delta has occurred (Williams, 1983). Nielson and Gordon (1980) attribute the scour to a number of interrelated factors, including: increased ebb jet flow velocities; greater channel and bar depths; and, reduced littoral sand delivery from adjacent beaches. One consequence of inlet scouring has been a reduction in tidal energy dissipation along the inlet, manifest in the entrance by a 22cm increase in high water (springs) and an 18cm increase in low water (springs), that in turn translates to an increased tidal range throughout Wallis Lake (Williams, 1983).

The response of tidal inlets to training wall construction is not simple, however. Williams (1983) notes that very little change is evident in the entrance to Wagonga Inlet, following breakwater construction in 1977. The lack of scouring in Wagonga is attributed by Williams (1983) to the pre-breakwater condition of the entrance channel. That is, littoral sand input was negligible and tidal delta shoal depths were sufficient to ensure efficient tidal ventilation (see Fig. 6.3). Tidal gaugings did not reveal any clear change to tidal flow velocities after breakwater construction, suggesting that the wall has not significantly altered conditions in Wagonga.

It is evident from these two examples that the response of estuary inlets to training is variable and it is probable that responses to dredging and channel alterations are similarly varied. However, two common factors are apparent from the Wallis Lake and Wagonga Inlet responses: (a) the volume of sand in the inlet before disturbance; and, (b) the changes to tidal flow energy following disturbance (Williams, 1983).

The responses of the remaining estuarine units to disturbance are somewhat predictable. The basin shoreline and backbarrier units are particularly susceptible to increased wave action bought about by shipping and/or recreational boating movements. The barrier/beachridge units will respond to disturbance by initiating dune activity in previously stable (vegetated) areas. The floodplain and supratidal fluvial delta units are not likely to display immediate evidence of increased erosion. Both units are relatively remote from erosive processes and until fluvial channel migration occurs, will remain essentially unaltered. Finally, the least sensitive unit to erosion is probably the barrier basin, especially where the basin floor is below the depth of wave reworking.

It should be emphasised that internal and external human activities can be at a scale that an estuary displays both depositional and erosional responses. For example, catchment clearing coupled with fluvial channel straightening could result in increased sediment transport along the channel and channel downcutting. Similarly, increased deposition on the intertidal fluvial delta may be occurring at a site where boat movements have increased local wave activity. Monitoring must, therefore, be carried out judiciously with an awareness of all factors that may influence the final result.

The fluvial delta and lower reaches of the floodplain are suggested as prime monitoring sites for detecting estuarine responses to catchment disturbance. Monitoring should involve: repeated surface sediment mapping; shallow (<2m) coring dating of sediments using lead-210 and/or caesium-137 methods; and, sediment tracing studies (e.g. mineral magnetic analysis). The flood-tidal delta should also be sampled after floods in order to detect mixing of fluvial with marine sands. Process measurements are also necessary. For example, the velocity of tidal flows through tidal inlets and into the basin should be monitored at sites where training walls are built or dredging has taken place.

10.4 SUMMARY

A wide range of topics have been covered in this chapter in the endeavour to demonstrate the relevance and applicability of estuarine studies to geological and environmental problems. In the geological context, the focus has been upon the preservation potential and economic merit of estuarine facies. Environmental concerns have targeted likely responses of estuarine complexes to human disturbance, such as greenhouse induced sea-level rise and altering the natural balance between depositional processes and facies.

The potential for estuarine facies to be incorporated in the geologic record varies in accord with the location of a deposit in the valley, the rate of sea-level rise and the length of the sea-level lowstand period following deposition. The basal (subtidal) and landward units are the most likely to feature in the geologic record. The deposits with lowest preservation potential are the upper (supratidal and intertidal) units of Zone A. Generally, the degree of preservation of all units will be greater when sea-level rise is rapid and reworking of coastal deposits is minimal. The survival chances of Zone A deposits under regressive conditions is considered to be poor, especially if the regression is protracted. If, however, a barrier is located within a deeply recessed embayment the likelihood of preservation is improved. The so called Inner Barrier (Pleistocene) of N.S.W. central coast estuaries is an example of barriers outlasting a regression (Thom et al., 1981).

Zone B facies are also likely to be well represented in the rock record. The barrier basin unit, in particular, has a high preservation potential because of its subtidal position. The Late Quaternary record in N.S.W. estuaries suggests that barrier basin sediments are oxidised and partially eroded during sea-level lowstands and ensuing transgressions. Reworking, however, appears limited to the seaward and upper portion of the deposit. In contrast, the supratidal and intertidal shoreline units of Zone B will endure neither a transgression nor a regression.

Zone C deposits are considered to have a moderate preservation potential. Under transgressive conditions, the upper position of fluvial sediments in the valley will be prone to reworking. However, the location of Zone C at the landward end of the estuary will favour greater preservation in comparison to upper Zone A deposits. When sea-level drops, the tide-influenced fluvial sediments will be reworked and replaced by purely fluvial deposits.

Given the strong possibility that wave-dominated estuarine deposits will outlast repeated fluctuations in relative sea-level, it is anticipated that ancient equivalents exist and, more importantly, that the ancient deposits harbour economically significant quantities of hydrocarbons. The juxtaposition of coarse grained, well sorted Zone A deposits with fine grained, organic rich Zone B and Zone C deposits in a bedrock controlled valley makes for an ideal stratigraphic arrangement for the formation of petroleum reservoirs.

The modern estuarine facies examined in this study were shown to possess textural, structural and geochemical properties that are consistent with ancient hydrocarbon bearing deposits. While the ancient examples cited here had already been assigned a broad estuarine origin, it is argued that studies of modern morphostratigraphic units can contribute to a more accurate interpretation of ancient deposits.

From the review of responses to direct forms of human disturbance, it is clear that geomorphic studies can contribute significantly to the task of estuarine management. An understanding of the distribution and form of morphostratigraphic units may be utilised to predict likely responses to human induced change and to identify areas of an estuary that are most likely to respond to disturbance. Target sites for future monitoring can then be selected.

A range of responses to greenhouse induced sea-level rise are envisaged. The response of a particular estuary depends largely upon the present form of the estuary. For example, if sufficient sediment is available in existing barrier and tidal delta deposits for recycling then Zone A will persist and migrate landward at the same rate as sea-level rise. On the other hand, if the rate of sea-level rise exceeds the rate of sediment supply, the barrier may erode and the flood-tidal delta will drown. Similarly, severe erosion will result if alterations to the entrance channel (e.g. training wall construction) are made. The implications of the combined effects of sea-level rise and engineering works have not been considered here, but it is logical to expect that erosion will be exacerbated.

Geomorphic changes to Zone B and C resulting from sea-level rise and disturbance to the estuary proper and catchment include: increased basin depths; drowning and partial reworking of shoreline deposits; and, inundation of fluvial delta and floodplain deposits. The impact of higher sea-level may be partially countered by an increase in rates of sediment delivery from catchments in association with the onset of a flood-dominated regime. Fluvial deltas, therefore, should not be forced to migrate landward as far as flood-tidal deltas are likely to. Along the N.S.W. south coast, the net result may be for estuaries to become more infilled at their landward end.

Changes to the hydrological characteristics of an estuary following sea-level rise and engineering works may include: increased tidal range; stronger tidal currents; higher salinity levels in the fluvial reaches; and, increased wave activity in the enlarged basin. These hydrological changes may also receive expression in the condition of the estuarine biota. Specifically, increased salinity levels and more frequent inundation will probably cause dieback of pioneer plants and the landward migration of mangrove and saltmarsh communities. The species composition of molluscan fauna may also change. If salinity levels increase in an estuary, euryhaline species will migrate upstream to the present freshwater reaches and stenohaline-marine may become more common in the lake basin and tidal entrance.

The preceding assessment of the preservation potential of estuarine facies and responses of facies to environmental change provides an appropriate foundation for the design of a summary facies model. A model describing the ideal vertical sequence for wave-dominated estuaries is detailed in the following chapter, for an estuary that has reached maturity under a long period of sea-level stillstand and then rapidly transgressed.

CHAPTER 11: A GENERAL FACIES MODEL AND CONCLUSIONS

11.1 INTRODUCTION

The final chapter of the thesis has three objectives: (i) To bring together the sedimentological information collected from Wapengo Lagoon and Narrawallee Inlet in the form of a general vertical facies sequence for south coast estuaries; (ii) to review briefly the major findings of the thesis and in doing so, place south coast estuaries in a regional and a global context; and, (iii) to nominate areas for further work that have become evident during the course of this study.

11.2 GENERALISED FACIES MODEL

Because the preservation potential of incised valley estuaries is considered to be greater under transgressive conditions than during a regression, a vertical transgressive facies sequence is presented here for a typical south coast estuary. The model has been designed on the basis of two conditions. First, that sea-level stillstand has prevailed for more than 80% of the life of the estuary, since N.S.W. estuaries have evolved under a stillstand regime since 6500 years BP. Second, that the stillstand is succeeded by a rapid transgression, because the potential for maximum preservation of estuarine deposits is greatest when they are rapidly drowned (Davis and Clifton, 1987).

Subsurface investigations undertaken for this study indicate that at no point within south coast estuaries does there exist a vertical sequence complete with all facies. The following model, therefore, represents an ideal sequence derived by projecting horizontally all facies zones landward, thereby mimicking the maximum level of transgression.

The base of the ideal vertical sequence for wave-dominated stillstand estuaries consists of pre-modern barrier basin muds (Fig. 11.1). An erosional unconformity marks the boundary between these deposits and the lower unit of the modern sequence. The Zone C morphostratigraphic units of tide-influenced floodplain, fluvial delta and fluvial channel comprise this lower unit. The average thickness of modern Zone C deposits is approximately five metres. It is difficult to distinguish between the floodplain, fluvial delta and channel deposits from the subsurface record because all three are characterised by fining upward and massive (bioturbated) beds of medium to coarse gravelly sands of mixed mineralogy with little or no internal cross-bedding (Table 11.1). Tidal features are conspicuously absent in the microtidal estuaries studied here. Graded beds appear to be the only structural feature.

Some distinction between the units may be made using coarse gravel interbeds and carbonate and organic contents as indicators of relative proximity to the channel. Gravel interbeds occur in all Zone C deposits but they appear thicker and more common in channel fills and delta sediments than in off-channel floodplain deposits. In contrast, peak carbonate and organic carbon contents occur in off-channel deposits. In channel and delta sediments, $CaCO_3$ and TOC contents are in the low to moderate range. Lateral variations should, therefore, be evident in a valley fill, primarily in the form of decreasing grain size and increasing carbonaceous content with increased distance from the channel. In estuaries that have experienced a prolonged period of stillstand, the

Zone C facies will be areally extensive and possibly extend to the seaward limit of Zone B deposits, thereby recording complete infilling of the basin.

The fluvial facies assemblage is overlain by a five to ten metre thick bed of Zone B sediments. The majority of the bed is comprised of fine grained barrier basin deposits that may grade into a thin (<2m) deposit of intertidal and supratidal shoreline units. The basin unit displays an overall coarsening upward trend from silty clay to sandy clay. Laminae appear better preserved toward the bottom of the unit, while burrow traces predominate in the upper portion. In addition, the upper portion includes occasional thin interbeds of silty sands. These beds record high energy depositional conditions associated with river floods. Carbonate and organic content in basin sediments is in the low to very high range. The capping shoreline unit is characterised by poorly sorted massive and coarsening upward beds of medium silty sands and gravels. $CaCO_3$ and TOC content are typically low to moderate. The shoreline unit may not be present in all estuarine sequences because it is prone to reworking, even during a rapid transgression.

An assemblage of Zone A morphostratigraphic units constitutes the upper facies in the transgressive estuarine sequence. It is predicted that flood-tidal delta and entrance channel units will dominate the Zone A portion of the fill. The typical thickness of tidal delta and channel units is five to ten metres. Up to three sub-units should be recognisable in the tidal delta unit. The sub-units equate with the seaward, medial and landward shoals of the Wapengo flood-tidal delta. When arranged vertically, these units will display an overall upward coarsening trend from slightly silty medium sands to silt free medium and coarse sands. Planar and trough cross-bedding should increase in frequency up-sequence and

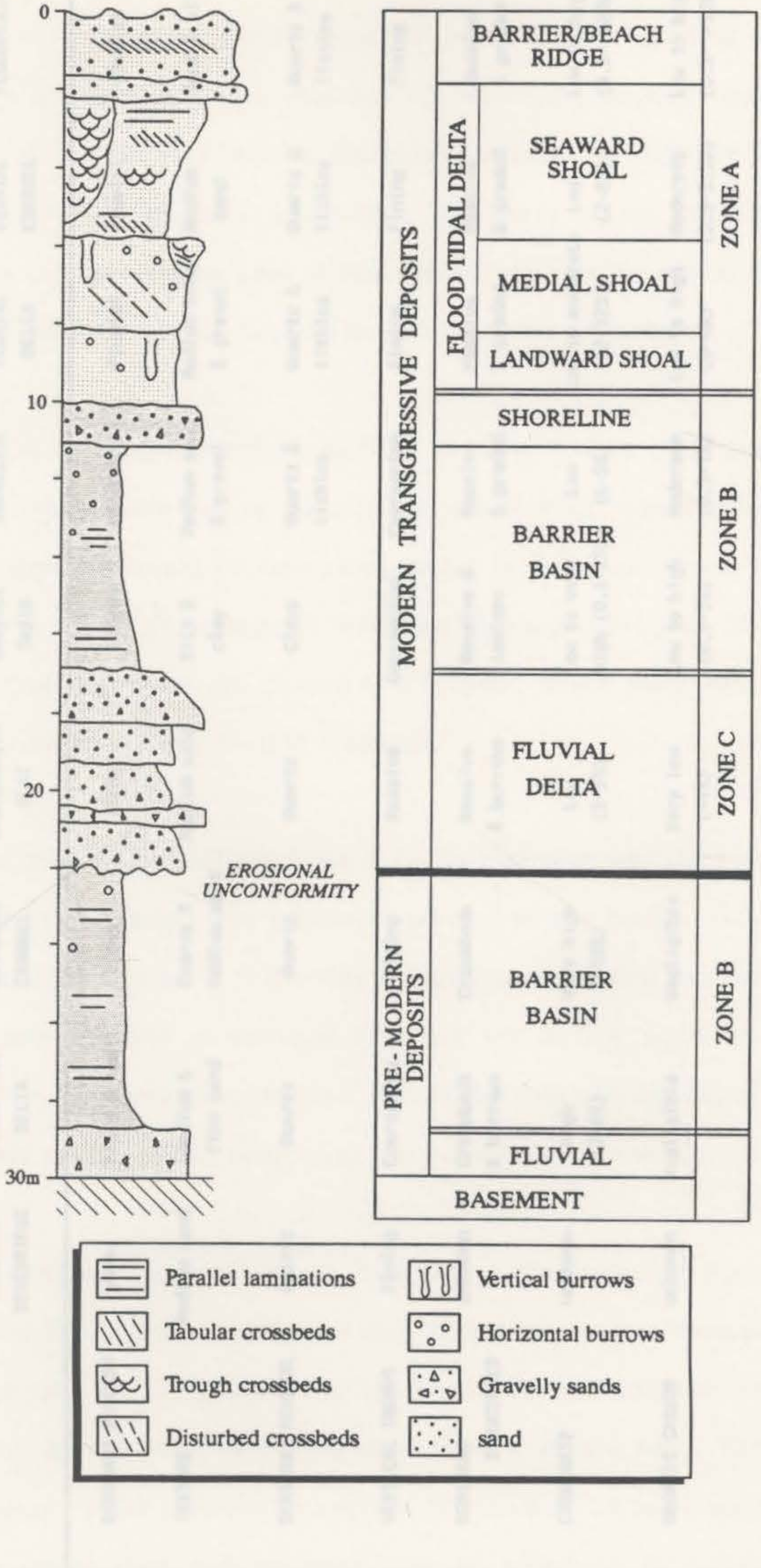

Figure 11.1: Summary vertical facies sequence for wave-dominated estuaries. The sequence represents a typical south coast estuary that has experienced a relatively long period of sea-level stillstand followed by a rapid transgression.

Table 11.1: Summary of sedimentological properties and preservation potential of estuarine morphostratigraphic units

		ZONE A			ZONE B			ZONE C	
	BARRIER/ BEACHRIDGE	FLOOD-TIDE DELTA	ENTRANCE CHANNEL	BACKBARRIER FLAT	BARRIER BASIN	SHORELINE	FLUVIAL DELTA	FLUVIAL CHANNEL	FLOODPLAIN
DOMINANT PROCESS	Waves	Tides & swell	Tides	Tides	Tides	Wind waves	Fluvial	Fluvial	Fluvial
TEXTURE	Medium sand	Medium & fine sand	Coarse & medium sand	Medium sand	Silt & clay	Medium sand & gravel	Medium sand & gravel	Medium sand	Sand & silt
DOMINANT MINERAL	Quartz	Quartz	Quartz	Quartz	Clays	Quartz & lithics	Quartz & lithics	Quartz & lithics	Quartz & lithics
VERTICAL TRENDS	Fining	Coarsening	Fining	Massive	Coarsening	Coarsening	Fining	Fining	Fining
DOMINANT STRUCTURES	unknown	Crossbeds & burrows	Crossbeds	Massive & burrows	Massive & laminae	Massive & graded	Massive & graded	Massive & graded	Massive & graded
CARBONATE	unknown	High (2-6%)	Very high (>10%)	Low (3-5%)	Low to very high (0.5-25%)	Low (4-5%)	Low to moderate (2-12%)	Low (2-8%)	Low to high (0.5- >20%)
ORGANIC CARBON	unknown	Negligible	Negligible	Very low (<1%)	Low to high (0.1-3%)	Moderate (0.5-1%)	Low to high (0-4%)	Moderate (0.5-3.5%)	Low to high (0.3- >10%)
PRESERVATION POTENTIAL									
transgression	Low	High	High	Moderate	High	Low	Moderate	Moderate	Moderate to high
regression	High	Moderate	Low	Moderate	Moderate to low	Low	Moderate	Moderate	Moderate
RESERVOIR POTENTIAL	Very good	Excellent	Excellent	Very good	Poor	Moderate	Moderate	Good	Poor
SOURCE ROCK &/OR SEAL POTENTIAL	Poor	Poor	Poor	Poor	Excellent	Moderate	Moderate	Moderate	Good

the degree of bioturbation decrease. If present, these changes in sedimentary structures are assumed to be evidence for maximum tidal current energy in the vicinity of the estuary mouth. Carbonate content is high and TOC content negligible throughout Zone A deposits. The sands of the backbarrier flat unit should be incorporated in Zone A deposits but may not be distingishable from the landward tidal delta shoal because it is also heavily bioturbated.

Where present, channel cut-and-fill deposits will be characterised by fining upward trends from coarse to medium sands with cross-bedding throughout. Channel deposits should be most recognisable in the upper two to three metres of the Zone A facies in association with the seaward shoal. The channels that cut into the seaward shoal are deeper and broader, hence more likely to survive a transgression, than those further landward.

The capping beds of the Zone A facies will represent the basal transgressive component and possibly the regressive portion of the barrier and/or beach-ridge morphostratigraphic units. Following a rapid transgression, the final thickness of these deposits should be between five and ten metres. Although not shown in Figure 11.1, the estuarine deposits should be overlain by shoreface sands and inner shelf muddy sands, completing the transgressive sequence.

It is probable that variations from the vertical sequence described here will exist down-valley. The thickness of each facies may exceed the values cited here, and some beds may be absent from the record. In addition, the total thickness of the valley deposit will vary from one estuary to the next. The Wapengo and Narrawallee studies indicate an average thickness of 20 to 30 metres for a single sequence. More than one sequence may be preserved in a valley, indicating repeated cycles of sea-level highstand and low-stand. Typically, the lower sequence is only partially preserved. It follows that the thickness of the youngest (Holocene) sequence depends largely on the degree of preservation of older (Pleistocene) deposits.

11.3 REVIEW OF MAJOR FINDINGS

In the context of the aims defined at the outset of the thesis, the primary results of this study may be summarised as follows:

(a) Tripartite facies zonation: It is evident from the statistical analysis of facies morphometric data that the estuaries of the N.S.W. south coast display a common tripartite facies zonation. The tripartite character of estuarine deposits in southeast Australia was recognised by previous workers in individual estuaries, including: the Gippsland Lakes in Victoria (Bird, 1967a, 1978); Mallacoota Inlet, northeast Victoria (Reinson, 1973, 1977); and several larger N.S.W. central and south coast estuaries (e.g Roy and Peat, 1973, 1975a, 1975b, 1976; Roy, 1984a). This study has shown that the tripartite pattern is not restricted to a few sites and may, therefore, be considered a uniform characteristic among N.S.W. estuaries.

Tripartism has been specified in estuaries elsewhere, such as the microtidal James estuary in Virginia (Nichols et al., 1989) and the macrotidal Gironde estuary, western France (Allen, 1989). An examination of the literature indicates that three facies zones occur in a range of wave-dominated estuarine settings including: the Atlantic and north Pacific coasts of North America (e.g. Peterson et al., 1983; Boyd et al., 1987; Kraft et al., 1987; Carter et al., 1989b; Clifton et al., 1989; Duffy et al. 1989); the central coast of China (Li and Ping, in press); the southeast Irish coast (Carter et al., 1989a) and the east African coast (Orme, 1973). Ancient estuarine deposits also display a tripartite zonation of major facies (Rahmani, 1988; Reinson et al., 1988; Zaitlin and Shultz, 1990).

The general sedimentological character of the three facies zones appears to be consistent among the wave-dominated estuarine deposits described in the literature. This is seen to be the result of the interface of fluvial processes with marine processes in estuaries and the attendant mixing of terrestrial sediment with marine sediment. Variation is evident, of course, between coasts due to different geologic and climatic settings. The primary control, however, on the morphology of each facies in individual estuaries appears to be relative sea-level (Carter et al., 1989b). That is, coasts that are presently experiencing relatively rapid sea-level rise (e.g. Nova Scotia) display an estuarine morphology that is characterised by landward migrating barriers (Zone A) and a poorly developed fluvial facies (Zone C). At the other extreme, coasts that have enjoyed relative sea-level stability during the late Holocene (e.g. N.S.W.), feature stationary and prograded barriers and a mature fluvial facies. The N.S.W. coast, therefore, is an important estuarine setting in global terms because it may be considered an end-member on the spectrum of estuary types, in terms of the relative dominance of wave energy and the stability of sea-level (Dalrymple and Zaitlin, 1989).

Regional variations exist along the N.S.W. south coast, notably in the relative dominance of individual facies and respective morphostratigraphic units. When classified by statistical methods, these variations are represented by three primary groups of estuaries with the following properties: (i) an immature group of estuaries that display only minimal facies development and are dominated areally by Zone B; (ii) two sub-groups of estuaries that are dominated by fluvial facies

(Zone C). One sub-group is at an intermediate stage of infill, the other at an advanced stage; and, (iii) two estuary sub-groups dominated by marine facies (Zone A). The sub-groups are divided on the basis of different fluvial facies areas. Relative Zone A areas for each sub-group are approximately equal.

The significance of fluvial facies, notably floodplain development, in determining the stage of infill in any estuary is recognised as a critical factor in estuary evolution. There appears to be a relationship between the characteristics of the catchments (lithology, slope, area) and the degree of Zone C deposition. However, it is not a simple linear relationship and additional factors, such as the volume of the receiving basin must also be considered. Subsurface studies and reconstructions of the Late Quatenary history of the two study sites help resolve this problem.

(b) Late Quaternary history and summary facies model: The Late Pleistocene and Holocene evolution of south coast estuaries, as determined by studies of Wapengo Lagoon and Narrawallee Inlet, may be distilled to four stages:

(i) A period of estuarine deposition during the Last Interglacial period, between about 140Ka and 120Ka ago. Sea-level stood four to six metres above present at the time, allowing for the formation of estuaries and deposition of facies similar to those observed in modern estuaries;

(ii) A protracted period of sea-level lowstand, with intervening interstadials, lasting until about 12Ka. Scouring of Last Interglacial valley fills was achieved during the glacial period but the amount of sediment removed appears to vary from one estuary to the next.

(iii) The lowstand was followed by a rapid transgression that terminated at about 6.5Ka, resulting in the formation of Holocene estuaries. Radiocarbon dating of marine sands in estuary mouths suggests that the majority of the Zone A facies was deposited during the mid-Holocene. In many cases, the delivery of marine sediment to estuaries appears to have slowed to a negligible rate by about 4Ka, although some prograded barriers continued to grow until the late Holocene. The lack of variation in Zone A area among south coast estuaries is interpreted as evidence for the relict condition of many barrier and tidal inlet deposits.

(iv) Sea-level has remained relatively stable since 6.5Ka and estuaries have proceeded to infill their valleys. Fluvial facies development has been the predominant form of estuary filling since sea-level stillstand. The current infill stage of an estuary is considered to be a function of contemporary catchment yields and fluvial discharge *and* the volume of the receiving basin. The latter variable appears to be determined by the amount of Pleistocene material inherited by an estuary. Thus, Narrawallee has a strong Pleistocene inheritance and is infilled, while the Wapengo inheritance is weaker and it is at an intermediate infill stage.

Many of the findings regarding the facies model were summarised in the preceding section. It it should be emphasised, however, that while the sedimentologic properties described in this study represent only two sites, observations in other south coast estuaries and information presented in previous studies along the coast of southeast Australia suggest that the facies model and evolution of Wapengo and Narrawallee is replicated at many sites, indicating a uniformity among southeast Australian wave-dominated estuaries (e.g. Reinson, 1977; Bird, 1978; Thom et al., 1978; Roy et al., 1980; Roy, 1984a).

(c) Preservation potential and economic value: The preservation potential of estuarine deposits that occupy incised valleys is considered to be high, though not equal for all facies, especially if the sequence is transgressed rather than being subject to scouring during a regression (Davis and Clifton, 1987). The deeper and landward deposits are most likely to appear in the rock record. These deposits include the subtidal flood-tidal delta, channel fill and backbarrier flat morphostratigraphic units of Zone A; the subtidal barrier basin unit of Zone B; and, subtidal and intertidal fluvial delta, channel and floodplain units of Zone C. That these deposits have been documented from ancient deposits is evidence for their high preservation potential (Zaitlin and Shultz, 1990).

Furthermore, estuarine facies of the type described in this study are excellent composite deposits from which hydrocarbons may be sourced and held in reservoirs (Bjorlykke, 1989). The tripartite zonation of facies provides an ideal setting for hydrocarbons to migrate from Zone B, and to a lesser extent Zone C, into the reservoir sands of Zone A. Stratigraphic traps are provided by the fine-grained Zone B rocks, the valley sides and capping transgressive facies such as shelf muds. Ancient incised valley estuarine deposits are, therefore, a worthwhile exploration target.

(d) Significance of geomorphic/sedimentologic studies to environmental management: Detailed studies of the geomorphic and sedimentologic character of estuaries can provide valuable information for the purposes of environmental management. In particular, likely responses to human disturbance may be predicted. From the wide variety of forms of human disturbance, the focus here is upon greenhouse induced sea-level rise and changes to estuarine process and form bought about by engineering works. Both types of disturbance have the potential to effect major alterations to the present condition of estuaries.

Sea-level rise may be expressed in the estuary by a landward migration of facies. In extreme cases, deposits such as flood-tidal deltas may be drowned altogether and barriers destroyed. At the fluvial end of estuaries, the onset of a flood-dominated regime under a warmer climate may cause increased rates of floodplain and delta deposition. Zone C, therefore, may not be forced to migrate as far landward as Zone A. Wave activity in estuaries may increase due to an expansion of barrier basin area and increased depths. Consequently, erosion of intertidal and supratidal deposits may be accelerated. Furthermore, salinity levels are likely to increase with a rising sea, bringing about change to the distribution and species composition of estuarine flora and fauna.

Engineering works, such as breakwater construction and dredging have been shown to lead to changes in the tidal regime in estuaries. By artificially improving tidal ventilation, tidal range and the strength of tidal currents are increased. As a result, large volumes of tidal delta sands are removed from an estuary and further changes to estuarine processes are likely, thereby setting up a feedback relationship. It is clear from the brief review presented here that monitoring geomorphic responses to all forms of human disturbance is critical to the effective management of estuaries.

11.4 CONCLUDING COMMENTS

In view of the results from this study, the final comments offered in the thesis concern suggestions for further work. Four primary areas for future research are identified:

(a) Drilling and continuous coring in infilled estuaries to determine: (i) lateral variations in valley fill; (ii) the extent of Pleistocene subsurface deposits. Narrawallee estuary is worthy of further drilling, particularly in the seaward reaches. Seismic and/or ground penetrating radar surveys in infilled estuaries are also necessary to add to our limited knowledge of bedrock profiles in incised valleys.

(b) A topic of particular interest concerns the nature of differences of facies character between different estuary types. This study has restricted itself to examining estuaries with a relative dominance of Zone C and Zone B facies. The logical progression is to compare estuaries such as Wapengo and Narrawallee with sites that display a dominance of Zone A facies (e.g. Lake Merimbula, Wonboyn River, Nullica River, Tomaga River). It is anticipated that one important contrast will be in the barrier type. In particular, several south coast estuaries with a Zone A dominance possess a prograded type barrier. This begs the question, therefore; can the existence of two groups of estuary with contrasting Zone A areas be attributed simply to coastwise variations in offshore sediment supplies?

(b) Dating studies to tighten reconstructions of estuary evolution, with a particular emphasis on: (i) the age and rate of deposition of tidal delta and stationary barrier deposits; (ii) rates of sediment accumulation in barrier basins and river deltas. The results presented in this study are of a first order nature only and it is clear that considerable variation exists both within an estuary and over time.

(c) Catchment studies to improve our understanding of the relationships between estuaries and catchments. Paramount to this problem are calculations of sediment yields and erosion rates over time scales ranging from 10^1 years to 10^4 years. In addition, improved monitoring of the processes that deliver sediment to south coast estuaries and transport sediment within estuaries is required.

While the suggested targets for future work are of regional significance, the results will have broader applications to estuarine studies. For example, development of rigorous estuarine facies models requires continuous testing of existing models. Testing requires new data that must derive from studies of the full spectrum of estuarine settings. N.S.W. estuaries represent an important endmember along that spectrum. In addition, new information may be used to refine predictions of responses to environmental change, to design more effective management practices and increase the likelihood that estuarine ecosystems are preserved.

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NOTE: APPENDICES E TO L ARE LOCATED INSIDE AN ENVELOPE ON THE INSIDE BACK COVER.

APPENDIX A: SOUTH COAST ESTUARY CATCHMENT AND PALAEOVALLEY AREAS

ESTUARY	CATCH. (sq. km)	P.V. (sq km)	ESTUARY	CATCH. (sq km)	P.V. (sq km)
Nadgee L.	14.46	3.20	Little L.	2.33	0.35
Nadgee R.	59.77	2.16	Wagonga Inlet	96.94	8.52
Little Ck.	17.25	0.26	Kianga L.	8.20	0.47
Newtons B.	7.10	0.45	Dalmeny L.	27.74	2.30
Merrica R.	60.73	0.20	Brou L.	44.38	4.76
Wonboyn R.	320.00	12.44	Arourga L.	6.44	0.55
Woodburn Ck.	25.43	0.32	Brunderee L.	5.90	0.73
Fisheries Ck.	7.33	0.27	Tuross L.	1816.12	34.93
Towamba R.	1037.10	7.31	Coila L.	59.00	9.44
Nullica R.	60.13	3.28	Meringo Beach	5.57	0.42
Curalo Lagoon	30.43	2.42	Meringo Ck.	3.13	0.41
Pambula L.	299.48	11.66	Congo Ck.	43.43	8.32
Merimbula L.	47.99	11.12	Moruya R.	1445.47	39.74
Back Lagoon	31.25	1.01	Candlagan Ck.	29.50	8.42
Bournda Lagoon	34.52	0.17	Tomaga R.	98.57	10.50
Bondi L.	3.12	1.22	Clyde R.	1791.36	31.33
Wallagoot L.	30.59	7.42	Cullendulla Ck.	16.98	2.81
Bega R.	1941.18	18.77	Long Beach	2.17	0.75
Nelson Lagoon	30.09	2.45	Chain Bay	8.79	0.94
Middle Lagoon	27.46	3.15	South Durras	7.53	0.61
Wapengo Lagoon	72.93	7.86	Durras L.	63.23	6.34
Bunga Lagoon	12.19	0.44	Kioloa L.	8.90	2.60
Murrah Lagoon	203.46	5.70	Murramarang B.	2.35	0.93
Cuttagee L.	54.72	2.45	Willinga L.	3.99	2.43
Barragoot L.	13.14	1.79	Meroo L.	20.85	2.59
Bermagui R.	94.45	4.30	Termeil L.	15.12	2.12
Wallaga L.	270.41	14.55	Toubouree L.	48.32	7.17
Bobundara S.	14.75	1.26	Burrill L.	65.29	6.28
Little L.	2.61	0.40	Mollymook Ck.	2.71	0.42
Tilba Tilba L.	18.54	2.12	Narrawallee R.	84.96	10.81
Corunna L.	32.28	2.91	Conjola L.	145.73	12.07
Nargal L.	1.07	0.29	Nerrindillah Ck.	17.82	0.21
Nangudga L.	10.40	1.52	Berrara Ck.	36.00	0.97
Bullengella L.	0.85	0.24	Swan L.	32.46	9.36

Appendix A: Summary table of estuarine facies zone morphometric data.

	GROUPED RAW DATA: ZONES A,B,C (SQ. KM)			GROUPED % DATA: ZONES A,B,C		
ESTUARY	ZONE A	ZONE B	ZONE C	ZONE A	ZONE B	ZONE C
Nadgee L.	0.54	1.00	1.66	16.88	31.25	51.88
Nadgee R.	0.10	0.00	2.06	4.63	0.00	95.37
Little Ck.	0.05	0.00	0.21	19.23	0.00	80.77
Newtons Beach	0.24	0.02	0.19	53.33	4.44	42.22
Merrica R.	0.07	0.00	0.13	35.00	0.00	65.00
Wonboyn R.	9.76	1.36	1.32	78.46	10.93	10.61
Woodburn Ck.	0.07	0.00	0.25	21.88	0.00	78.13
Fisheries Ck.	0.19	0.00	0.08	70.37	0.00	29.63
Towamba R.	1.41	0.18	5.72	19.29	2.46	78.25
Nullica R.	2.59	0.00	0.69	78.96	0.00	21.04
Curalo Lagoon	0.38	1.42	0.62	15.70	58.68	25.62
Pambula L.	1.22	1.95	8.49	10.46	16.72	72.81
Merimbula L.	5.97	2.81	2.34	53.69	25.27	21.04
Back Lagoon	0.15	0.36	0.50	14.85	35.64	49.50
Bournda Lagoon	0.10	0.03	0.04	58.82	17.65	23.53
Bondi L.	0.36	0.25	0.61	29.51	20.49	50.00
Wallagoot L.	1.48	3.83	2.11	19.95	51.62	28.44
Bega R.	1.90	4.96	11.91	10.12	26.43	63.45
Nelson Lagoon	0.74	0.24	1.47	30.20	9.80	60.00
Middle Lagoon	0.24	0.52	2.39	7.62	16.51	75.87
Wapengo Lagoon	2.28	1.41	4.17	29.01	17.94	53.05
Bunga Lagoon	0.21	0.18	0.05	47.73	40.91	11.36
Murrah Lagoon	0.46	0.53	4.71	8.07	9.30	82.63
Cuttagee L.	0.60	1.25	0.60	24.49	51.02	24.49
Barragoot L.	0.94	0.47	0.38	52.51	26.26	21.23
Bermagui R.	1.26	0.39	2.65	29.30	9.07	61.63
Wallaga L.	2.42	8.04	4.09	16.63	55.26	28.11
Bobundara Swamp	0.16	0.00	1.10	12.70	0.00	87.30
Little L. A	0.13	0.07	0.20	32.50	17.50	50.00
Tilba Tilba L.	0.27	1.11	0.74	12.74	52.36	34.91
Corunna L.	0.64	1.78	0.49	21.99	61.17	16.84
Nargal L.	0.10	0.18	0.01	34.48	62.07	3.45
Nangudga L.	0.32	0.85	0.35	21.05	55.92	23.03
Bullengella L.	0.07	0.17	0.01	29.17	70.83	0.00
Little L. B	0.20	0.15	0.01	57.14	42.86	0.00
Wagonga Inlet	2.24	4.87	1.41	26.29	57.16	16.55
Kianga L.	0.13	0.23	0.11	27.66	48.94	23.40
Dalmeny L.	0.56	1.52	0.22	24.35	66.09	9.57
Brou L.	1.11	1.94	1.71	23.32	40.76	35.92
Arourga L.	0.20	0.28	0.07	36.36	50.91	12.73
Brunderee L.	0.52	0.17	0.04	71.23	23.29	5.48
Tuross L.	2.49	7.03	25.41	7.13	20.13	72.75
Coila L.	1.30	6.08	2.06	13.77	64.41	21.82
Meringo Beach	0.25	0.09	0.08	59.52	21.43	19.05
Meringo Ck.	0.25	0.08	0.08	60.98	19.51	19.51
Congo Ck.	0.45	1.25	6.62	5.41	15.02	79.57
Moruya R.	13.14	3.15	23.45	33.06	7.93	59.01
Candlagan Ck.	3.92	2.30	2.20	46.56	27.32	26.12
Tomaga R.	13.23	0.21	8.94	59.12	0.94	39.95
Clyde R.	4.77	1.50	25.06	15.23	4.79	79.99
Cullendulla Ck.	1.59	0.00	1.22	56.58	0.00	43.42
Long Beach	0.69	0.06	0.00	92.00	8.00	0.00
Chain Bay	0.39	0.00	0.55	41.49	0.00	58.51
South Durras	0.03	0.00	0.58	4.92	0.00	95.08
Durras L.	2.52	3.07	0.75	39.75	48.42	11.83
Kioloa L.	0.98	0.01	1.61	37.69	0.38	61.92
Murramarang B.	0.23	0.04	0.66	24.44	4.32	71.24
Willinga L.	0.23	0.14	2.06	9.47	5.76	84.77
Meroo L.	0.49	1.13	0.97	18.92	43.63	37.45
Termeil L.	0.62	0.33	1.17	29.25	15.57	55.19
Toubouree L.	3.66	0.54	2.97	51.05	7.53	41.42
Burrill L.	2.00	3.04	1.24	31.85	48.41	19.75
Mollymook Ck.	0.12	0.00	0.30	28.57	0.00	71.43
Narrawallee Ck.	1.36	0.00	9.45	12.58	0.00	87.42
Conjola L.	3.96	5.25	2.86	32.81	43.50	23.70
Nerrindillah Ck	0.14	0.00	0.07	66.67	0.00	33.33
Berrara Ck.	0.80	0.00	0.17	82.47	0.00	17.53
Swan L.	3.39	4.67	1.30	36.22	49.89	13.89

Appendix B: Summary table of sediment texture data for Wapengo and Narrawallee cores.

WAPENGO

SAMPLE	DEPTH (m)	% SAND	% SILT	% CLAY
VC-1 10	20.80	32.29	48.65	19.06
VC-1 13.5	28.50	81.89	13.19	4.93
VC-1 20	35.28	28.73	46.46	24.81
VC-1 40	56.41	24.04	47.21	28.75
VC-1 60	77.55	31.10	45.89	23.00
VC-1 80	98.49	69.21	20.87	9.93
VC-1 100	119.31	54.55	40.15	5.30
VC-1 120	140.14	57.39	13.77	28.83
VC-1 140	160.96	77.43	20.81	1.76
VC-1 150	171.00	95.03	2.68	2.29
VC-1 160	181.13	47.18	33.50	19.32
VC-1 180	202.41	38.90	39.11	21.99
VC-1 200	223.70	29.43	45.17	25.40
VC-1 220	244.98	26.41	46.43	27.16
VC-1 240	266.27	27.49	40.89	31.61
VC-1 258	285.43	28.75	43.42	27.83
VC-1 280	308.84	12.98	54.01	33.01
VC-2 20	41.00	1.75	43.38	54.87
VC-2 30	56.15	5.93	51.40	42.66
VC-2 40	68.00	86.80	7.70	5.49
VC-2 70	99.03	71.96	17.18	10.86
VC-2 90	121.31	62.79	24.28	12.93
VC-2 110	142.67	50.42	32.53	17.06
VC-2 130	163.63	37.92	41.41	20.67
VC-2 150	184.59	39.42	40.06	20.52
VC-2 170	205.55	30.35	44.74	24.91
VC-2 190	226.51	30.24	46.03	23.73
VC-2 200	236.99	15.91	56.20	27.88
VC-2 220	257.95	13.21	60.14	26.65
VC-2 240	278.90	33.32	40.07	26.61
VC-2 260	299.60	22.43	44.47	33.10
VC-2 280	320.27	6.01	54.80	39.18
VC-2 300	340.93	19.43	49.87	30.70
VC-2 320	361.00	5.60	55.28	39.12
VC-2 340	381.00	34.34	41.74	23.91
VC-2 360	400.00	10.02	54.03	35.95
VC-3 0	0.00	61.30	23.96	14.75
VC-3 10	13.42	83.11	11.25	5.65
VC-3 20	24.26	92.59	5.30	2.11
VC-3 36	41.10	75.80	15.89	8.31
VC-3 50	55.10	91.41	5.80	2.79
VC-3 64	69.55	49.54	32.96	17.50
VC-3 80	87.00	95.82	0.95	3.22
VC-4 0	100.00	72.07	20.01	7.92
VC-4 20	121.69	44.79	32.16	23.05
VC-4 40	143.17	49.97	31.38	18.66
VC-4 60	164.19	54.89	24.77	20.34
VC-4 80	185.22	48.40	29.91	21.69
VC-4 100	206.25	62.95	18.41	18.64
VC-4 120	227.64	14.18	38.18	47.64
VC-4 140	248.00	52.40	23.89	23.71
VC-4 160	268.00	58.51	22.83	18.66
VC-5 160	302.63	12.46	47.54	40.00
VC-5 182	330.00	18.83	43.18	37.99
VC-5 204	350.00	22.94	46.64	30.43
VC-5 220	384.00	21.16	46.42	32.42
VC-5 238	404.00	26.74	44.95	28.30
VC-5 260	424.00	69.14	19.80	11.06
VC-5 278	444.00			
VC-11 4	4.79	82.95	10.75	6.30
VC-11 20	23.95	86.22	9.23	4.55
VC-11 40	47.90	81.57	11.46	6.96
VC-11 60	71.85	83.55	10.02	6.42

VC-11 80	95.81	85.73	8.07	6.20
VC-11 100	119.76	84.93	8.29	6.79
VC-11 120	143.71	77.94	12.26	9.80
VC-11 140	168.06	38.37	39.26	22.37
VC-11 160	192.52	28.94	44.42	26.65
VC-11 180	214.30	31.22	31.62	37.17
VC-11 200	235.85	8.28	45.47	46.25
VC-11 220	257.78	6.43	46.66	46.92
VC-11 264	305.65	44.31	32.43	23.25
VC-11 280	324.03	11.92	47.21	40.88
VC-11 310	359.00	1.07	30.34	68.60
VC-12 0	0.00	89.85	6.21	3.94
VC-12 20	22.64	91.35	4.22	4.43
VC-12 40	45.28	88.18	6.42	5.40
VC-12 60	67.92	85.24	8.37	6.39
VC-12 80	90.56	87.00	7.14	5.87
VC-12 100	113.20	71.82	16.93	11.26
VC-12 120	135.71	62.54	25.17	12.29
VC-12 140	158.23	64.83	25.12	10.05
VC-12 160	180.74	64.84	23.24	11.92
VC-12 180	203.40	52.23	31.80	15.97
VC-12 200	225.77	46.46	37.00	16.54
VC-12 220	249.07	27.72	48.94	23.33
PC-12 0	0.00	85.79	8.82	5.39
PC-12 20	26.72	84.71	9.29	6.00
PC-12 40	53.44	78.67	12.99	8.34
PC-12 60	79.45	57.09	29.14	13.77
PC-12 80	104.76	54.99	34.03	10.98
PC-12 100	130.06	31.39	48.29	20.32
PC-12 120	155.37	45.50	36.75	17.75
PC-12 140	180.67	46.78	40.78	12.44
VC-18 0	0.00	84.01	9.27	6.72
VC-18 20	28.48	60.54	18.86	20.60
VC-18 40	56.96	79.62	10.39	10.00
VC-18 60	85.44	91.91	3.30	4.79
VC-18 80	113.92	95.80	0.84	3.36
VC-18 100	142.40	96.95	0.69	2.35
VC-18 120	162.40	93.34	1.43	5.23
VC-18 140	183.47	95.71	0.69	3.60
VC-18 160	205.85	95.68	0.81	3.52
VC-18 200	250.62	96.35	0.59	3.07
VC-18 218	270.76	97.78	0.58	1.64
VC-21 0	0.00	86.51	6.13	7.36
VC-21 20	23.47	93.45	2.36	4.19
VC-21 40	46.94	91.34	4.35	4.31
VC-21 60	70.42	92.48	2.76	4.76
VC-21 80	93.89	88.84	4.08	7.08
VC-21 100	117.36	88.29	3.85	7.85
VC-21 120	140.84	88.08	3.79	8.12
VC-21 140	163.53	90.38	2.46	7.16
VC-21 160	185.57	90.38	2.86	6.76
VC-21 180	207.12	86.63	5.41	7.96
VC-21 200	228.00	82.86	5.56	11.58
VC-21 220	248.00	58.85	5.97	35.18
VC-7 4	6.40	0.00	37.87	62.13
VC-7 14	19.17	7.81	41.66	50.54
VC-7 24	29.73	72.67	19.88	7.44
VC-7 44	50.63	37.14	44.20	18.66
VC-7 64	71.77	39.62	45.77	14.60
VC-7 84	92.85	28.55	49.48	21.97
VC-7 104	113.42	28.86	43.59	27.54
VC-7 124	133.98	22.95	49.50	27.55
VC-7 139	149.40	43.59	44.99	11.42
VC-7 159	169.83	17.34	29.08	53.58
VC-7 179	190.36	11.35	57.17	31.48
VC-7 199	210.89	26.36	44.32	29.32
VC-7 219	231.62	4.65	56.99	38.36
VC-7 239	252.40	17.50	48.48	34.02
VC-7 259	273.40	39.58	38.87	21.56
VC-7 279	294.20	15.74	52.10	32.16
VC-7 299	315.00	29.47	55.38	15.14
VC-7 319	335.00	24.12	45.72	30.16
VC-7 359	375.00	15.81	46.22	37.97
PC-8 0	0.00	93.52	3.38	3.10
PC-8 18	24.90	91.88	3.80	4.32
PC-8 28	62.25	88.60	5.85	5.55
PC-8 48	99.60	66.73	20.34	12.93
PC-8 70	137.08	53.64	29.71	16.65
PC-8 108	173.95	59.05	26.97	13.98
PC-10 0	0.00	85.19	7.18	7.63
PC-10 30	46.28	82.28	7.10	10.62
PC-10 55	91.64	68.17	15.01	16.82
PC-10 72	122.48	89.35	4.35	6.30
PC-10 91	146.96	78.46	13.13	8.40
PC-10 128	185.00	23.21	25.63	51.16
PC-11 0	0.00	96.25	2.03	1.72
PC-11 20	29.78	79.12	14.85	6.03
PC-11 50	45.64	65.27	21.35	13.38
PC-11 80	78.82	69.39	19.77	10.84
PC-11 110	115.33	33.12	39.37	27.51
PC-11 146	178.38	16.70	47.57	35.73

NARRAWALLEE N2

DEPTH m	% SAND	% SILT	% CLAY
0.00	49.92	42.10	7.98
0.20	57.93	28.79	13.28
0.40	65.58	22.91	11.51
0.60	75.45	15.76	8.79
0.71	73.57	18.28	8.15
1.50	85.85	11.69	2.45
1.68	77.88	15.18	6.95
1.87	44.62	33.93	21.46
2.07	29.27	39.98	30.75
2.27	70.55	18.68	10.78
2.47	58.08	19.72	22.20
2.67	4.42	37.20	58.38
2.77	40.74	27.33	31.93
2.97	73.91	19.87	6.22
3.11	69.63	15.16	15.20
3.60	84.34	10.37	5.28
3.80	84.42	12.23	3.35
4.00	89.27	9.06	1.67
4.10	47.32	34.95	17.73
4.20	25.62	50.38	24.00
4.40	15.88	37.68	46.44
4.48	58.28	21.90	19.82
4.50	43.04	28.31	28.66
5.00	47.63	24.39	27.98
5.49	55.66	22.82	21.51
5.60	55.50	20.33	24.17
5.80	50.49	20.63	28.88
5.98	73.89	14.28	11.84
6.00	70.45	30.25	-0.71
7.40	34.82	36.93	28.25
7.50	23.53	32.18	44.30
7.53	15.50	39.85	44.65
7.70	34.16	35.59	30.25
7.85	72.65	23.25	4.10
8.00	19.83	43.44	36.73
8.20	53.13	31.26	15.61
8.40	63.92	19.70	16.37
8.50	63.73	25.73	10.54
8.60	80.33	13.31	6.36
10.50	17.90	47.95	34.15
10.65	16.69	47.27	36.04
10.70	59.82	20.84	19.34
10.90	35.87	27.25	36.87
11.10	34.80	40.88	24.32
15.00	98.50	1.50	0.00
22.00	95.24	4.65	0.11

NARRAWALLEE N3

DEPTH m	% SAND	% SILT	% CLAY
0.06	3.82	52.70	43.48
0.26	6.48	43.64	49.88
0.46	14.01	48.77	37.21
0.66	71.81	17.45	10.74
1.62	76.19	16.01	7.80
1.82	69.96	19.22	10.83
2.07	81.88	12.21	5.91
2.09	93.53	5.75	0.72
2.22	65.23	18.71	16.07
2.66	70.09	18.91	11.00
2.78	63.91	22.85	13.24
2.86	76.95	15.85	7.20
2.98	86.50	8.52	4.99
3.70	51.40	28.21	20.38
3.79	92.47	6.18	1.34
3.84	71.97	18.12	9.91
4.08	95.31	3.89	0.80
4.18	61.95	21.38	16.67
4.36	90.39	6.61	3.01
4.46	73.38	16.10	10.52
5.93	74.86	14.45	10.69
6.00	95.42	3.24	1.34
7.50	100.00	0.00	0.00
7.78	83.66	11.03	5.31
7.98	83.03	10.63	6.34
8.18	86.09	8.03	5.89
8.22	43.31	38.39	18.30
8.48	63.18	17.22	19.60
8.75	57.21	22.77	20.02
8.95	56.12	14.36	29.52
9.15	45.83	24.76	29.41
9.21	45.92	27.36	26.72
9.27	15.59	43.49	40.92
9.47	2.32	12.02	85.66
9.67	68.89	8.71	22.40
9.87	1.07	13.09	85.84
10.05	17.16	35.71	47.13
10.15	29.29	34.58	36.13
10.25	28.76	47.87	23.37
10.45	55.20	25.47	19.33
10.65	56.84	25.14	18.02
10.85	22.09	45.37	32.54
11.05	3.35	47.13	49.52
11.11	26.57	38.87	34.55
11.21	14.79	56.58	28.63
11.30	85.41	10.52	4.08
12.70	100.00	0.00	0.00
13.70	94.69	3.50	1.82
13.90	95.18	4.74	0.08

NARRAWALLEE N5

DEPTH m	% SAND	% SILT	% CLAY
1.31	89.53	4.71	5.76
1.51	89.28	6.81	3.91
1.71	87.57	5.73	6.70
1.87	86.32	5.78	7.91
3.08	92.85	6.21	0.94
3.28	91.76	6.28	1.96
3.52	86.04	9.33	4.63
3.66	67.77	22.00	10.24
6.08	80.27	15.53	4.20
6.26	55.87	31.14	12.99
6.34	85.49	9.93	4.57
6.48	2.64	20.80	76.56
8.95	89.46	3.92	6.61
9.15	73.10	10.29	16.61
9.35	35.64	35.33	29.02
9.55	30.37	38.80	30.84
9.75	66.93	18.95	14.12
11.98	40.77	35.89	23.34
12.18	34.36	34.83	30.81
12.38	78.04	11.33	10.63
12.86	99.32	2.64	0.00
13.06	99.92	1.99	0.00
13.26	99.68	1.80	0.00
13.46	90.28	6.27	3.44
13.62	82.87	9.01	8.12
14.32	100.33	2.73	0.00
14.42	99.89	1.62	0.00
14.52	99.68	1.16	0.00
14.62	99.69	1.56	0.00
14.72	100.57	0.47	0.00
14.82	99.82	0.00	0.68
14.90	99.87	1.56	0.00
15.68	92.38	6.55	1.07
15.74	99.60	1.17	0.00
15.86	98.10	1.85	0.04
16.06	97.48	1.66	0.86
16.15	98.30	1.27	0.43
16.25	96.83	1.88	1.29
17.48	99.90	2.19	0.00
17.68	99.83	1.89	0.00
17.88	84.70	10.27	5.03
19.82	93.44	3.39	3.17
19.94	96.58	1.56	1.86
20.00	84.43	9.57	5.99
20.20	91.59	5.14	3.27
20.40	72.58	12.29	15.13
20.60	89.93	6.42	3.64
20.80	99.86	0.14	0.00
21.00	86.63	10.78	2.59
21.20	11.35	47.96	40.69
21.40	2.74	42.78	54.49
21.60	2.97	55.50	41.53
21.80	3.84	37.70	58.46
22.00	1.83	53.60	44.56
23.08	84.15	8.44	7.41
23.28	2.34	57.81	39.84
23.48	3.13	34.33	62.54
23.68	7.47	28.68	63.84
23.88	7.60	33.24	59.16
24.08	1.94	50.99	47.07
24.30	2.37	34.15	63.48
24.50	1.75	27.85	70.40
24.70	2.42	49.76	47.81
24.90	9.41	39.78	50.82
25.10	16.64	41.87	41.49
25.30	12.94	52.93	34.13
25.50	15.73	46.97	37.30
25.70	14.32	45.94	39.74
25.90	18.17	47.70	34.12
26.23	10.12	40.50	49.38
26.43	9.63	56.21	34.15
26.63	9.78	44.39	45.83
26.83	11.26	40.41	48.33
27.03	9.49	58.11	32.40
27.23	8.91	45.98	45.11
27.43	12.23	48.46	39.31
27.63	29.82	46.38	23.79
27.83	37.85	38.83	23.32
28.03	65.18	18.80	16.02
28.23	72.61	12.64	14.75
28.43	79.01	8.45	12.54

NARRAWALLEE N6

DEPTH m	% SAND	% SILT	% CLAY
1.25	78.65	3.16	18.18
1.55	94.81	0.35	4.84
1.85	94.16	0.66	5.18
2.30	86.77	4.30	8.93
2.50	94.16	0.58	5.27
2.99	92.32	0.00	7.68
3.39	94.00	0.00	6.00
3.57	94.98	0.43	4.60
3.77	94.65	1.01	4.35
3.97	15.74	59.48	24.77
6.94	90.51	2.74	6.75
7.14	90.84	3.17	6.00
7.34	88.91	4.03	7.06
7.70	86.73	4.35	8.92
8.10	92.92	0.65	6.43
8.97	90.63	1.49	7.88
9.64	87.33	4.92	7.75
9.86	92.57	1.36	6.07
10.15	87.09	4.97	7.94
11.48	90.66	1.11	8.23
11.68	95.67	1.49	2.84
11.88	96.57	1.42	2.01
12.08	90.81	1.94	7.26
12.98	89.68	3.12	7.20
13.38	93.19	3.17	3.65
14.48	92.91	1.86	5.23
16.49	93.19	2.40	4.41
16.69	77.73	12.59	9.68
17.82	52.37	22.04	25.59
19.59	85.71	4.14	10.15
19.92	24.54	42.06	33.40
20.06	80.74	8.75	10.51
20.11	9.28	39.95	50.77
20.31	92.15	1.75	6.10
22.68	85.28	7.02	7.69
23.08	76.63	10.56	12.81
23.48	71.55	12.28	16.17
23.88	89.45	5.32	5.23
24.28	79.38	8.51	12.11
24.67	83.92	8.01	8.07

WAPENGO

SAMPLE & DEPTH (CM)	PER CENT CaCO3
SURF ZONE	3.25
PC1:0-10	2.12
PC1:18-20	1.81
PC1:20-22	1.99
PC1:25-30	1.81
PC1:40-50	1.87
PC1:50-60	2.55
PC1:70-85	2.78
PC2:0-10	4.05
PC2:20-30	5.03
PC2:35-40	6.80
PC2:40-50	7.57
PC2:60-70	5.54
PC2:80-90	4.61
PC2:90-95	3.86
PC2:100-110	1.26
PC3:0-10	2.30
PC3:20-30	1.95
PC3:40-50	3.06
PC3:60-70	3.90
PC3:80-90	4.07
PC3:100-110	4.88
PC4:0-10	2.24
PC4:10-20	3.21
PC4:25-35	9.43
PC4:50-60	11.54
PC4:70-80	3.91
PC4:90-100	4.48
PC4:110-120	6.32
PC4:130-140	6.30
PC5:0-10	2.57
PC5:20-30	9.00
PC5:43-50	3.37
PC5:60-68	6.20
PC5:68-78	5.86
PC5:90-100	4.24
PC5:120-130	2.52
PC6:0-10	5.24
PC6:50-60	4.46
PC6:90-100	6.12
PC6:110-120	9.98
PC6:140-150	6.37
PC7:0-10	4.67
PC7:10-20	9.75
PC7:30-40	5.90
PC7:60-70	7.50
PC7:90-100	4.12
PC7:120-130	6.37
PC14:0-10	0.88
PC14:40-50	1.12
PC14:90-100	1.75
PC14:105-115	2.21
PC14:140-145	2.24
PC15:0-10	0.63
PC15:60-70	1.24
PC15:120-130	5.30
PC15:140-150	11.91
PC15:150-155	9.96
PC15:160-170	4.16
PC16:0-7	1.16
PC16:20-30	0.93
PC16:50-60	2.76
PC16:66-76	2.47
PC16:80-90	7.14
PC16:120-130	5.70
PC16:150-160	1.92
PC17:0-10	2.54
PC17:35-45	3.62
PC17:76-83	2.43
PC17:90-100	2.15
PC17:115-125	3.50
PC17:134-140	5.66
PC17:152-157	8.09
PC18:0-10	2.31
PC18:20-30	2.30
PC18:60-70	3.02
PC18:82-92	3.33
PC18:115-125	7.41
PC18:135-145	1.96
PC19:0-10	0.33
PC19:30-40	0.25
PC19:50-60	0.25
PC19:80-90	0.19
PC19:110-130	0.15
PC19:150-161	2.10

SAMPLE	% CaCO3
VC-1 10	9.64
VC-1 13.5	2.94
VC-1 20	8.86
VC-1 40	8.07
VC-1 60	6.07
VC-1 80	4.69
VC-1 100	7.28
VC-1 120	4.85
VC-1 140	3.79
VC-1 150	2.30
VC-1 160	4.18
VC-1 180	7.46
VC-1 200	4.35
VC-1 220	6.25
VC-1 240	8.44
VC-1 258	11.03
VC-1 280	7.91
VC-2 20	21.66
VC-2 30	6.29
VC-2 40	2.85
VC-2 70	5.82
VC-2 90	5.24
VC-2 110	8.32
VC-2 130	11.61
VC-2 150	9.13
VC-2 170	7.34
VC-2 190	6.89
VC-2 200	7.61
VC-2 220	6.23
VC-2 240	14.31
VC-2 260	8.29
VC-2 280	8.96
VC-2 300	9.35
VC-2 320	8.44
VC-2 340	6.43
VC-2 360	8.30
VC-3 0	8.06
VC-3 10	3.35
VC-3 20	2.18
VC-3 36	3.10
VC-3 50	1.30
VC-3 64	3.65
VC-3 80	0.78
VC-4 0	2.91
VC-4 20	4.84
VC-4 40	7.59
VC-4 60	10.42
VC-4 80	7.23
VC-4 100	8.38
VC-4 120	10.60
VC-4 140	7.95
VC-4 160	7.17
VC-11 4	6.95
VC-11 20	3.08
VC-11 40	4.54
VC-11 60	4.74
VC-11 80	4.47
VC-11 100	9.10
VC-11 120	17.93
VC-11 140	10.30
VC-11 160	8.36
VC-11 180	77.66
VC-11 200	18.84
VC-11 220	14.62
VC-11 264	12.51
VC-11 280	8.66
VC-11 310	5.84
VC-12 0	3.93
VC-12 20	2.46
VC-12 40	3.43
VC-12 60	6.99
VC-12 80	11.01
VC-12 100	13.83
VC-12 120	7.59
VC-12 140	6.57
VC-12 160	6.25
VC-12 180	7.46
VC-12 200	6.78
VC-12 220	8.57
PC-12 0	3.00
PC-12 20	4.23
PC-12 40	6.65
PC-12 60	8.08
PC-12 80	7.91
PC-12 100	11.91
PC-12 120	9.70
PC-12 140	6.54
VC-18 0	9.48
VC-18 20	1.98
VC-18 40	5.63
VC-18 60	2.77
VC-18 80	1.85
VC-18 100	2.32
VC-18 120	2.56
VC-18 140	1.92
VC-18 160	1.70
VC-18 200	1.79
VC-18 218	1.84
VC-21 0	3.63
VC-21 20	2.39
VC-21 40	3.11
VC-21 60	2.61
VC-21 80	2.98
VC-21 100	2.76
VC-21 120	3.33
VC-21 140	14.90
VC-21 160	12.16
VC-21 180	2.21
VC-21 200	1.96
VC-21 220	3.07
VC-7 4	36.20
VC-7 14	5.12
VC-7 24	2.54
VC-7 44	5.34
VC-7 64	6.14
VC-7 84	8.69
VC-7 104	9.11
VC-7 124	7.84
VC-7 139	8.06
VC-7 159	9.63
VC-7 179	10.36
VC-7 199	12.69
VC-7 219	9.65
VC-7 239	8.79
VC-7 259	6.60
VC-7 279	7.11
VC-7 299	3.69
VC-7 319	5.08
VC-7 359	5.65
VC-5 160	7.79
VC-5 182	5.03
VC-5 204	3.15
VC-5 220	5.59
VC-5 238	3.20
VC-5 260	4.31
VC-5 278	6.32
PC-8 0	2.94
PC-8 18	3.33
PC-8 28	3.83
PC-8 48	3.16
PC-8 70	7.73
PC-8 108	8.44
PC-10 0	2.58
PC-10 30	8.10
PC-10 55	4.68
PC-10 72	3.33
PC-10 91	2.52
PC-10 128	3.25
PC-11 0	2.19
PC-11 20	3.13
PC-11 50	3.45
PC-11 80	14.98
PC-11 110	5.67
PC-11 146	5.31

Appendix C: Summary table of carbonate data for Wapengo and Narrawallee

SAMPLE	m	% CaCO3
N2.1	0.00	6.97
N2.1	0.20	3.36
N2.1	0.40	2.12
N2.1	0.60	2.33
N2.1	0.71	0.76
N2.2	1.50	0.80
N2.2	1.68	2.00
N2.2	1.87	1.00
N2.2	2.07	1.58
N2.2	2.27	1.61
N2.2	2.47	0.92
N2.2	2.67	1.64
N2.2	2.77	1.16
N2.2	2.97	0.32
N2.2	3.11	1.21
N1.2	3.60	0.96
N1.2	3.80	0.62
N1.2	4.00	0.63
N1.2	4.10	1.11
N1.2	4.20	1.24
N1.2	4.40	1.94
N1.2	4.48	0.87
N2.4	4.50	1.66
N2.4	5.00	1.23
N2.4	5.49	1.19
N2.4	5.60	0.85
N2.4	5.80	0.90
N2.4	5.98	0.45
N2.5	6.00	0.35
N2.5	7.40	1.30
N2.6	7.50	2.83
N2.5	7.53	2.91
N2.6	7.70	1.74
N2.6	7.85	1.02
N2.6	8.00	3.90
N2.6	8.20	2.14
N2.6	8.40 t	0.21
N2.6	8.50	1.46
N2.6	8.60	1.68
N2.7	10.50 t	2.56
N2.7	10.65	23.31
N2.7	10.70	29.48
N2.7	10.90 t	3.32
N2.7	11.10 t	0.31
N2.8	15.00	0.84
N2.9	22.00	2.27

SAMPLE	m	% CaCO3
N6.1	1.25	6.81
N6.1	1.55	3.40
N6.1	1.85	4.21
N6.2	2.30	4.29
N6.2	2.50	3.09
N6.3	2.99	3.49
N6.3	3.39	4.03
N6.4	3.57	2.15
N6.4	3.77	2.74
N6.4	3.97	18.45
N6.5	6.94	5.40
N6.5	7.14	5.85
N6.5	7.34	4.50
N6.6	7.70	11.62
N6.7	8.10	6.37
N6.8	8.97	4.46
N6.9	9.64	2.60
N6.9	9.86	2.14
N6.9	10.15	3.42
N6.10	11.48	3.03
N6.10	11.68	2.74
N6.10	11.88	2.48
N6.10	12.08	2.35
N6.11	12.98	2.76
N6.11	13.38	2.29
N6.12	14.48	2.73
N6.13	16.49	2.92
N6.13	16.69	6.35
N6.14	17.82	11.22
N6.15	19.59	4.06
N6.15	19.92	11.36
N6.15	20.06	6.95
N6.15	20.11	6.90
N6.15	20.31	2.00
N6.16	22.68	7.90
N6.16	23.08	5.90
N6.17	23.48	5.59
N6.17	23.88	7.22
N6.17	24.28	5.32
N6.18	24.67	4.63

SAMPLE	m	% CaCO3
N3.1	0.06	7.68
N3.1	0.26	4.76
N3.1	0.46	1.96
N3.1	0.66	0.72
N3.1	1.62	0.97
N3.2	1.82	1.35
N3.2	2.07	1.09
N3.2	2.09	0.81
N3.2	2.22	3.43
N3.2	2.42	20.58
N3.2	2.54	16.14
N3.2	2.60	14.79
N3.2	2.66	9.87
N3.2	2.68	7.65
N3.2	2.78	8.97
N3.2	2.86	7.77
N3.2	2.98	5.91
N3.3	3.70	3.58
N3.3	3.79	1.89
N3.3	3.84	2.93
N3.3	4.08	3.14
N3.3	4.18	4.70
N3.3	4.36	3.36
N3.3	4.46	3.73
N3.4	5.93	6.18
N3.4	5.95	9.36
N3.5	6.00	2.08
N3.6	7.50	16.09
N3.6	7.78	29.19
N3.6	7.98	15.58
N3.6	8.18	14.48
N3.6	8.22 t	1.72
N3.6	8.48	2.08
N3.7	8.75 t	0.42
N3.7	8.95	2.24
N3.7	9.15	1.88
N3.7	9.21 t	0.14
N3.7	9.27	2.56
N3.7	9.47	4.61
N3.7	9.67 t	0.34
N3.7	9.87	4.29
N3.7	10.05	2.73
N3.8	10.15	2.99
N3.8	10.25 t	0.34
N3.8	10.45	1.78
N3.8	10.65 t	0.43
N3.8	10.85	2.75
N3.8	11.05	2.77
N3.8	11.11	2.93
N3.8	11.21 t	0.23
N3.8	11.30	1.44
N3.10	12.70	1.60
N3.11	13.70	1.14
N3.11	13.90	0.96

SAMPLE	m	% CaCO3
N5.1	1.31	3.90
N5.1	1.51	3.90
N5.1	1.71	4.08
N5.1	1.87	5.19
N5.2	3.08	4.75
N5.2	3.28	9.21
N5.2	3.52	9.15
N5.2	3.66	5.61
N5.3	6.08	4.32
N5.3	6.26	3.77
N5.3	6.34	3.11
N5.3	6.48	5.43
N5.4	8.95	5.34
N5.4	9.15	3.38
N5.4	9.35	2.27
N5.4	9.55	2.24
N5.4	9.75	1.65
N5.5	11.98	2.38
N5.5	12.18	2.38
N5.5	12.38	2.37
N5.6	12.86	1.44
N5.6	13.06	1.79
N5.6	13.26	1.03
N5.6	13.46	1.61
N5.6	13.62	1.20
N5.7	14.32	1.50
N5.7	14.42	1.52
N5.7	14.52	1.97
N5.7	14.62	1.65
N5.7	14.72	1.57
N5.7	14.82	1.95
N5.7	14.90	2.23
N5.8	15.68	2.08
N5.8	15.74	1.84
N5.8	15.86	1.64
N5.8	16.06	1.87
N5.8	16.15	1.30
N5.8	16.25	1.20
N5.9	17.48	1.60
N5.9	17.68	1.27
N5.9	17.88	4.58
N5.10	19.82	3.69
N5.10	19.94	2.81
N5.10	20.00	49.69
N5.10	20.20	39.04
N5.10	20.40	31.60
N5.10	20.60	34.57
N5.11	20.80	19.74
N5.11	21.00	21.49
N5.11	21.40	37.23
N5.12	21.80	30.83
N5.13	23.08	9.30
N5.13	23.48	27.17
N5.13	23.88	22.24
N5.14	24.30	17.13
N5.14	24.50	18.99
N5.14	24.90	17.46
N5.15	25.10	8.81
N5.15	25.50	8.48
N5.15	25.70	10.10
N5.16	26.23	10.81
N5.16	26.63	13.97
N5.16	26.83	12.13
N5.17	27.23	14.06
N5.17	27.43	12.81
N5.18	27.83	12.50
N5.18	28.03	4.27
N5.18	28.23	3.94
N5.18	28.43	3.31

WAPENGO

SAMPLE	DEPTH (m)	%TOC
VC-1 10	20.80	6.01
VC-1 13.5	28.50	0.57
VC-1 20	35.28	3.76
VC-1 40	56.41	2.15
VC-1 60	77.55	1.33
VC-1 80	98.49	1.48
VC-1 100	119.31	1.96
VC-1 120	140.14	1.47
VC-1 140	160.96	1.51
VC-1 150	171.00	-0.09
VC-1 160	181.13	1.91
VC-1 180	202.41	3.75
VC-1 200	223.70	1.55
VC-1 220	244.98	1.88
VC-1 240	266.27	2.64
VC-1 258	285.43	7.17
VC-1 280	308.84	1.66
VC-2 20	41.00	11.14
VC-2 30	56.15	0.63
VC-2 40	68.00	0.42
VC-2 70	99.03	1.75
VC-2 90	121.31	0.75
VC-2 110	142.67	1.41
VC-2 130	163.63	0.83
VC-2 150	184.59	0.94
VC-2 170	205.55	1.40
VC-2 190	226.51	0.75
VC-2 200	236.99	1.03
VC-2 220	257.95	0.78
VC-2 240	278.90	3.31
VC-2 260	299.60	1.76
VC-2 280	320.27	1.53
VC-2 300	340.93	3.05
VC-2 320	361.00	1.30
VC-2 340	381.00	1.71
VC-2 360	400.00	1.44
VC-3 0	0.00	4.93
VC-3 10	13.42	3.00
VC-3 20	24.26	0.85
VC-3 36	41.10	1.66
VC-3 50	55.10	0.21
VC-3 64	69.55	1.35
VC-3 80	87.00	0.06
VC-4 0	100.00	0.78
VC-4 20	121.69	1.86
VC-4 40	143.17	2.08
VC-4 60	164.19	4.97
VC-4 80	185.22	1.47
VC-4 100	206.25	2.39
VC-4 120	227.64	2.18
VC-4 140	248.00	1.12
VC-4 160	268.00	1.21
VC-5 160	302.63	2.69
VC-5 182	330.00	0.10
VC-5 204	350.00	-0.12
VC-5 220	384.00	0.06
VC-5 238	404.00	-0.43
VC-5 260	424.00	-0.44
VC-5 278	444.00	0.41
VC-11 4	4.79	1.77
VC-11 20	23.95	0.27
VC-11 40	47.90	0.76
VC-11 60	71.85	1.54
VC-11 80	95.81	1.07
VC-11 100	119.76	2.07
VC-11 120	143.71	1.41
VC-11 140	168.06	2.66
VC-11 160	192.52	2.07
VC-11 180	214.30	-0.28
VC-11 200	235.85	1.43
VC-11 220	257.78	0.79
VC-11 264	305.65	2.72
VC-11 280	324.03	1.01
VC-11 310	359.00	-0.28
VC-12 0	0.00	0.01
VC-12 20	22.64	0.19
VC-12 40	45.28	0.78
VC-12 60	67.92	2.39
VC-12 80	90.56	0.51
VC-12 100	113.20	2.95
VC-12 120	135.71	0.68
VC-12 140	158.23	0.88
VC-12 160	180.74	1.15
VC-12 180	203.40	2.18
VC-12 200	225.77	1.05
VC-12 220	249.07	1.52
PC-12 0	0.00	0.10
PC-12 20	26.72	0.73
PC-12 40	53.44	2.52
PC-12 60	79.45	1.85
PC-12 80	104.76	2.73
PC-12 100	130.06	4.20
PC-12 120	155.37	3.17
PC-12 140	180.67	1.15
VC-18 0	0.00	-0.10
VC-18 20	28.48	0.68
VC-18 40	56.96	0.12
VC-18 60	85.44	0.00
VC-18 80	113.92	-0.04
VC-18 100	142.40	-0.02
VC-18 120	162.40	0.01
VC-18 140	183.47	0.00
VC-18 160	205.85	-0.02
VC-18 200	250.62	-0.07
VC-18 218	270.76	-0.13
VC-21 0	0.00	0.31
VC-21 20	23.47	0.44
VC-21 40	46.94	0.08
VC-21 60	70.42	0.06
VC-21 80	93.89	0.09
VC-21 100	117.36	0.18
VC-21 120	140.84	0.16
VC-21 140	163.53	-0.08
VC-21 160	185.57	0.69
VC-21 180	207.12	0.03
VC-21 200	228.00	-0.11
VC-21 220	248.00	-0.08
VC-7 4	6.40	10.72
VC-7 14	19.17	1.13
VC-7 24	29.73	0.29
VC-7 44	50.63	1.05
VC-7 64	71.77	0.37
VC-7 84	92.85	1.50
VC-7 104	113.42	2.55
VC-7 124	133.98	1.32
VC-7 139	149.40	1.46
VC-7 159	169.83	0.86
VC-7 179	190.36	1.13
VC-7 199	210.89	2.09
VC-7 219	231.62	0.88
VC-7 239	252.40	0.40
VC-7 259	273.40	1.13
VC-7 279	294.20	1.20
VC-7 299	315.00	0.25
VC-7 319	335.00	-0.06
VC-7 359	375.00	-0.45
PC-8 0	0.00	-0.04
PC-8 18	24.90	1.05
PC-8 28	62.25	1.92
PC-8 48	99.60	0.34
PC-8 70	137.08	2.05
PC-8 108	173.95	1.69
PC-10 0	0.00	0.29
PC-10 30	46.28	1.40
PC-10 55	91.64	0.87
PC-10 72	122.48	0.54
PC-10 91	146.96	0.05
PC-10 128	185.00	-0.05
PC-11 0	0.00	0.19
PC-11 20	29.78	1.18
PC-11 50	45.64	1.32
PC-11 80	78.82	2.85
PC-11 110	115.33	1.93
PC-11 146	178.38	1.21

Appendix D: Summary table of total organic carbon data for Wapengo and Narrawallee cores.

NARRAWALLEE N2

DEPTH (M)	%T.O.C.
0.00	5.04
0.20	1.37
0.40	0.36
0.60	0.18
0.71	0.28
1.50	0.22
1.68	0.71
1.87	0.52
2.07	0.56
2.27	0.29
2.47	0.53
2.67	0.40
2.77	0.43
2.97	0.12
3.11	0.12
3.60	0.24
3.80	0.16
4.00	0.11
4.10	0.13
4.20	0.23
4.40	0.34
4.48	0.20
4.50	0.39
5.00	0.32
5.49	0.30
5.60	0.23
5.80	0.27
5.98	0.19
6.00	0.09
7.40	0.38
7.50	1.02
7.53	1.33
7.70	0.63
7.85	0.18
8.00	0.70
8.20	2.14
8.40	0.19
8.50	0.80
8.60	0.16
10.50	-0.07
10.65	1.74
10.70	0.90
10.90	-0.05
11.10	0.12
15.00	0.02
22.00	0.12

NARRAWALLEE N6

DEPTH (m)	%T.O.C.
1.25	1.87
1.55	0.35
1.85	0.12
2.30	0.23
2.50	-0.15
2.99	0.00
3.39	-0.07
3.57	-0.08
3.77	0.03
3.97	0.33
6.94	1.58
7.14	2.20
7.34	1.36
7.70	0.96
8.10	0.57
8.97	0.34
9.64	0.12
9.86	0.07
10.15	0.06
11.48	0.03
11.68	-0.06
11.88	-0.13
12.08	-0.05
12.98	-0.05
13.38	-0.13
14.48	-0.07
16.49	-0.07
16.69	0.22
17.82	1.41
19.59	-0.13
19.92	4.08
20.06	0.21
20.11	0.07
20.31	-0.09
22.68	-0.35
23.08	-0.08
23.48	0.34
23.88	-0.40
24.28	-0.18

NARRAWALLEE N3

DEPTH (m)	%T.O.C.
0.06	6.00
0.26	3.32
0.46	0.82
0.66	0.16
1.62	0.33
1.82	0.82
2.07	1.17
2.09	0.31
2.22	3.04
2.42	3.84
2.54	2.43
2.60	1.09
2.66	0.35
2.68	0.64
2.78	0.97
2.86	0.44
2.98	0.02
3.70	0.86
3.79	0.18
3.84	0.32
4.08	-0.12
4.18	0.59
4.36	0.05
4.46	0.14
5.93	1.54
5.95	1.56
6.00	0.10
7.50	-1.93
7.78	0.28
7.98	0.08
8.18	0.22
8.48	-0.09
8.75	0.49
8.95	-0.14
9.15	-0.10
9.27	-0.15
9.47	0.03
9.87	-0.05
10.05	-0.11
10.15	-0.10
10.45	-0.05
10.85	-0.13
11.05	0.20
11.11	0.39
11.30	-0.03
12.70	-0.03
13.70	-0.03
13.90	0.01

NARRAWALLEE N5

DEPTH (m)	%TOC
1.31	0.89
1.51	1.01
1.71	1.00
1.87	0.91
3.08	0.48
3.28	0.96
3.52	1.04
3.66	0.83
6.08	0.36
6.26	0.31
6.34	0.26
6.48	0.36
8.95	0.04
9.15	0.02
9.35	0.97
9.55	0.83
9.75	0.46
11.98	0.61
12.18	1.05
12.38	0.06
12.86	-0.02
13.06	-0.06
13.26	-0.04
13.46	0.04
13.62	-0.01
14.32	0.08
14.42	0.00
14.52	-0.06
14.62	-0.03
14.72	-0.04
14.82	-0.08
14.90	-0.12
15.68	0.02
15.74	-0.03
15.86	-0.11
16.06	-0.15
16.15	-0.06
16.25	-0.06
17.48	-0.01
17.68	-0.02
17.88	0.19
19.82	-0.15
19.94	-0.17
20.00	-0.27
20.20	-0.16
20.40	-0.13
20.60	-0.48
20.80	-0.13
21.00	-0.12
21.40	0.63
21.80	0.48
23.08	0.53
23.48	0.50
23.88	0.45
24.30	0.29
24.50	0.56
24.90	0.80
25.10	1.82
25.50	2.37
25.70	2.89
26.23	1.48
26.63	2.07
26.83	1.66
27.23	2.14
27.43	3.00
27.83	2.96
28.03	0.69
28.23	0.39
28.43	0.23

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APPENDIX G: GRAIN SIZE SUMMARY STATISTICS FOR THE SAND FRACTION OF WAPENGO LAGOON SAMPLES

CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS	CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS
WAPENGO PC1	5	1.63	0.25	-0.42	WAPENGO VC1	21	3.06	0.59	-2.64
	19	1.77	0.18	1.54		29	1.26	0.67	0.87
	21	1.63	0.19	-0.16		35	2.96	0.57	-1.12
	27	1.66	0.21	-0.66		56	2.92	0.77	-1.36
	45	1.50	0.24	1.42		78	2.46	1.10	-0.80
	55	1.38	0.23	1.04		98	1.75	1.04	0.29
	77	1.36	0.27	0.36		119	1.91	0.90	0.08
WAPENGO PC2	5	1.74	0.29	0.39		161	1.68	0.99	0.30
	25	1.75	0.31	1.09		171	1.18	0.91	1.01
	45	1.87	0.36	-0.07		181	1.89	1.26	-0.15
	65	1.85	0.32	0.15		202	2.79	0.49	-0.89
	85	1.75	0.33	-0.14		224	2.01	1.04	0.10
	93	1.78	0.46	-2.62		245	2.43	0.88	-0.32
	105	1.28	0.75	-0.79		266	2.64	0.77	-1.38
WAPENGO PC3	5	1.38	0.33	-1.22		285	2.96	0.43	0.13
	25	1.43	0.30	-1.57		309	3.23	0.39	-0.47
	45	1.66	0.21	1.20	WAPENGO VC2	41	1.91	1.36	-0.38
	65	1.71	0.27	-3.75		56	1.26	1.01	0.69
	85	1.71	0.32	0.00		68	2.54	0.63	-0.34
	105	1.79	0.36	-0.27		99	2.64	0.78	-1.37
WAPENGO PC4	5	1.46	0.38	-0.83		121	2.57	0.72	-0.92
	30	1.89	0.43	-0.20		143	2.64	0.58	-0.92

CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS
PC4 CONT.	55	1.94	0.58	0.29
	75	1.56	0.38	-0.06
	95	1.60	0.48	-0.15
	115	1.61	0.51	-0.15
	135	1.58	0.45	0.26
WAPENGO PC5	5	1.53	0.35	-0.78
	25	1.82	0.54	0.32
	46	1.52	0.45	0.27
	64	1.69	0.51	0.45
	73	1.62	0.50	-0.20
	95	1.54	0.52	-0.42
	125	1.56	0.43	-0.68
WAPENGO PC6	5	1.70	0.50	0.84
	55	1.66	0.50	0.09
	95	1.71	0.53	0.09
	115	1.69	0.53	0.35
	145	1.46	0.53	-0.22
WAPENGO PC7	5	1.85	0.34	-0.10
	15	1.97	0.46	-0.15
	35	1.83	0.44	-0.94
	65	1.83	0.54	-0.76
	95	1.60	0.41	-0.19
	125	1.34	0.41	-1.20
WAPENGO PC8	0	1.94	0.50	-1.37
VC2 CONT.	164	2.81	0.59	-1.20
	185	2.92	0.73	-1.05
	206	3.27	0.47	-1.44
	227	3.16	0.37	0.23
	237	2.88	0.44	0.52
	258	3.03	0.43	-0.75
	279	2.39	0.93	-1.42
WAPENGO VC3	0	1.92	0.88	-0.22
	13	2.01	0.52	0.82
	24	1.31	0.48	1.59
	41	2.19	0.61	0.40
	55	1.45	0.63	0.56
	70	2.31	1.00	-0.80
	87	0.55	0.38	0.78
WAPENGO VC4	100	1.74	0.80	0.35
	122	1.71	0.87	0.47
	143	2.23	0.76	-0.05
	164	1.84	0.81	0.17
	185	1.90	0.74	0.02
	206	1.80	0.77	-0.11
	228	2.38	0.76	-0.21
	248	2.02	0.62	0.61
	268	1.85	0.81	0.39
WAPENGO VC5	303	2.92	0.91	-1.94

CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS	CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS
PC8 CONT.	30	2.04	0.74	-0.66	VC5 CONT.	330	2.55	0.83	-0.88
	46	1.85	0.89	-0.65		350	2.53	0.88	-0.92
	79	2.33	0.50	0.22		384	2.13	1.07	-0.44
	115	2.27	0.63	-0.21		404	2.13	1.07	-0.27
	178	2.57	0.65	0.16		424	1.09	1.07	0.89
WAPENGO PC10	0	2.10	0.68	-1.66	WAPENGO VC7	6	2.51	0.81	-0.91
	46	1.82	0.74	-1.08		19	2.31	0.78	-0.33
	92	1.94	0.56	-0.42		30	2.61	0.78	-1.35
	122	1.75	0.75	-1.21		51	2.65	0.72	-0.90
	147	1.97	0.78	-1.34		72	2.71	0.76	-1.17
	185	2.33	1.23	-1.03		93	2.86	0.53	-1.03
WAPENGO PC11	0	1.84	0.61	0.04		113	2.67	0.68	-0.63
	25	1.76	0.66	-0.07		134	2.43	0.56	0.49
	62	1.67	0.68	0.02		149	2.84	0.69	-1.04
	100	2.06	0.69	-0.11		170	2.75	0.78	-1.06
	137	2.25	0.58	0.33		190	2.85	0.51	-1.21
	174	2.23	0.64	0.50		211	2.86	0.86	-2.03
WAPENGO PC12	0	2.20	0.52	0.47		232	2.73	0.63	-1.37
	27	2.13	0.58	0.20		252	2.58	0.68	-0.47
	53	2.21	0.65	-0.48		273	2.60	0.66	-0.27
	79	2.70	0.62	-0.62	WAPENGO VC11	5	1.86	0.77	-0.12
	105	2.60	0.56	0.09		24	1.73	0.75	0.41
	130	2.95	0.49	-0.99		48	1.48	0.91	0.43
	155	2.89	0.44	0.27		72	1.37	0.87	0.55

CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS	CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS
PC12 CONT.	181	2.28	0.73	0.23	VC11 CONT.	96	1.61	0.83	0.04
WAPENGO PC14	5	1.32	0.55	-0.58		120	1.34	0.84	0.57
	45	1.51	0.46	-0.78		144	1.39	0.87	0.47
	95	1.22	0.63	-0.94		168	2.86	0.65	-0.69
	110	1.76	0.41	0.81		193	2.61	0.76	-0.90
	142	1.49	0.46	0.31		214	1.68	0.76	-0.40
WAPENGO PC15	5	1.38	0.40	-0.24		236	2.25	0.68	-1.04
	45	1.38	0.47	-0.22		258	2.87	0.46	0.51
	65	1.42	0.40	-0.56	WAPENGO VC12	0	1.94	0.56	0.26
	105	1.46	0.48	0.43		23	1.79	0.61	0.29
	125	1.49	0.46	0.24		45	1.78	0.71	0.33
	145	1.42	0.49	-0.18		68	1.84	0.69	0.17
	152	1.47	0.49	-0.04		91	1.82	0.70	0.19
	165	1.55	0.42	0.81		113	1.89	0.73	0.28
WAPENGO PC16	2	1.38	0.39	-0.25		136	1.93	0.68	0.08
	25	1.65	0.43	0.71		158	2.14	0.56	0.59
	55	1.65	0.44	0.90		181	1.97	0.53	0.73
	70	1.55	0.42	0.19		203	2.14	0.66	0.49
	85	1.63	0.46	0.88		226	2.06	0.71	0.57
	125	1.48	0.48	0.24		249	2.39	0.78	-0.16
	155	1.44	0.39	0.09	WAPENGO VC18	0	1.75	0.46	-1.29
WAPENGO PC17	5	1.22	0.29	0.73		28	1.77	0.43	-0.53
	40	1.60	0.24	0.88		57	1.72	0.42	-0.42
	80	1.41	0.31	-0.38		85	1.70	0.46	-1.51

CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS	CORE	DEPTH (cm)	MEAN (phi)	SORTING (phi)	SKEWNESS
PC17 CONT.	95	1.52	0.30	-0.60	VC18 CONT.	114	1.67	0.49	-1.66
	120	1.60	0.33	-0.81		142	1.74	0.44	-1.37
	137	1.50	0.43	-0.74		162	1.77	0.37	0.11
	155	1.58	0.43	-0.99		183	1.52	0.46	-0.70
WAPENGO PC18	5	1.20	0.30	0.14		206	1.63	0.30	-0.14
	25	1.25	0.29	-0.78		251	1.64	0.35	-0.59
	65	1.49	0.32	-1.56		271	1.61	0.31	0.65
	87	1.47	0.31	-1.02	WAPENGO VC21	23	1.77	0.41	0.01
	120	1.50	0.33	-1.03		47	1.88	0.45	-0.14
	140	1.66	0.33	1.83		70	1.88	0.45	-0.44
WAPENGO PC19	5	1.54	0.40	0.38		94	1.88	0.45	-0.44
	35	1.48	0.42	-0.28		117	1.88	0.46	-0.74
	55	1.46	0.48	-0.24		141	1.85	0.43	-1.19
	85	1.38	0.40	-0.38		164	1.74	0.58	-1.60
	120	1.33	0.38	-0.13		186	1.76	0.48	-1.02
	155	1.47	0.49	0.49		207	1.75	0.49	-1.04

		PHI FRACTION AS PERCENTAGE OF TOTAL SAMPLE WEIGHT						
CORE	DEPTH (cm)	4 PHI	4.5 PHI	5 PHI	5.5 PHI	6 PHI	7 PHI	8 PHI
	93	10.53	11.61	9.05	6.01	7.58	4.70	21.97
	113	6.57	8.98	6.61	5.32	9.38	6.74	27.54
	134	7.43	9.01	9.13	7.06	10.48	6.39	27.55
	149	3.82	8.20	23.11	2.46	3.94	3.47	11.42
	170	6.88	12.05	11.46	8.92	11.98	6.61	31.81
	190	6.78	11.18	11.56	8.74	11.96	6.95	31.48
	211	6.78	9.28	7.06	5.42	8.89	6.90	29.32
	232	4.99	9.80	11.44	9.39	13.61	7.76	38.36
	252	5.63	7.69	8.80	7.27	11.90	7.19	34.02
	273	8.83	7.85	5.89	5.00	6.79	4.50	21.56
	294	6.61	9.08	9.31	7.23	12.65	7.23	32.16
	315	13.32	10.74	10.24	7.19	9.01	4.88	15.14
	335	8.99	10.35	7.92	5.82	8.02	4.62	30.16
	375	8.60	8.02	8.50	6.19	9.41	5.51	37.97
WAPENGO VC11	5	4.62	2.79	1.23	0.51	1.14	0.45	6.30
	24	3.83	2.04	1.20	0.67	0.77	0.72	4.55
	48	3.44	2.27	1.56	1.22	1.72	1.25	6.96
	72	2.58	2.00	1.40	1.22	1.64	1.18	6.42
	96	2.15	1.57	0.98	0.82	1.57	0.98	6.20
	120	1.77	1.50	1.23	0.97	1.50	1.32	6.79
	144	2.70	2.10	1.88	1.26	2.70	1.62	9.80
	168	5.90	7.75	6.98	4.64	8.03	5.96	22.37
	193	7.20	7.36	7.24	6.13	10.02	6.45	26.65
	214	4.18	3.92	2.81	4.12	8.17	8.43	37.17
	236	2.81	5.51	7.15	6.93	12.83	10.24	46.25
	258	2.95	5.62	7.70	7.52	12.94	9.92	46.92
	306	4.45	5.24	4.54	4.13	7.50	6.57	23.25
	324	8.04	6.60	7.96	5.63	11.20	7.77	40.88
	359	1.50	2.03	3.18	4.17	8.89	10.57	68.60
WAPENGO VC12	0	2.02	1.45	0.91	0.56	0.74	0.53	3.94
	23	1.10	0.67	0.76	0.33	0.79	0.58	4.43
	45	1.82	1.29	0.82	0.72	1.03	0.73	5.40

		PHI FRACTION AS PERCENTAGE OF TOTAL SAMPLE WEIGHT						
CORE	**DEPTH (cm)**	**4 PHI**	**4.5 PHI**	**5 PHI**	**5.5 PHI**	**6 PHI**	**7 PHI**	**8 PHI**
	68	2.14	1.43	1.40	0.83	1.52	1.06	6.39
	91	1.99	1.28	1.02	0.74	1.11	0.99	5.87
	113	4.13	2.98	2.78	1.76	2.88	2.39	11.26
	136	5.17	4.57	4.61	3.32	4.58	2.92	12.29
	158	5.80	5.31	4.33	2.93	4.08	2.68	10.05
	181	4.69	4.57	3.97	2.92	4.43	2.66	11.92
	203	6.26	6.71	5.34	4.16	5.72	3.62	15.97
	226	7.05	8.10	6.43	4.94	6.79	3.70	16.54
	249	9.73	8.93	8.77	7.25	9.49	4.78	23.33
WAPENGO VC18	0	1.70	1.92	1.96	0.99	1.75	0.95	6.72
	28	1.05	2.94	3.45	2.46	5.10	3.86	20.60
	57	1.23	2.15	2.18	1.56	1.61	1.65	10.00
	85	0.39	0.54	0.58	0.49	1.05	0.25	4.79
	114	0.11	0.05	0.13	0.17	0.23	0.14	3.36
	142	0.06	0.05	0.06	0.11	0.32	0.10	2.35
	162	0.03	0.21	0.11	0.20	0.46	0.42	5.23
	183	0.08	0.01	0.06	0.10	0.21	0.24	3.60
	206	0.14	0.07	0.01	0.14	0.22	0.22	3.52
	251	0.10	0.10	-0.02	0.17	0.08	0.16	3.07
	271	0.05	0.05	-0.05	0.17	0.22	0.14	1.64
WAPENGO VC21	0	0.76	0.72	0.84	0.70	1.98	1.14	7.36
	23	0.41	0.42	0.42	0.20	0.51	0.39	4.19
	47	2.87	-0.32	0.72	0.43	0.37	0.28	4.31
	70	0.74	0.50	0.34	0.32	0.55	0.32	4.76
	94	0.98	0.54	0.54	0.45	1.02	0.55	7.08
	117	0.75	0.51	0.72	0.46	0.89	0.51	7.85
	141	0.59	0.52	0.58	0.43	0.84	0.84	8.12
	164	0.21	0.20	0.27	0.62	0.53	0.63	7.16
	186	0.37	0.32	0.32	0.40	0.49	0.95	6.76
	207	0.93	0.98	0.74	0.69	1.07	1.01	7.96
	228	0.89	0.91	0.88	0.75	1.25	0.87	11.58
	248	0.76	0.48	0.66	0.69	1.79	1.60	35.18

		PHI FRACTION AS PERCENTAGE OF TOTAL SAMPLE WEIGHT						
CORE	DEPTH (cm)	4 PHI	4.5 PHI	5 PHI	5.5 PHI	6 PHI	7 PHI	8 PHI
WAPENGO PC8	0	0.63	0.37	0.25	0.25	0.14	0.40	1.72
	30	3.98	3.61	2.24	1.54	1.82	1.66	6.03
	46	3.86	5.07	3.26	2.30	3.67	3.19	13.38
	79	5.14	4.60	3.08	1.73	3.05	2.17	10.84
	115	4.60	7.20	6.21	5.44	9.34	6.58	27.51
	178	6.16	7.92	7.81	6.84	11.45	7.38	35.73
WAPENGO PC10	0	1.39	1.25	1.35	0.93	1.25	1.01	7.63
	46	1.71	1.40	1.02	0.43	1.10	1.45	10.62
	92	1.02	1.99	2.58	2.15	4.04	3.25	16.82
	122	0.47	0.67	0.35	0.55	1.31	1.00	6.30
	147	2.58	2.14	2.11	1.21	2.81	2.30	8.40
	185	5.14	4.35	3.23	2.39	5.74	4.77	51.16
WAPENGO PC11	0	0.96	0.69	0.57	0.20	0.62	0.35	3.10
	25	1.15	0.53	0.69	0.26	0.76	0.41	4.32
	62	1.35	1.21	0.84	0.65	1.05	0.74	5.55
	100	4.65	4.45	3.53	1.97	3.15	2.58	12.93
	137	5.90	6.20	5.06	3.30	5.82	3.43	16.65
	174	5.84	5.55	4.76	2.89	4.89	3.04	13.98
WAPENGO PC12	0	3.28	2.03	1.34	0.82	0.84	0.51	5.39
	27	2.65	1.88	1.40	0.98	1.28	1.11	6.00
	53	3.52	2.57	1.84	1.35	2.18	1.53	8.34
	79	9.51	5.79	3.87	2.71	4.48	2.77	13.77
	105	10.11	7.29	5.91	3.25	4.91	2.56	10.98
	130	14.51	8.76	6.57	4.74	7.65	6.06	20.32
	155	8.67	6.13	5.07	4.14	7.19	5.55	17.75
	181	6.72	6.83	6.96	4.55	7.83	7.89	12.44

APPENDIX I: GRAIN SIZE DATA FOR NARRAWALLEE CORE N5

SAND FRACTION SUMMARY STATISTICS				PHI INTERVAL AS PERCENTAGE OF SAMPLE WEIGHT						
DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS	4 phi	4.5 phi	5 phi	5.5 phi	6 phi	7 phi	8 phi
1.31	2.08	0.53	0.79	2.10	0.29	0.94	0.69	0.36	0.33	5.76
1.51	2.08	0.57	0.54	2.00	1.04	1.07	0.51	1.24	0.96	3.91
1.71	2.16	0.59	0.51	1.70	1.34	0.40	0.57	1.30	0.42	6.70
1.87	2.14	0.55	0.76	1.05	1.27	0.65	0.93	0.80	1.08	7.91
3.08	2.21	0.55	0.47	1.87	0.88	0.43	0.88	0.77	1.39	0.94
3.28	2.07	0.62	0.03	1.93	0.78	0.66	0.43	1.50	0.98	1.96
3.52	2.16	0.62	0.63	2.25	1.42	1.45	0.91	1.15	2.16	4.63
3.66	2.73	0.72	-0.70	6.07	4.17	2.72	2.57	3.96	2.51	10.24
6.08	2.24	0.66	0.39	4.39	3.00	1.84	1.42	2.97	1.91	4.20
6.26	2.39	0.86	-0.82	8.26	6.41	5.12	3.32	4.87	3.17	12.99
6.34	1.14	0.94	0.90	3.07	1.80	1.27	1.12	1.47	1.21	4.57
8.95	0.36	0.74	1.95	0.63	0.35	0.49	0.26	1.09	1.09	6.61
9.15	0.44	0.73	2.41	1.09	1.11	0.98	1.76	2.52	2.83	16.61
9.35	2.87	0.48	-0.37	8.18	5.78	4.90	3.96	7.30	5.21	29.02
9.75	2.70	0.52	0.09	5.98	3.64	2.54	1.80	2.99	2.01	14.12
11.98	3.06	0.66	-2.26	7.86	7.93	6.25	4.39	5.65	3.80	23.34
12.18	2.71	0.65	-0.34	5.98	6.28	5.37	4.43	7.20	5.57	30.81
12.38	2.11	0.55	-0.27	2.46	2.10	1.44	1.56	2.18	1.59	10.63
12.86	2.05	0.35	0.95	0.68	0.00	0.00	0.00	0.00	0.00	0.00
13.06	1.98	0.38	0.03	0.08	0.00	0.00	0.00	0.00	0.00	0.00

DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS	4 phi	4.5 phi	5 phi	5.5 phi	6 phi	7 phi	8 phi
13.46	2.09	0.48	0.35	1.20	1.28	-0.06	1.48	1.54	0.83	3.44
13.62	2.07	0.49	0.60	2.56	1.17	1.29	0.93	1.90	1.16	8.12
14.32	2.10	0.37	-0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.42	2.12	0.35	0.24	0.11	0.00	0.00	0.00	0.00	0.00	0.00
14.52	2.14	0.34	-0.45	0.32	0.00	0.00	0.00	0.00	0.00	0.00
14.72	2.15	0.32	-0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.90	2.19	0.33	1.03	0.13	0.00	0.00	0.00	0.00	0.00	0.00
15.68	2.39	0.34	0.33	7.62	0.00	0.00	0.00	0.00	0.00	1.07
15.86	2.41	0.31	0.64	1.90	0.00	0.00	0.00	0.00	0.00	0.04
16.06	2.40	0.31	0.63	2.52	0.00	0.00	0.00	0.00	0.00	0.86
16.25	2.39	0.32	0.68	3.17	0.00	0.00	0.00	0.00	0.00	1.29
17.48	2.26	0.33	0.69	0.10	0.00	0.00	0.00	0.00	0.00	0.00
17.68	2.10	0.33	0.89	0.17	0.00	0.00	0.00	0.00	0.00	0.00
17.88	2.39	0.39	-0.02	1.50	2.03	1.73	1.50	2.00	1.50	5.03
19.82	2.27	0.35	0.47	1.01	0.63	0.65	0.20	0.83	0.07	3.17
20.00	2.56	0.42	0.49	-0.23	3.78	1.01	1.48	1.40	2.14	5.99
20.20	2.35	0.40	-1.32	8.41	0.00	0.00	0.00	0.00	0.00	3.27
20.40	2.31	0.47	0.27	1.61	1.29	1.77	1.74	2.79	3.08	15.13
20.60	2.27	0.44	0.26	1.45	1.30	0.56	-0.12	1.72	1.51	3.64
20.80	2.06	0.43	0.28	0.14	0.00	0.00	0.00	0.00	0.00	0.00
21.00	2.28	0.42	0.23	3.21	1.72	1.29	0.97	2.26	1.32	2.59
21.40	2.76	0.80	-1.08	3.56	4.46	7.62	6.64	11.22	9.28	54.49
21.80	NOT	ANALYSED		2.91	4.96	5.28	6.69	10.74	7.10	58.46
23.08	2.02	0.63	-0.08	2.34	1.36	0.23	1.78	1.22	1.50	7.41

DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS	4 phi	4.5 phi	5 phi	5.5 phi	6 phi	7 phi	8 phi
23.88	2.40	1.01	0.16	3.52	3.97	3.35	4.06	9.99	8.34	59.16
24.30	3.13	0.59	-1.75	3.00	3.54	4.40	4.02	9.60	9.60	63.48
24.50	NOT ANALYSED			2.21	2.81	4.93	1.94	8.30	7.65	70.40
24.90	NOT ANALYSED			7.96	5.73	6.23	4.69	8.42	6.73	50.82
25.10	NOT ANALYSED			9.42	6.13	5.90	5.18	8.81	6.43	41.49
25.50	3.36	0.43	-2.21	12.19	7.89	5.96	6.65	8.59	5.69	37.30
25.70	3.29	0.52	-5.56	14.30	4.77	6.97	3.52	9.41	6.97	39.74
26.23	3.13	0.64	-2.27	7.63	6.13	5.04	5.09	10.07	6.54	49.38
26.63	NOT ANALYSED			8.22	8.22	5.61	5.39	10.06	6.89	45.83
26.83	NOT ANALYSED			9.55	4.82	5.47	5.96	9.55	5.06	48.33
27.23	3.24	0.72	-4.46	9.02	7.75	6.88	7.75	6.58	8.00	45.11
27.83	3.05	0.56	-2.15	10.22	7.67	5.00	4.12	7.10	4.72	23.32
28.03	1.69	0.96	0.37	4.45	3.30	2.78	1.97	3.58	2.73	16.02
28.23	1.47	0.93	0.73	2.68	2.01	1.93	1.52	2.31	2.20	14.75
28.43	1.36	0.87	0.92	2.01	1.15	1.22	1.22	1.70	1.15	12.54

APPENDIX J: GRAIN SIZE DATA FOR NARRAWALLEE CORE N3

SAND FRACTION SUMMARY STATISTICS				PHI INTERVAL AS PERCENTAGE OF SAMPLE WEIGHT						
DEPTH (m)	**MEAN (phi)**	**SORTING (phi)**	**SKEWNESS**	**4 phi**	**4.5 phi**	**5 phi**	**5.5 phi**	**6 phi**	**7 phi**	**8 phi**
0.06	3.07	0.48	-3.02	2.69	8.73	9.08	7.71	11.21	13.29	43.48
0.26	NOT	ANALYSED		5.16	4.84	5.47	5.66	11.99	10.53	49.88
0.46	3.19	0.54	-1.43	7.07	8.54	7.98	6.56	11.88	6.73	37.21
0.66	2.66	0.51	-1.05	6.42	3.13	1.94	1.43	2.73	1.79	10.74
1.62	2.46	0.52	0.17	4.97	2.88	1.81	1.53	2.69	2.14	7.80
1.82	2.88	0.58	-0.02	6.19	3.63	2.49	1.93	2.68	2.29	10.83
2.07	2.57	0.48	-0.37	3.51	2.21	1.76	1.26	1.97	1.50	5.91
2.09	2.33	0.52	-0.02	1.38	1.12	0.81	0.44	1.07	0.92	0.72
2.22	2.79	0.49	-0.47	6.76	3.54	1.80	1.57	2.67	2.38	16.07
2.66	2.84	0.43	-0.52	5.03	3.76	1.53	1.89	3.14	3.56	11.00
2.78	2.84	0.43	-0.53	5.20	3.63	3.05	2.41	4.76	3.80	13.24
2.86	NOT	ANALYSED		3.51	2.85	2.37	1.69	3.19	2.24	7.20
2.98	2.53	0.57	0.55	2.17	1.52	0.99	0.92	1.59	1.32	4.99
3.70	2.64	0.63	0.08	6.67	4.63	4.39	3.70	5.68	3.14	20.38
3.79	2.00	0.59	0.81	2.32	0.85	0.85	0.56	0.89	0.72	1.34
3.84	NOT	ANALYSED		5.34	3.39	2.87	1.73	2.62	2.17	9.91
4.08	1.63	0.60	0.74	1.10	0.66	0.46	0.55	0.53	0.59	0.80
4.18	2.21	0.76	0.04	5.38	3.97	3.25	2.45	3.92	2.41	16.67
4.36	1.73	0.63	0.62	2.03	1.01	0.77	0.60	1.31	0.90	3.01
4.46	1.98	0.59	0.49	2.65	1.94	1.90	1.79	3.87	3.94	10.52

DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS	4 phi	4.5 phi	5 phi	5.5 phi	6 phi	7 phi	8 phi
6.00	1.84	0.67	0.19	1.04	0.50	0.32	0.27	0.54	0.56	1.34
7.78	2.40	0.68	-0.79	2.99	1.75	1.58	1.32	2.04	1.35	5.31
7.98	2.27	0.89	-0.55	2.79	1.64	1.57	1.17	2.12	1.33	6.34
8.18	2.38	0.90	-0.65	2.46	1.15	0.92	0.84	1.44	1.22	5.89
8.48	2.66	0.54	0.31	5.73	3.31	2.48	1.60	2.24	1.86	19.60
8.95	2.86	0.45	-0.34	5.42	2.91	1.80	1.18	1.74	1.32	29.52
9.15	2.72	0.89	-0.99	7.02	4.75	3.50	2.80	3.73	2.96	29.41
9.27	2.86	0.87	-1.89	9.88	8.39	7.43	4.80	7.79	5.20	40.92
9.47	NOT	ANALYSED		1.55	1.12	1.21	0.95	3.32	3.87	85.66
9.87	NOT	ANALYSED		0.38	0.81	0.36	1.58	3.36	6.58	85.84
10.05	2.89	0.53	-1.48	4.97	4.66	4.84	4.35	8.70	8.19	47.13
10.15	2.64	0.97	-1.46	6.72	5.45	4.60	3.91	7.89	6.00	36.13
10.45	2.99	0.43	0.23	7.20	4.87	3.05	2.79	4.08	3.48	19.33
10.85	3.35	0.44	-6.46	11.23	8.97	7.15	4.64	7.64	5.74	32.54
11.05	NOT	ANALYSED		4.00	6.31	7.60	7.02	13.01	9.19	49.52
11.11	3.35	0.36	0.05	10.82	6.77	5.21	4.15	7.03	4.90	34.55
11.30	0.99	1.06	1.10	2.80	1.74	1.28	1.13	1.87	1.69	4.08
12.70	1.60	0.39	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13.70	1.18	0.80	1.15	0.88	0.57	0.25	0.32	0.79	0.69	1.82
13.90	1.11	0.53	-0.37	1.00	0.83	0.61	0.47	0.94	0.89	0.08

APPENDIX K: GRAIN SIZE DATA FOR NARRAWALLEE CORE N1/2

SAND FRACTION SUMMARY STATISTICS				PHI INTERVAL AS PERCENTAGE OF SAMPLE WEIGHT						
DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS	4 phi	4.5 phi	5 phi	5.5 phi	6 phi	7 phi	8 phi
0.00	2.46	0.71	-0.12	5.70	7.46	5.61	5.35	10.35	7.63	7.98
0.20	2.17	0.90	-0.26	5.71	5.12	3.94	3.14	6.10	4.78	13.28
0.40	2.28	0.79	-0.24	6.04	4.10	3.31	2.41	4.08	2.97	11.51
0.60	2.25	0.79	-0.15	5.18	2.78	2.15	1.42	2.44	1.80	8.79
0.71	2.20	0.90	-0.51	5.55	3.04	2.21	1.85	3.18	2.44	8.15
1.50	2.25	0.87	-0.78	4.01	2.13	1.53	0.79	1.39	1.85	2.45
1.68	2.21	0.72	-0.01	4.10	2.90	1.87	1.40	2.63	2.28	6.95
1.87	3.15	0.32	0.40	11.73	7.38	4.53	3.02	4.18	3.09	21.46
2.07	2.60	0.73	-0.69	9.27	6.69	6.65	4.41	8.03	4.93	30.75
2.27	1.96	0.68	0.20	3.18	3.49	2.68	2.09	4.05	3.19	10.78
2.47	2.79	0.41	-0.14	5.69	4.25	2.77	1.91	3.08	2.03	22.20
2.67	NOT ANALYSED			3.12	3.92	5.64	5.32	9.44	9.76	58.38
2.77	2.24	0.89	-0.28	4.33	4.72	4.54	3.13	6.15	4.46	31.93
2.97	1.85	0.94	0.21	5.28	3.85	3.03	2.32	2.98	2.40	6.22
3.11	1.98	0.86	0.21	3.77	2.23	1.62	1.49	2.95	3.09	15.20
3.60	2.45	0.73	-0.95	3.33	2.17	1.24	1.02	1.51	1.10	5.28
3.80	2.20	0.83	-0.04	3.73	2.35	1.67	0.98	2.12	1.38	3.35
4.00	1.64	0.88	0.60	2.71	1.79	1.24	0.61	1.63	1.08	1.67
4.10	2.31	0.88	-0.11	9.62	8.28	5.32	3.09	5.26	3.38	17.73
4.20	2.82	0.74	-0.97	9.99	10.39	9.20	6.45	8.74	5.60	24.00
4.40	2.93	0.59	-1.08	3.58	4.74	5.91	4.85	10.60	8.01	46.44

DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS	4 phi	4.5 phi	5 phi	5.5 phi	6 phi	7 phi	8 phi
4.50	1.80	1.13	-0.17	4.37	3.63	3.81	3.53	7.23	5.73	28.66
5.00	2.48	0.65	-0.06	4.77	2.95	3.28	2.92	5.23	5.23	27.98
5.49	2.50	0.56	-0.25	3.29	3.58	3.15	3.79	5.13	3.89	21.51
5.60	2.52	0.65	0.32	4.15	3.42	2.67	2.19	4.24	3.65	24.17
5.80	2.56	0.64	-0.18	4.76	2.90	2.68	2.53	3.90	3.86	28.88
5.98	NOT ANALYSED			3.78	1.95	1.58	1.60	2.72	2.65	11.84
6.00	2.45	0.73	0.20	15.47	11.07	1.98	0.98	0.46	0.30	0.00
7.40	2.58	0.84	-0.55	8.82	7.14	6.12	3.86	6.48	4.50	28.25
7.50	2.65	0.89	-1.23	4.97	4.71	3.79	4.05	7.54	7.11	44.30
7.53	2.99	0.78	-1.45	6.81	6.09	5.30	4.74	9.38	7.53	44.65
7.70	2.79	0.92	-1.26	9.73	6.42	5.71	3.31	5.79	4.63	30.25
7.85	2.59	0.92	-0.59	13.51	4.80	1.65	0.95	1.42	0.93	4.10
8.00	3.22	0.58	-1.73	8.28	8.25	6.72	5.10	9.07	6.03	36.73
8.20	2.88	0.56	-0.17	8.75	6.16	4.58	3.35	4.77	3.65	15.61
8.50	2.96	0.61	-0.62	9.84	5.50	3.47	1.95	2.97	1.99	10.54
8.60	2.19	0.76	-0.24	3.88	1.82	1.55	1.25	2.71	2.10	6.36
10.65	NOT ANALYSED			4.50	7.16	12.00	7.63	7.92	8.06	36.04
10.70	2.55	0.45	0.71	2.65	3.34	3.80	2.35	4.15	4.55	19.34
15.00	1.61	0.69	0.46	0.92	0.32	0.19	0.12	0.25	0.20	0.00
22.00	2.29	0.66	0.10	2.28	0.97	0.41	0.29	0.47	0.24	0.11

APPENDIX L: GRAIN SIZE SUMMARY STATISTICS FOR THE SAND FRACTION OF NARRAWALLEE N6 SAMPLES

DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS
1.25	1.99	0.46	-0.80
1.55	1.46	0.61	-0.04
1.85	2.04	0.34	-0.84
2.30	1.86	0.47	0.73
2.50	1.63	0.41	-0.19
2.99	1.77	0.42	-0.12
3.39	1.71	0.46	-0.06
3.57	1.89	0.33	0.52
3.77	1.88	0.40	1.38
3.97	2.52	0.55	-2.44
6.94	1.83	0.64	-1.12
7.14	2.05	0.42	-0.54
7.34	2.17	0.41	0.04
7.90	2.02	0.43	-0.24
8.10	2.32	0.42	-0.05
8.97	2.41	0.43	0.52
9.64	2.31	0.59	0.27
9.86	1.84	0.52	-0.01
10.15	2.40	0.59	-0.12
11.48	1.98	0.55	-0.29
11.68	2.01	0.43	0.69
11.88	1.85	0.51	0.54
12.08	1.90	0.52	0.33
12.98	2.29	0.50	0.68
13.38	2.16	0.48	0.84
14.48	1.49	0.71	0.15
16.49	1.47	0.52	0.53
16.69	1.88	0.88	-0.05
17.82	2.24	0.62	-0.73
19.59	2.27	0.40	-0.17
19.92	2.61	0.71	-0.60
20.06	2.65	0.39	0.63

DEPTH (m)	MEAN (phi)	SORTING (phi)	SKEWNESS
20.31	1.90	0.40	1.00
22.68	2.35	0.42	0.58
23.08	2.40	0.42	0.50
23.48	2.41	0.46	0.88
23.88	2.40	0.40	0.67
24.28	2.41	0.43	0.81
24.67	2.06	0.47	0.88

APPENDIX H: GRAIN SIZE DATA FOR THE FINE FRACTION OF WAPENGO LAGOON SAMPLES

		PHI FRACTION AS PERCENTAGE OF TOTAL SAMPLE WEIGHT						
CORE	**DEPTH (cm)**	**4 PHI**	**4.5 PHI**	**5 PHI**	**5.5 PHI**	**6 PHI**	**7 PHI**	**8 PHI**
WAPENGO VC1	21	13.79	9.75	7.19	4.42	7.10	6.41	19.06
	29	4.29	2.19	1.33	0.22	1.68	3.46	4.93
	35	10.24	9.58	5.95	6.09	7.22	7.38	24.81
	56	10.04	9.56	7.83	6.19	7.26	6.34	28.75
	78	10.23	9.30	8.36	5.38	7.41	5.21	23.00
	98	7.53	3.56	3.03	1.78	3.58	1.38	9.93
	119	6.99	6.70	5.24	20.07	-4.10	5.24	5.30
	161	2.74	11.50	-7.66	1.79	1.94	10.50	1.76
	171	0.34	1.71	0.55	2.20	-2.86	0.74	2.29
	181	6.52	7.29	5.52	3.99	5.43	4.75	19.32
	202	6.02	7.10	6.17	4.73	6.88	8.22	21.99
	224	8.66	8.40	7.74	5.16	9.38	5.82	25.40
	245	7.32	9.96	8.62	5.99	10.00	4.54	27.16
	266	6.20	6.58	7.30	5.42	8.37	7.01	31.61
	285	7.05	7.11	8.09	5.10	8.78	7.29	27.83
	309	9.10	11.51	9.56	6.51	9.24	8.09	33.01
WAPENGO VC2	41	1.65	7.10	6.70	5.35	10.69	11.89	54.87
	56	5.48	6.59	9.20	7.24	13.74	9.14	42.66
	68	2.39	1.67	1.11	0.72	1.03	0.79	5.49
	99	6.56	2.95	2.36	1.24	2.07	2.01	10.86
	121	10.35	5.18	2.39	1.75	2.37	2.23	12.93
	143	10.87	7.40	4.28	3.08	4.08	2.82	17.06
	164	14.83	8.53	5.82	3.31	5.05	3.88	20.67
	185	12.71	8.14	5.70	4.13	5.12	4.27	20.52
	206	9.55	9.32	7.87	4.66	7.54	5.80	24.91
	227	13.73	9.65	6.68	4.72	6.76	4.49	23.73
	237	13.67	12.24	9.53	6.03	9.03	5.72	27.88
	258	16.80	12.66	9.76	6.51	8.08	6.34	26.65
	279	8.75	7.95	5.94	3.91	7.29	6.22	26.61
	300	6.85	7.97	9.16	4.72	8.94	6.83	33.10

		PHI FRACTION AS PERCENTAGE OF TOTAL SAMPLE WEIGHT						
CORE	DEPTH (cm)	4 PHI	4.5 PHI	5 PHI	5.5 PHI	6 PHI	7 PHI	8 PHI
	320	5.95	9.43	10.22	14.59	5.64	8.97	39.18
	341	9.81	10.94	5.10	4.68	10.61	8.73	30.70
	361	5.74	9.76	10.95	7.61	13.23	7.98	39.12
	381	5.56	7.99	6.93	6.19	8.94	6.14	23.91
	401	7.33	11.24	8.83	8.07	10.89	7.66	35.95
WAPENGO VC3	0	2.96	4.96	4.38	2.83	4.64	4.19	14.75
	13	2.05	2.69	1.58	1.14	1.95	1.84	5.65
	24	0.88	1.27	0.81	0.66	0.94	0.74	2.11
	41	3.65	3.31	2.13	1.78	2.57	2.45	8.31
	55	0.81	1.00	0.83	0.68	1.47	1.01	2.79
	70	9.70	6.57	5.37	3.54	4.82	2.95	17.50
	87	0.23	0.18	0.08	0.12	0.22	0.12	3.22
WAPENGO VC4	100	5.79	5.06	3.33	2.05	2.50	1.28	7.92
	122	6.74	5.49	4.87	3.60	6.23	5.22	23.05
	143	8.59	6.83	5.00	3.34	4.29	3.32	18.66
	164	5.13	5.20	3.97	2.78	3.94	3.76	20.34
	185	4.55	5.59	4.91	5.17	6.40	3.29	21.69
	206	3.39	2.77	2.97	2.02	4.31	2.95	18.64
	228	2.71	4.85	5.90	4.95	10.20	9.57	47.64
	248	2.50	3.27	3.84	3.46	5.94	4.87	23.71
	268	3.66	3.91	3.54	2.78	4.83	4.11	18.66
WAPENGO VC5	303	5.58	8.13	9.10	6.46	11.38	8.07	40.00
	330	7.58	9.13	7.44	5.41	8.40	5.91	37.99
	350	8.67	9.23	8.44	6.06	8.94	6.12	30.43
	384	7.36	8.31	9.02	5.62	10.27	6.50	32.42
	404	7.33	8.02	7.91	5.81	9.56	7.01	28.30
	424	3.62	3.83	3.24	2.61	4.07	2.84	11.06
WAPENGO VC7	6	0.60	7.67	7.73	4.67	8.20	9.00	62.13
	19	4.12	5.07	6.28	6.11	11.47	8.62	50.54
	30	7.01	4.77	2.76	1.78	2.32	1.24	7.44
	51	13.44	11.80	6.99	4.07	5.00	2.90	18.66
	72	14.14	12.67	8.09	4.07	4.50	2.31	14.60

NERRINDILLAH CK					*	-2.9	6.13	-2.84	1.14	-5.03
BERRARA CK.					*	-2.56	4.58	-0.23	3.4	-6.51
SWAN L.	*					-3.61	0.07	-1.56	4.4	1.69

APPPENDIX F: ENTROPY CLASSIFICATION RESULTS AND PRINCIPAL COMPONENTS ANALYSIS OUTPUT

ESTUARY	ENTROPY CLASSIFICATION					PCA OBJECT SCORES: 13 VARIABLES			PCA OBJECT SCORES: 3 VARIABLES	
	1	2A	2B	3A	3B	1ST PC	2ND PC	3RD PC	1ST PC	2ND PC
NADGEE L.		•				1.75	-2.04	0.14	-1.22	2.05
NADGEE R.			•			6.96	-1.12	0.08	-7.76	0.76
LITTLE CK.			•			2.88	1.93	0.18	-5.67	-0.6
NEWTONS BEACH					•	1.2	2.57	-3.81	-0.09	-3.44
MERRICA R.			•			-0.62	3.45	3.39	-3.41	-2.08
WONBOYN R.				•		-2.2	3.55	6.11	4.5	-5.29
WOODBURN CK.			•			3.17	1.74	-0.34	-5.29	-0.85
FISHERIES CK.					•	0.49	3.32	2.77	1.67	-5.38
TOWAMBA R.			•			2.83	0.62	1.21	-5.28	-0.42
NULLICA R.					•	-0.38	4.3	5.11	2.9	-6.18
CURALO LAGOON	•					-1.69	-1.2	0.33	2.81	4.29
PAMBULA L.		•				3.87	-1.23	0.6	-4.37	1.52
MERIMBULA L.				•		-1.77	1.03	-0.7	3.14	-1.86
BACK LAGOON		•				-0.45	-1.97	-0.17	-0.84	2.58
BOURNDA L.				•		-2	2.33	-2.4	2.71	-2.93
BONDI L.		•				1.68	-0.61	-1.5	-1.06	0.03
WALLAGOOT L.	•					-1.69	-1.97	0.09	2.33	3.34
BEGA R.		•				1.03	-1.24	0.41	-2.93	2.3
NELSON LAGOON		•				3.54	-0.49	0.9	-2.59	-0.86
MIDDLE LAGOON		•				4.02	-1.84	-0.24	-4.81	1.77
WAPENGO L.		•				1.71	-0.74	0.86	-1.52	-0.12
BUNGA LAGOON				•		-3.79	-0.17	-1.8	4.68	-0.08
MURRAH LAGOON		•				4.23	-1.18	-0.04	-5.85	1.16
CUTTAGEE L.	•					-3.64	-2.37	0.41	2.89	2.87
BARRAGOOT L.				•		-2.77	1.34	-2.54	3.13	-1.67
BERMAGUI R.		•				1.85	0.74	0.32	-2.83	-0.84
WALLAGA L.	•					-3.18	-3.29	0.98	2.42	3.94
BOBUNDARA CK.			•			6.99	-0.93	-1.26	-6.61	0.007
LITTLE L. (a)		•				-0.6	0.56	-1.03	-1.09	-0.48
TILBA TILBA L.	•					-3.24	-2.99	0.29	1.41	4.08

CORUNNA L.	*					-4.37	-3.53	0.86	4.09	3.9
NARGAL L.	*					-5.35	-1.38	-1.53	6.02	2.8
NANGUDGA L.	*					-1.73	-1.43	0.05	3.15	3.58
BULLENGELLA L.	*					-4.07	1.14	-0.96	6.6	3.98
LITTLE L. (b)				*		-4.95	0.44	-1.47	6.33	-0.81
WAGONGA INLET	*					-4.36	-2.95	1.2	4.09	3.18
KIANGA L.	*					-2.65	-2.25	-0.66	3.03	2.42
DALMENY L.	*					-4.91	-3.69	0.61	5.18	4.06
BROU L.	*					-1.17	-2.09	0.42	1.16	2.19
AROURGA L.	*					-5.42	-1.24	-0.61	4.58	1.76
BRUNDEREE L.				*		-3.42	2.05	1.18	5.36	-3.65
TUROSS L.		*				-0.57	-0.57	1.38	-4.32	2.09
COILA L.	*					-3.44	-2.37	0.63	3.41	4.92
MERINGO BEACH				*		-2.01	1.75	-2.7	3.39	-2.7
MERINGO CK.				*		-3.78	2.81	-2.62	3.31	-2.98
CONGO CK.		*				5.49	-1.99	-0.34	-5.35	1.86
MORUYA R.		*				3.19	0.7	2.22	-2.47	-1.28
CANDLAGAN CK.				*	—	-0.52	0.37	4.63	2.43	-1.03
TOMAGA R.			*			5.74	-0.7	-0.08	-6.28	0.15
CLYDE R.			*			2.41	1.01	1.61	-5.51	0.14
CULLENDULLA CK.					*	2.04	2.25	4.41	-0.31	-4.09
LONG BEACH				*		-3.61	4.53	-3.1	5.99	-6.78
CHAIN BAY					*	3.52	0.88	-0.64	-2.47	-2.68
SOUTH DURRAS			*			7.64	-1.41	-0.62	-7.72	0.73
DURRAS L.	*					-4.25	-1.68	0.3	4.68	1.25
KIOLOA L.			*			3.94	1.03	-2.21	-2.96	-2.3
MURRAMARANG B.			*			4.84	-0.1	-1.88	-4.26	-0.75
WILLINGA L.			*			6.01	-1.22	-0.62	-6.19	0.76
MEROO L.	*					-1.2	-1.25	0.55	0.96	2.82
TERMEIL L.		*				0.78	0.25	-0.94	-1.85	-0.33
TOUBOUREE L.					*	0.94	1.43	-1.35	0.05	-2.99
BURRILL L.	*					-4.74	-1.74	1.16	3.55	1.98
MOLLYMOOK CK.			*			4.78	0.69	-2.19	-4.33	-1.47
NARRAWALLEE CK.			*			6.84	-0.96	-0.71	-6.62	0.02
CONJOLA L.	*					-2.64	-1.68	0.32	2.94	1.51

MIDDLE LAGOON	2.10	0.10	0.00	0.19	0.00	0.52	0.00	0.00	0.04	0.00	0.00	0.20	0.00
WAPENGO L.	3.50	0.20	0.00	0.44	0.03	1.17	0.24	0.00	1.54	0.51	0.00	0.23	0.00
BUNGA LAGOON	0.05	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.06	0.00	0.15	0.00
MURRAH LAGOON	3.68	0.21	0.00	0.51	0.31	0.53	0.00	0.00	0.06	0.13	0.00	0.27	0.00
CUTTAGEE L.	0.34	0.09	0.00	0.17	0.00	1.25	0.00	0.00	0.25	0.00	0.00	0.32	0.03
BARRAGOOT L.	0.27	0.00	0.00	0.09	0.02	0.47	0.00	0.00	0.08	0.05	0.00	0.81	0.00
BERMAGUI R.	1.80	0.80	0.05	0.00	0.00	0.39	0.00	0.00	0.00	0.99	0.00	0.27	0.00
WALLAGA L.	2.71	0.75	0.00	0.54	0.09	8.04	0.00	0.00	0.80	0.86	0.00	0.48	0.28
BOBUNDARA CK.	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00
LITTLE L. (a)	0.11	0.01	0.00	0.08	0.00	0.07	0.00	0.00	0.01	0.02	0.00	0.10	0.00
TILBA TILBA L.	0.38	0.03	0.00	0.33	0.00	1.11	0.00	0.00	0.01	0.05	0.00	0.21	0.00
CORUNNA L.	0.34	0.00	0.00	0.15	0.00	1.78	0.00	0.00	0.30	0.16	0.00	0.18	0.00
NARGAL L.	0.01	0.00	0.00	0.00	0.00	0.16	0.02	0.00	0.00	0.00	0.00	0.10	0.00
NANGUDGA L.	0.35	0.00	0.00	0.00	0.00	0.52	0.09	0.24	0.01	0.04	0.00	0.18	0.09
BULLENGELLA L.	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.11	0.00	0.00	0.00	0.07	0.00
LITTLE L. (b)	0.00	0.00	0.00	0.00	0.00	0.14	0.01	0.00	0.00	0.09	0.00	0.11	0.00
WAGONGA INLET	0.74	0.11	0.00	0.35	0.21	4.77	0.00	0.10	1.09	0.69	0.00	0.33	0.13
KIANGA L.	0.11	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.01	0.03	0.00	0.09	0.00
DALMENY L.	0.22	0.00	0.00	0.00	0.00	1.52	0.00	0.00	0.22	0.13	0.00	0.21	0.00
BROU L.	1.44	0.14	0.00	0.11	0.02	1.85	0.00	0.09	0.45	0.28	0.00	0.38	0.00
AROURGA L.	0.00	0.00	0.00	0.07	0.00	0.28	0.00	0.00	0.05	0.00	0.00	0.15	0.00
BRUNDEREE L.	0.00	0.00	0.00	0.04	0.00	0.10	0.00	0.07	0.38	0.00	0.00	0.14	0.00
TUROSS L.	8.34	4.72	0.14	10.78	1.43	7.00	0.00	0.03	1.28	0.25	0.00	0.50	0.46
COILA L.	1.23	0.12	0.00	0.09	0.62	4.49	0.21	1.38	0.21	0.40	0.00	0.69	0.00
MERINGO BEACH	0.08	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.03	0.00	0.00	0.20	0.02

APPENDIX E: RAW ESTUARINE MORPHOMETRIC DATA

	SURFACE AREA OF MORPHOSTRATIGRAPHIC UNITS : SQUARE KILOMETRES												
	ZONE C					ZONE B			ZONE A				
ESTUARY	Floodplain	Fluvial channel	Point bar	Supratidal fluvial delta	Intertidal fluvial delta	Central basin	Supratidal shoreline	Intertidal shoreline	Flood tidal delta	Back barrier flat	Beach ridge plain	Barrier	Entrance channel
NADGEE L.	1.65	0.00	0.00	0.01	0.00	0.87	0.00	0.13	0.22	0.00	0.07	0.25	0.00
NADGEE R.	1.82	0.19	0.05	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.02	0.00
LITTLE CK.	0.12	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.04	0.00
NEWTONS BEACH	0.19	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.24	0.00
MERRICA R.	0.02	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
WONBOYN R.	0.07	1.21	0.04	0.00	0.00	1.04	0.17	0.15	1.03	1.21	6.85	0.00	0.67
WOODBURN CK.	0.16	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.00
FISHERIES CK.	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.10	0.05	0.00
TOWAMBA R.	3.38	1.37	0.38	0.26	0.33	0.18	0.00	0.00	1.09	0.00	0.00	0.19	0.13
NULLICA R.	0.50	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	2.03	0.44	0.00
CURALO LAGOON	0.51	0.02	0.00	0.09	0.00	0.75	0.67	0.00	0.06	0.07	0.00	0.25	0.00
PAMBULA L.	7.04	0.71	0.11	0.35	0.28	1.17	0.37	0.41	0.40	0.00	0.00	0.00	0.82
MERIMBULA L.	2.06	0.07	0.00	0.16	0.05	2.22	0.31	0.28	1.97	0.86	0.00	2.92	0.22
BACK LAGOON	0.36	0.04	0.00	0.10	0.00	0.36	0.00	0.00	0.02	0.00	0.00	0.13	0.00
BOURNDA L.	0.03	0.01	0.00	0.00	0.00	0.03	0.00	0.00	0.02	0.00	0.00	0.08	0.00
BONDI L.	0.61	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.08	0.00	0.28	0.00
WALLAGOOT L.	1.94	0.00	0.00	0.17	0.00	2.91	0.46	0.46	0.45	0.15	0.00	0.88	0.00
BEGA R.	7.90	2.73	0.90	0.31	0.07	4.82	0.14	0.00	0.15	0.35	0.00	1.28	0.12
NELSON LAGOON	1.43	0.04	0.00	0.00	0.00	0.21	0.00	0.03	0.45	0.00	0.16	0.13	0.00

MERINGO CK.	0.01	0.02	0.00	0.05	0.00	0.08	0.00	0.00	0.00	0.04	0.00	0.20	0.01
CONGO CK.	6.48	0.14	0.00	0.00	0.00	1.00	0.25	0.00	0.04	0.05	0.00	0.36	0.00
MORUYA R.	20.32	3.01	0.12	0.00	0.00	1.92	0.57	0.66	1.70	0.13	9.16	1.66	0.49
CANDLAGAN CK.	2.10	0.10	0.00	0.00	0.00	2.04	0.26	0.00	0.00	0.00	3.92	0.00	0.00
TOMAGA R.	7.82	0.80	0.32	0.00	0.00	0.21	0.00	0.00	0.12	0.89	0.00	0.31	0.03
CLYDE R.	12.77	11.78	0.51	0.00	0.00	1.50	0.00	0.00	0.35	0.00	0.00	0.10	4.32
CULLENDULLA CK.	1.04	0.16	0.00	0.02	0.00	0.00	0.00	0.00	0.27	0.00	1.23	0.05	0.04
LONG BEACH	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.32	0.00	0.37	0.00
CHAIN BAY	0.52	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.09	0.00
SOUTH DURRAS	0.56	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
DURRAS L.	0.46	0.14	0.00	0.15	0.00	3.07	0.00	0.00	0.66	0.25	0.00	0.98	0.63
KIOLOA L.	1.61	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.21	0.00	0.75	0.02
MURRAMARANG B.	0.66	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.22	0.00
WILLINGA L.	1.94	0.12	0.00	0.00	0.00	0.14	0.00	0.00	0.02	0.00	0.00	0.20	0.01
MEROO L.	0.64	0.03	0.00	0.30	0.00	0.75	0.17	0.21	0.06	0.28	0.00	0.14	0.01
TERMEIL L.	0.81	0.10	0.00	0.17	0.09	0.33	0.00	0.00	0.04	0.04	0.00	0.47	0.07
TOUBOUREE L.	2.65	0.00	0.00	0.03	0.29	0.51	0.00	0.03	0.30	1.33	0.00	1.76	0.27
BURRILL L.	0.09	0.33	0.04	0.65	0.13	3.04	0.00	0.00	0.70	0.69	0.00	0.42	0.19
MOLLYMOOK CK.	0.29	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00
NARRAWALLEE CK.	9.18	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.42	0.00	0.78	0.03
CONJOLA L.	2.27	0.27	0.00	0.27	0.05	5.06	0.19	0.00	1.40	0.71	0.00	1.50	0.35
NERRINDILLAH CK	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.13	0.00
BERRARA CK.	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.53	0.00	0.20	0.00
SWAN L.	0.94	0.03	0.00	0.20	0.13	3.35	0.15	1.17	0.07	0.08	0.00	3.18	0.06