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Autocyclic, allocyclic and anthropogenic impacts on Holocene delta evolution and future management implications: Macquarie Rivulet and Mullet/Hooka Creek, Lake Illawarra, New South Wales

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Autocyclic, allocyclic and anthropogenic impacts on Holocene delta evolution and future management implications: Macquarie Rivulet and Mullet/Hooka Creek, Lake Illawarra, New South Wales

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The information in this thesis is entirely the result of investigation conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Carl Hopley

For my princesses

Isabel and Amelia

Abstract

Within Australia, as in many areas of the world, population is commonly concentrated in coastal areas. While some of these population centres are located on large deltas many coastal population centres are built around smaller river systems and barrier estuaries where increasing land-use pressures are initiating development on small-scale low-lying deltaic areas. As such, the management of these areas is of prime interest to government bodies and to the broader community. To achieve this it is necessary to have an understanding of their geological evolution and associated depositional processes in order to better forecast the implications of management decisions and the potential impacts of climate change.

The Holocene evolution of the Macquarie Rivulet and Mullet/Hooka Creek bay-head deltas, Lake Illawarra, New South Wales, is discussed in this thesis. Both deltas are forming at the interface between the rivers and creeks draining the largest and second largest sub-catchments with areas of 96.35 km^2 and 75.2 km^2, respectively. These waterways originate on the Illawarra Escarpment prior to falling steeply and flowing across relatively narrow coastal plains. Due to the orographic effect and the shape of the escarpment rainfall events are typically compartmentalised. Ten soil associations occur within the catchment, with 60% of them classified as being extremely erodible. Since European settlement large tracks of land were cleared for agricultural purposes and subsequently replaced with urban/industrial development. This study has documented how the regional characteristics have played a role in shaping the deltas' evolution.

The information presented in this thesis is based on the sedimentological analysis of 147 cores and drill holes across the two study sites. The sedimentological analyses included core logging and detailed visual assessment, grain size analysis, X-ray Diffraction (XRD) and a variety of geochronological analyses. The geochronologies of the deltas were

established through amino acid racemisation (AAR), radiocarbon (^{14}C), accelerated mass spectrometry (AMS) and lead 210 (^{210}Pb) techniques.

The study has shown that the key processes controlling the evolution of small scale bay-head deltas prograding into wave dominated barrier estuaries differs from the 14 key delta evolutionary processes as identified by Coleman and Wright (1975), Coleman (1976) and Coleman (1980). The observed differences in evolutionary processes reflect a combination of factors including the:

- negligible influence of marine processes, particularly large waves and tides;
- reduced size of catchment and associated sediment yields;
- tectonic stability within the receiving basin.

The spatial resolution of previous studies into the evolution of these smaller deltas is limited. Typically, these studies suggest the evolution of bay-head deltas is simplistic and consists of prodelta muds overlain by deltaic sands and floodplain sediments. The high spatial resolution of this study has illustrated that this simplistic view does not adequately represent the complex interactions between autocyclic, allocyclic and anthropogenic processes throughout the Holocene. Specifically the study has identified and described ten main facies/facies associations, three minor facies and two imported units within the 147 cores analysed. Furthermore, the increased spatial resolution of this study suggests the observed facies relationships at the highest level are independent of scale, however, at the more focussed level the scale differences between the mega/continental scale deltas and the smaller bay-head deltas become evident.

Previous wave-dominated barrier estuary evolutionary models have lacked the detail to adequately reflect the evolution of the fluvial/bay-head deltas. This lack of representation reflects the limited data available to inform the development of these models. Consequently, the high resolution nature of this study has enhanced the understanding of the evolution of bay-head deltas enabling refinements to be made to these previously published estuary models. The data has also allowed the development

of a bay-head delta facies and evolution model applicable for use within any barrier estuary or lake.

The study has illustrated that an integrated approach to mapping, based on historical parish maps and aerial photographs within a GIS framework, can effectively track morphological changes since European settlement in Australia. This analysis has shown that Macquarie Rivulet and Mullet/Hooka Creek deltas have increased in area significantly, despite periods of negative growth. Both the positive and negative increases in area and associated morphological changes have occurred in response to a combination of anthropogenic catchment modifications and natural factors. Some of the key factors contributing to the observed changes include land clearing, urban/commercial development, flooding, wind-waves, bank stability, regional geology and erodible soils.

Predicting the future evolution of deltas under an altered climate scenario is challenging. This research has suggested the two deltas studied are highly vulnerable with large portions of the deltas likely to be inundated by 2050. This inundation will probably result in the deltas regressing and/or avulsing into new depocentres. Increased rainfall intensity and flooding, as predicted, may result in significant changes to the deltas' morphologies and sedimentation patterns. Predicted wind patterns, are likely to have minimal effect on the deltas' evolution. Future development within the deltas' catchments is likely to increase the vulnerability of the deltas. Significantly, this research has shown that current land use planning practices do not necessarily consider the whole of catchment implications, particularly the end deltaic regions. To effectively manage these systems into the future these issues will need to be addressed.

Acknowledgements

This thesis would not have been possible without the assistance of many people. Firstly, I would like to thank my supervisor Associate Professor Brian Jones whose guidance was invaluable. Whilst conducting this research there were many occasions when I questioned the enormity of the challenge I had taken on and if it was worth continuing. However, Brian's support, guidance and encouragement did not waiver throughout these occasions. Furthermore, I would like to thank Brian for taking the time to review this thesis and provide constructive feedback.

I also wish to thank Brian as he was my regular and reliable field assistant and supervisor. Brian was the voice of reason on the many occasions things just did not go as planned such as the numerous times I spent with my head under the bonnet of the drill rig for one reason or another. Without Brian's assistance I would still be in the field collecting cores trying to get that extra bit of information.

Brian, you were my mentor and my right hand man on this project. I can't thank you enough.

This thesis would not have been possible without the input and/or encouragement of support and academic staff from the School of Earth and Environmental Sciences. Thank you also to Professor Colin Murray-Wallace for his continued support and his willingness to talk through various stages of the project. I would also like to thank Heidi Brown, who helped me to push the boundaries of my GIS skills and Wendy Weeks whose administrative support made it possible for me to juggle full time work and this project.

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readiness to assist, her ability to remember what happens next and most impressive of all her willingness to ask questions and learn. I wish both Ali and Kele all the best with their future endeavours.

This work would not have been possible with out the assistance provided by Wollongong City Council. I would like to make special mention, Dr Suri Mora who continually motivated me to get the job done. He also provided assistance in the field and a sounding board when I needed to bounce ideas around. I would also like to acknowledge Dr Iradj Yassini whose critical review of my ideas challenged me to take the extra step. I also need to thank Gary Leonard who took the time to review several of the chapters included in this thesis. I would also like to acknowledge Robin Scott for her assistance.

The biggest acknowledgement needs to go to my wife Vicky and my little princesses Isabel and Amelia. Without their unconditional love and support it would not have been possible to complete this body of work. Vicky showed unbelievable patience and understanding during the many tense and trying times. This work is for you as much as it is for me.

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Abbreviation	**Definition**
^{14}C	Radiocarbon dating
^{210}Pb	Lead 210 dating
AAR	Amino acid racemisation
AHD	Australian height datum
AMS	Accelerated mass spectrometry
ANSTO	Australian Nuclear Science and Technology Organisation
BOM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GCP	Ground control point

GIS	Geographic information system
LIA	Lake Illawarra Authority
LiDAR	Light Detection And Ranging (remote sensing tool)
MC	Mullet/Hooka Creek core code
MR	Macquarie Rivulet core code
OSL	Optically stimulated luminescence
TIN	Triangulated irregular network
TL	Thermo-luminescence
WCC	Wollongong City Council
XRD	X-ray diffraction

Chapter 1

Introduction: Autocyclic, Allocyclic and Anthropogenic impacts on Holocene Delta Evolution: Macquarie Rivulet and Mullet/Hooka Creek, Lake Illawarra, New South Wales.

Within Australia, as in many areas of the world, population is commonly concentrated in coastal areas. While some of these population centres are located on large or mega deltas many coastal population centres are built around smaller river systems and coastal barrier estuaries where increasing land-use pressures are initiating development on small-scale low-lying deltaic areas where flood management issues are of major concern.

The management of these environmentally sensitive deltaic areas is of prime interest to government bodies at all levels and to the broader community. To effectively manage these areas it is imperative to have a comprehensive understanding of their geological evolution and the processes that affect their evolution. Developing this understanding will assist land managers to better forecast the implications of management decisions and the potential impacts of climate change.

This thesis aims to assess several hypotheses about small-scale delta evolution, as outlined below.

1. That the key evolutionary processes controlling the evolution of small scale bay-head deltas prograding into wave dominated barrier estuaries differs from the 14 key delta evolutionary processes as identified by Coleman and Wright (1975), Coleman (1976) and Coleman (1980). These difference are likely to reflect that the previously described processes were developed from the analysis of large or mega-scale deltas typically prograding into open marine environments.

2. That the spatial resolution of deltaic studies impacts on the ability to identify and establish the sedimentological and morphological response to autocyclic, allocyclic and anthropogenic processes. Specifically, higher resolution studies are better placed to more accurately establish delta evolution during the Late Pleistocene and into the Holocene due to the complex interaction of key evolutionary processes.
3. That facies relationships in river dominated deltas are independent of scale.
4. That existing barrier estuary evolutionary models (i.e. Roy 1984, Dalrymple 1992, Roy *et al.* 2001 and Sloss *et al.* 2005, 2006a) are based on limited data from the fluvial/bay-head deltas (Zone C) and thus they do not adequately represent the evolution of bay-head deltas.
5. That the rate of delta growth and morphological change has accelerated during the Anthropocene (post 1800s) in response to modification of the waterway and catchment and that future growth will continue to be influenced by these modifications.

The Holocene evolution of wave-dominated estuaries, as opposed to tidally influenced estuaries, along the southeast coast of Australia, including Lake Illawarra, has been researched and documented since the 1970's. However, much of this work has focussed on the seaward and central components of the estuaries, specifically Zone A (marine influenced zone e.g. flood-tide delta) and B (central basin) as denoted by Dalrymple *et al.* (1992). The lack of research into Zone C, the fluvial zone, limits our capacity to fully understand how estuaries have evolved throughout the Holocene in response to autocyclic, allocyclic and anthropogenic processes/factors. Significantly, this lack of understanding also impairs our ability to identify and manage these systems into the future as they adjust to climate change and increased anthropogenic pressure on the delta itself and the surrounding catchment. This knowledge gap in the evolution of fluvial zones was recognised and highlighted by Nichol *et al.* (1997), Hopley (2004) and Hopley and Jones (2006).

The planned high resolution nature of this study made it necessary to identify a site which was near the University of Wollongong and where site access permission could be gained, while still being able to provide the information required to address the research aims and hypotheses. The accessibility afforded by Macquarie Rivulet and Mullet/Hooka Creek deltas in Lake Illawarra enabled the collection of the 147 cores utilised in this study, along with the numerous site inspections required to gather the necessary data without incurring additional costs associated with transportation of equipment such as the university's drill rig. In addition urban development is already encroaching onto the Macquarie Rivulet delta causing a range of management issues that need to be addressed.

Macquarie Rivulet and Mullet/Hooka Creek deltas were identified as ideal sites to study the development of small-scale deltas for several reasons. Firstly, Macquarie Rivulet, a fluvially-dominated delta, and the Mullet/Hooka Creek delta, a cuspate wave-dominated delta, have differing end member morphologies while both prograding into the western portion of the Lake Illawarra barrier estuary system. The commonality between the depositional environment and respective catchments, such as the underlying geology, associated soils, climate and extent/type of anthropogenic modification, simplifies the analysis of the deltas evolution while increasing the resultant accuracy of the research. Thus in Lake Illawarra the differences in delta morphology can be assessed without the need to account for differing environmental and anthropogenic variables which may exists if the selected deltas were located in different regions.

This thesis provides an insight into the Holocene and recent stratigraphic evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas, Lake Illawarra. Both Macquarie Rivulet and Mullet/Hooka Creek deltas have been previously studied by authors such as Hean and Nanson (1985) and Sloss *et al.* (2004, 2005, 2006a). The conclusions presented in these earlier investigations were based on a limited number of cores, which reduced capacity of these studies to accurately determine the complex evolutionary history of the deltas studied. In this study the Holocene evolution of the Lake Illawarra deltas has been established using detailed stratigraphic logs produced from sub-surface cores, drill

holes, push probes and geotechnical reports. The geochronology of the facies has been established using amino acid racemisation (AAR), lead 210 (^{210}Pb), accelerated mass spectrometry (AMS) and conventional radiocarbon (^{14}C) dating techniques.

Technological developments in the fields of remote sensing and geographic information systems (GIS) can also be used to quickly and cost-effectively assess both temporal and spatial changes. These techniques have been utilised to assess the morphological changes and growth of the Macquarie Rivulet and Mullet/Hooka Creek deltas over the past 170 years. The validity, reliability and credibility of the application of these techniques in assessing the evolution of the deltas is critically analysed and discussed.

1.1: Thesis aims

The primary aim of this thesis is to: document the Holocene and recent (post-European) evolution of the fluvial zone of bay head deltas by conducting a high resolution sedimentological and morphological investigation of the Macquarie Rivulet and Mullet/Hooka Creek bay-head deltas in Lake Illawarra, NSW. Outcomes of the research will include the following secondary aims:

- Identification and documentation of the various facies intersected while undertaking the subsurface investigations, including an interpretation of their depositional environments.
- Reconstruction of the Macquarie Rivulet and Mullet/Hooka Creek deltas evolution throughout the Holocene, based on the sedimentological, morphological and geochronological data generated while undertaking the research. This reconstruction will be aided by the use of three dimensional models within a GIS framework to identify and illustrate spatial relationships between facies.
- Production of a stylised stratigraphic column which illustrates the key facies identified, their broad sedimentological characteristics and their relative stratigraphic positions.

- Reconstruct the morphological responses of Macquarie Rivulet and Mullet/Hooka Creek deltas since European settlement based on the orthorectification and analysis of historical maps and aerial photographs within a GIS framework.
- Provide a broad high-level commentary on the potential impacts of climate change and anthropogenic activities on the evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas into the future. This commentary is intended to form the basis for future research activities specifically investigating these complex issues.

1.2: Site specific research

The geomorphic/geological evolution of Lake Illawarra is relatively well understood due to the range of studies which have been undertaken since the 1970's. Some of the key authors who have studied the lake include Roy and Peat (1974, 1975), Young (1976), Jones *et al.* (1976), Jones and Chenhall (2001) and Sloss *et al.* (2004, 2004a, 2005, 2006a, 2007, 2011). Significantly, much of this work has focused on understanding the evolution of the coastal barrier and central basin, with limited research undertaken to establish the evolution of the bay-head deltas. This previous research provides a strong foundation on which to build a more detailed understanding of the bay-head deltas evolution.

In the late 1960's the Geological Survey of NSW commenced a series of studies to determine the geological history of estuaries along the NSW coast. In 1972 Roy and Peat (1974, 1975) commenced investigations into the evolution of Lake Illawarra. This work included a seismic survey, bathymetric assessment and the collection and analysis of grab samples and 10 cores from Lake Illawarra. The location of the seismic traces, cores collected, core logs and resultant sections are illustrated in Figures 1.1 and 1.2.

This initial research found the lake is dissected by a series of palaeochannels which had incised into the underlying bedrock during various sea level low stands. Within the central portion of Windang Peninsula the channels were found to be up to 40 m deep

relative to present sea level. The research also demonstrated these channels were infilled with Pleistocene and Holocene sediments. The sedimentary analysis of the cores and grab samples demonstrated that the lake is characterised by a typical tripartite facies zonation with the western margin of the lake characterised by fluvial sands, the central basin by mud and the eastern margin by barrier and flood-tide marine sands (Roy and Peat 1974). The study also showed these sediments typically overlie a mottled clay-rich layer interpreted to represent the Pleistocene land surface.

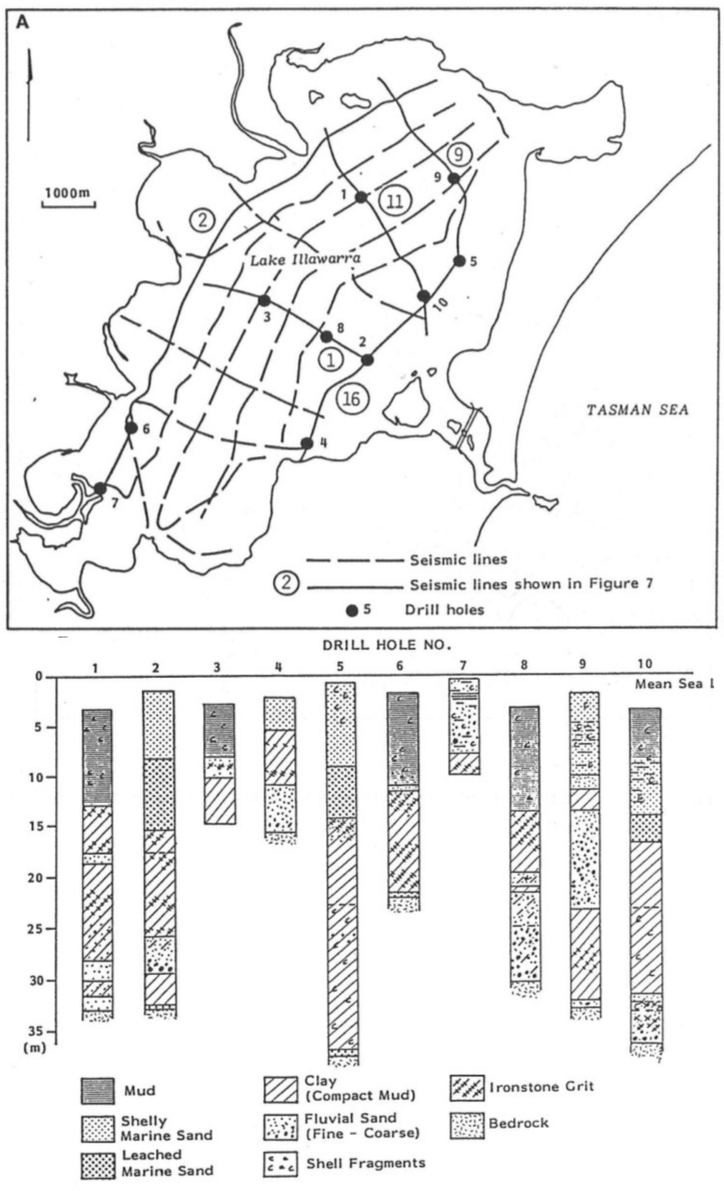

Figure 1.1: *Location of seismic traces, cores collected, core logs and resultant sections as published in Thom et al. (1986).*

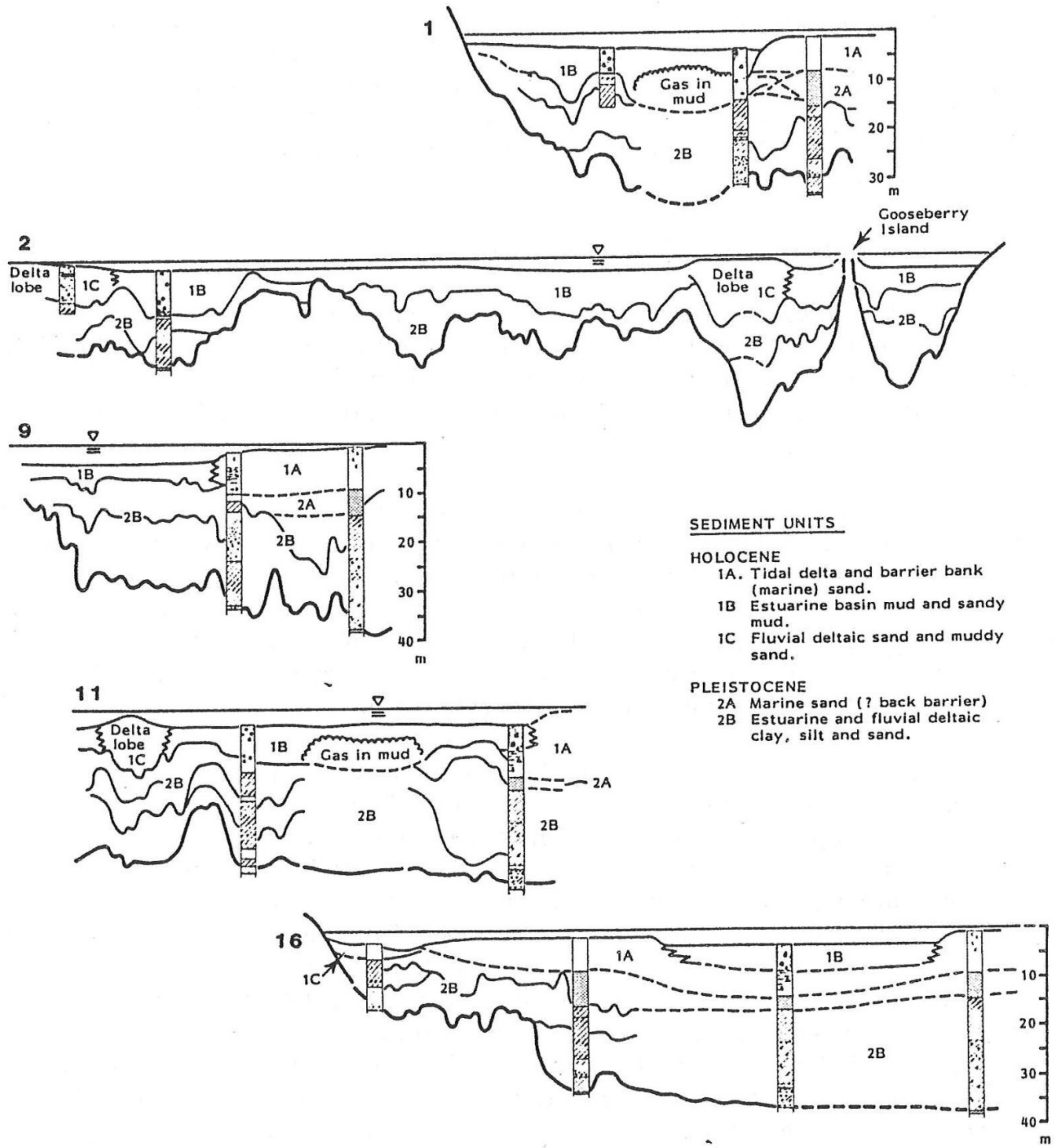

Figure 1.2: *Resultant sections derived from the analysis of seismic traces and 10 cores collected in 1972 (from Thom et al. 1986).*

Roy and Peat (1975) published the results from the analysis of the 118 grab samples collected in 1972. The sedimentological analysis resulted in the development of seven sediment classifications based on the sand to mud ratio and the sediment origin. Of the seven identified the lake bottom muds, clean lithic sand, muddy lithic sands and the lithic sandy muds are the most relevant to this study. The basal lake sediments were

characterised as clay/silt-rich black sediment with high organic content. Roy and Peat (1975) suggested the gentler inclination of the muddy bed proximal to Macquarie Rivulet when compared to the Mullet Hooka Creek delta reflected that Macquarie Rivulet transported grater volumes of mud. Portions of the landward margin of the lake is characterised by clean to muddy lithic sands particularly in the vicinity of Mullet the eastern distributary channel of Macquarie Rivulet and Mullet Creek. Sediments proximal to the mouth of Mullet Creek were found to be finer and more muddy. This decrease in grain size was attributed to the reduced modern carrying capacity of the creek and the sandy unit beyond the delta's mouth was probably deposited at some stage in the past.

Despite the limited capacity of Roy and Peat (1974, 1975) to accurately establish the geochronological evolution of Lake Illawarra, this early research formed the basis of later publications by the authors themselves (e.g. Roy 1984; Roy *et al* 2001) along with other authors (Dalrymple *et al.* 1992; Walker 1992; Sloss 2005; Hopley and Jones 2006). For instance, the information gained while conducting this initial research combined with the sedimentological data gathered while undertaking the broader study into the evolution of estuaries enabled the development of the estuarine evolutionary models published in papers such as Roy *et al.* (1980), Roy (1984), Dalrymple *et al.* (1992) and Roy *et al.* (2001). The resultant models have formed the basis of our understanding of estuarine evolution. More detail on the evolutionary models developed by Roy *et al.* (1980), Roy (1984) Dalrymple *et al.* (1992) and Roy *et al.* (2001) is provided in Chapter 3.

Approximately 30 years after this initial research, the evolution of Lake Illawarra was reinvestigated by Sloss (2001, 2005) while undertaking an Honours and later PhD research project with subsequent publications including Sloss *et al.* (2004), Sloss *et al.* (2004a), Sloss *et al.* (2005), Sloss *et al.* (2006a), Sloss *et al.* (2007) and Sloss *et al.* (2011). These studies were based on the sedimentological and geochronological analysis of 68 cores and the interpretation of five seismic sections (Figure 1.3). As illustrated in Figure 1.3 cores were collected from the Macquarie Rivulet and Mullet/Hooka Creek bay-head deltas. The results of this bay-head specific research are also detailed in Chapter 3.

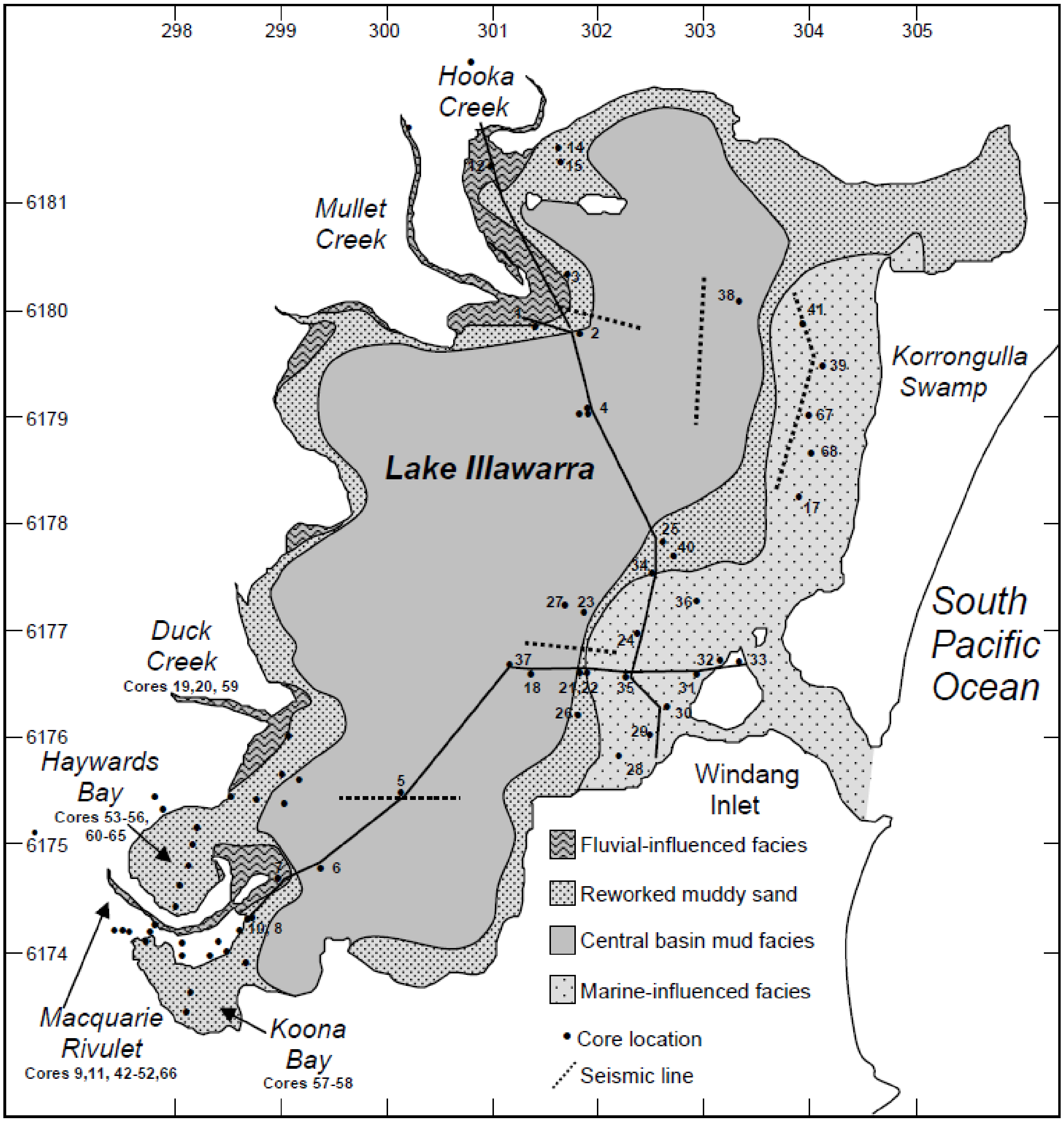

Figure 1.3: Location map showing core, seismic section and cross section locations utilised by Sloss (2005) to establish the Holocene evolution of Lake Illawarra.

The research undertaken by Sloss (2005) and published by Sloss *et al.* (2005) noted five evolutionary stages/timeframes that were discernable within the Lake Illawarra sediments (Figure 1.4). Stage 1 or the pre-Holocene stage is characterised by the down cutting of the Pleistocene palaeochannel in response to the lower sea level. During the last glacial maximum this channel appears to have flowed through a remnant OIS 5e

barrier near Korrongulla Swamp. The second evolutionary stage (*ca.* 7.6 ka – 5 ka) represents the inundation of the receiving basin and deposition of the transgressive marine sand sheet, which overlies the antecedent Pleistocene substrate. Due to the lack of an emergent barrier more open water conditions would have prevailed. As such the estuary would have behaved more like a drowned river estuary rather than the barrier estuary it is today. Between 5ka and 3.2ka (stage 3) Sloss *et al.* (2005) noted the Holocene barrier which encloses the lake evolved. During this time the lake entrance migrated south to its present position. This evolutionary phase is also characterised by the initial phase of bay-head delta progradation into the current lake. The forth stage (3.2 ka - 2.5 ka) is characterised by a reduction in the available accommodation space due to the sea level regressing by about 1.5 m. This reduction in accommodation space enabled the deltas to prograde farther into the receiving basin overtopping the older estuarine mud deposits. The final evolutionary stage identified by Sloss *et al.* (2005) ranges from 2.5 ka to present. During this stage bay-head delta progradation continued to infill the lagoon. This evolutionary stage is also characterised by greater restriction of the Windang entrance channel.

The research findings of Sloss (2005) are consistent with those of Roy and Peat (1974, 1975) and the resultant estuarine evolutionary and facies distribution models proposed by Roy *et al.* (1980), Roy (1984) Dalrymple *et al.* (1992) and Roy *et al.* (2001). However, the additional sedimentological and geochronological information enabled the refinement of these models. Specifically the research added details regarding the initial phases of the estuaries evolution.

However, despite nearly 30 years of research on Lake Illawarra and similar estuaries along the southeastern coast of Australia very little is known about the morphological and sedimentological evolution of bay-head deltas. This knowledge gap regarding the evolution of bay-head deltas prograding into wave dominated barrier estuaries was also been identified by Nichol *et al.* (1997), Hopley (2004) and Hopley and Jones (2006).

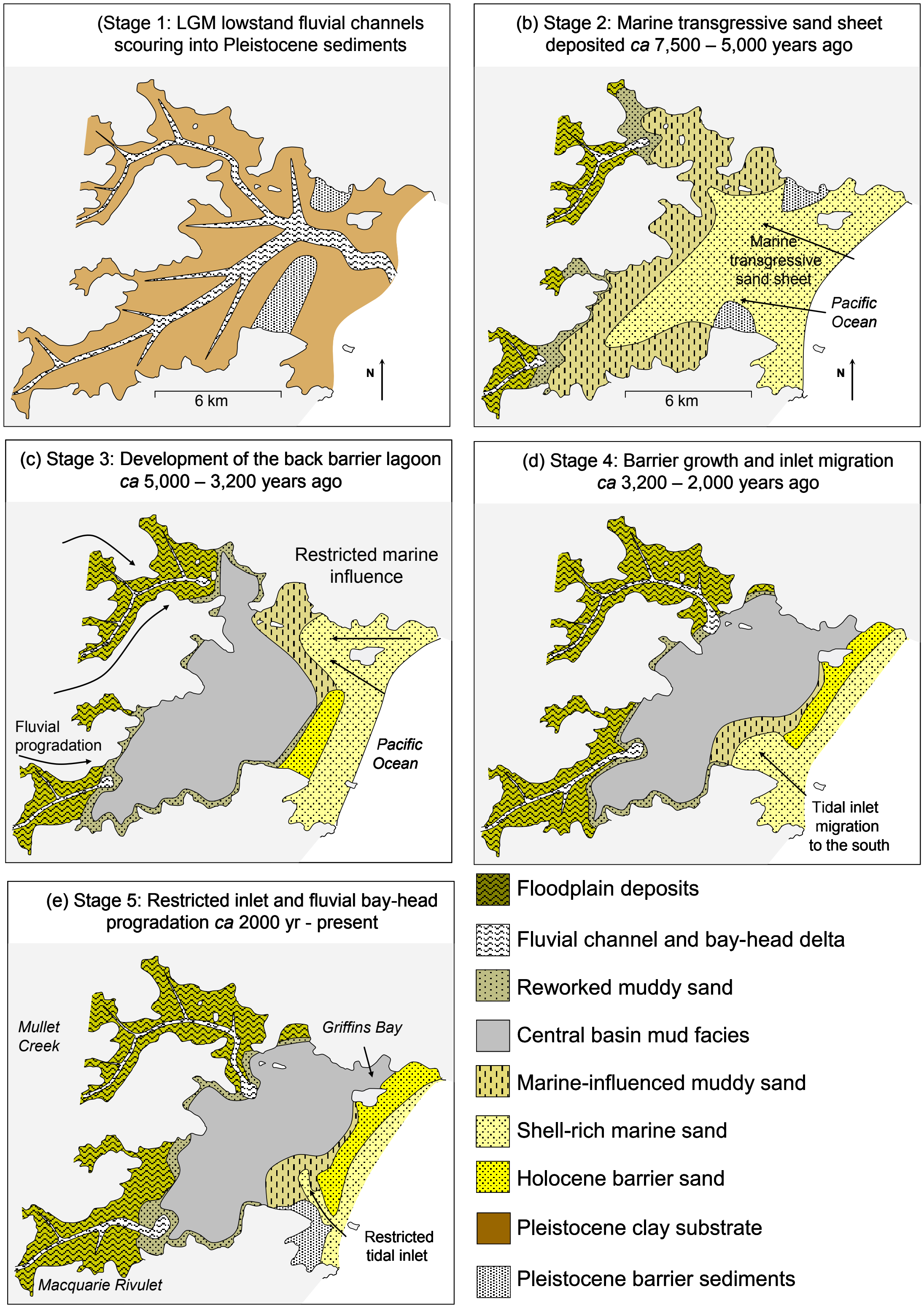

Figure 1.4: *Diagrammatic representation of the five evolutionary stages for Lake Illawarra as identified by Sloss et al., (2005).*

1.3: Thesis structure

This thesis is presented in two volumes. This multi volume approach was necessary due to the large volumes of data gathered and analysed while undertaking the research. Volume 1 documents the research and its findings in ten chapters. Volume 2 contains the appendices and supporting documentation.

The regional context of the study is outlined in Chapter 2. Initially, the chapter documents the geological and geomorphologic conditions prior to changing its focus to climate related factors such rainfall, flooding and Lake Illawarra's hydrodynamics. The historical, current and future land use within the Lake Illawarra catchment is also presented. The final portion of the chapter provides a historical overview of previous sedimentological/morphological research into the evolution of Lake Illawarra and its deltas.

Chapter 3 establishes the key natural and anthropogenic processes/factors, which have affected, either partially or fully, the evolution of deltas as presented in the literature. Specifically the chapter discusses Holocene sea level fluctuations, classification, zonation and evolution of estuaries and deltas. This chapter also discusses the formation and environmental implications, if disturbed, of sulfidic sediments associated with deltaic environments.

Chapter 4 documents the methodologies applied to acquire the required information to meet the thesis aims. The research methodologies discussed in this chapter include, but are not limited to, various subsurface sampling, sedimentological, geophysical, geochronological, X-ray diffraction (XRD) and geographic information system (GIS) techniques. The chapter also documents the results of analyses such as the sedimentary analysis, mineralogy and the geochronological results.

Chapters 5 through to 8 document and discuss the research findings in the context of the thesis aims. Chapter 5 provides detailed sedimentological descriptions of the facies

intersected. The chapter also establishes a sedimentary facies model for Holocene deltas prograding into tectonically stable barrier estuarine environments along the southeast Australian coast. This information is then built on in Chapter 6 and 7 where the Holocene evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas is discussed. The post-European settlement morphological response of Macquarie Rivulet and Mullet/Hooka deltas to natural and anthropogenic factors is discussed in Chapter 8.

Chapter 9 utilises the information presented in the previous chapters to predict the potential implications of climate change and anthropogenic activities on the deltas future evolution. The final chapter, chapter 10, synthesises the information presented in the previous chapters and presents the main conclusions.

Chapter 2

Regional Setting

2.1: Introduction

Holocene delta evolution is influenced by the inherited morphology and environmental parameters of the receiving basin and the catchment. In this chapter, the regional setting of the Macquarie Rivulet and Mullet/Hooka Creek deltas is established. Specifically, the location, geological setting, soil types and associated landscapes, climate, flooding, hydrodynamics and catchment area land use are discussed.

2.2: Location

Lake Illawarra, a wave-dominated barrier estuary, is located approximately 90 km south of Sydney (Figure 2.1). The lake is relatively shallow (~3.5 m maximum) with a total surface area of 35 km^2. Morphologically, the lake is elongate in a general northeast to southwest orientation, with a maximum length and width of 9.5 km and 5.5 km, respectively. Total catchment area of the lake is approximately 235 km^2 with twelve waterways draining five sub-catchments (WBM 2003). The five sub-catchments include Macquarie Rivulet (96.35 km^2), Mullet Creek (75.2 km^2), Duck Creek (28.2 km^2), Lake Illawarra south (18.8 km^2) and Lake Illawarra north (16.45 km^2; WBM 2003). The Macquarie Rivulet and Mullet/Hooka Creek deltas are both actively prograding from the western margin of Lake Illawarra.

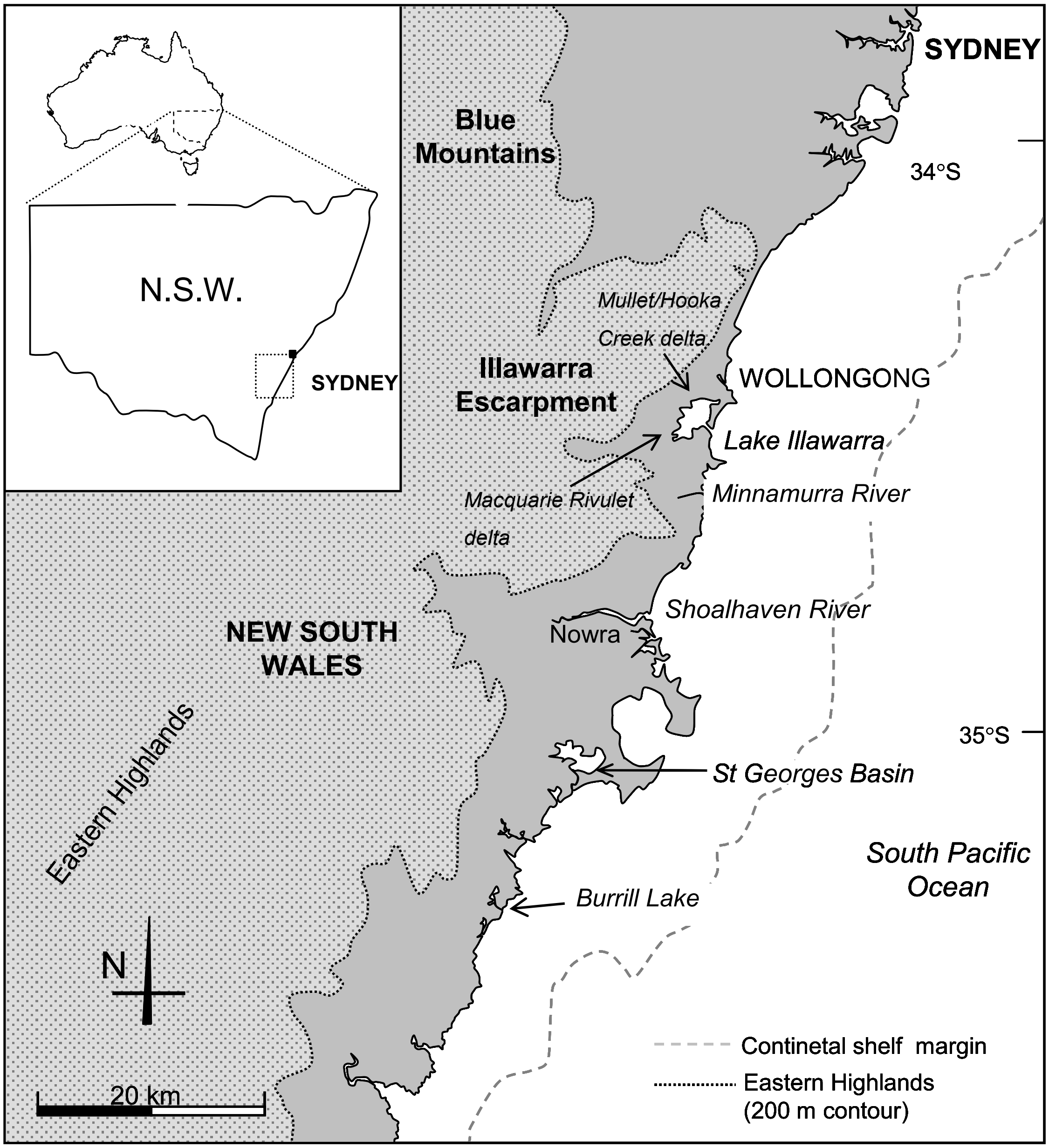

Figure 2.1 *Lake Illawarra location map (after Sloss 2005)*

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2.3: Geological and topographic setting

Lake Illawarra has formed within a depression eroded into the Late Permian Broughton Formation during Pleistocene sea level low stands (Carr 1982). South of the lake outcrops of the Kiama Sandstone and Bumbo Latite occur while Dapto Latite dominates the northern margin of the lake (Bowman 1974a, b). The lake's eastern margin consists of Quaternary aged sediments associated with the evolution of the sand barrier and associated environments including the flood and ebb-tide deltas. Quaternary aged

alluvial sediment also occurs to the west of the lake. However, some outcrops of the Broughton Formation and Dapto Latite occur, particularly in the Dapto area (Bowman 1974a). The interbedded strata of the Broughton Formation and Gerringong Volcanics extend from the western margin of Lake Illawarra, where exposed, to the foothills of the escarpment (Bowman 1974a-d). These interbedded units are overlain by the Illawarra Coal Measures, Narrabeen Group and Hawkesbury Sandstone (Bowman 1974c, d). The Hawkesbury Sandstone is the predominant cliff forming unit of the Illawarra escarpment. The headwaters of the Macquarie Rivulet are incising into the Tertiary Robertson Basalt and the Late Triassic Wianamatta Group prior to flowing down the escarpment (Bowman 1974c).

The Illawarra is characterised by a relatively narrow coastal plain which thins and eventually pinches out in a northerly direction near Thirroul. The coastal plain is at its widest (approximately 15 km) near Tongarra. Significantly, the coastal plain is dissected by several topographic highs which have defined the various sub-catchments associated with Lake Illawarra. The increased width of the coastal plain towards the south is likely to reflect the increased size and erosive capacity of the main waterways, being Macquarie Rivulet and Mullet Creek within the study area and Minnamurra River farther south, accelerating escarpment retreat in these locations (Young 1976; Ollier, 1995). The topographic highs dissecting the coastal plain grade into undulating foothills at the base of the escarpment. These foothills are often composed of units associated with the northwesterly dipping Illawarra Coal Measures and basal Narrabeen Group. The deeply incised large scale macro-channels, described by Hean and Nanson (1985), typically occur in the transitional area between the foothills and the coastal plain. The foothills then grade into the steep escarpment which consists of the upper Narrabeen Group and Hawkesbury Sandstone. The escarpment is typically between 350 m to 440 m above sea level within the study area. It forms the western margin of the lake's catchments and is a contributing factor to the intense high-volume, short-duration rainfall events which occur in the area (Hean and Nanson 1985).

2.4: Soil types and associated landscapes

One of the factors affecting the rate of delta progradation is the erodability of soils within a catchment area. Analysis of the 1:100,000 soil landscape maps for the Kiama (sheet 9028; Hazelton 1993) and Wollongong-Port Hacking (sheet 9029-9129; Hazelton *et al.* 1990) areas indicated ten soil landscape groupings occur in the Macquarie Rivulet, Mullet Creek and Lake Illawarra North catchment areas (Table 2.1). Of the identified soil types, six are rated as having high erodability potential, three moderate and one low. The soils and landscapes within the Macquarie Rivulet and Mullet Creek catchment areas, in particular, suggest a significant amount of sediment could be introduced to the deltaic system derived from soil erosion. The soils with extreme erodability are typically associated with steep topography. However, the relatively flat alluvial plains, floodplains, valley flats and terraces below the escarpment with reliefs <10 m are also rated as extremely erodible. This can be attributed to the unconsolidated nature of the material and because it is proximal to waterways which have the potential to erode the material. Hean and Nanson (1985) emphasised this when they estimated approximately 270,000 m^3 of sediment was eroded from the floodplains during the 1984 flood event.

2.5: Climate

Analysis of climate data, recorded by the University of Wollongong between 1970 and 2004, indicates climatic conditions within the Wollongong area are typical of those experienced along the south coast of Australia. During the warmer months of December to March mean average daily temperatures reach in excess of 25°C (Figure 2.2). A steady decline and subsequent increase in average daily temperatures are observed between the months April to July and September to November, respectively. Peak rainfall occurs between the months of January and April, with March being the wettest (Figure 2.3). The orographic effect is well developed in the Illawarra region due to the proximity of the escarpment to the ocean (WBM 2003). As a result of this orographic effect rainfall along the western margin of the catchment area ranges from 1600 mm to 1500 mm per year. This figure dramatically decreases towards the east where annual rainfall is in the vicinity of 1050 to 1100 mm in the Dapto area (WBM 2003). Northeasterly,

southeasterly and southerly winds, with velocities ranging up to 45-55 km/hr, are characteristic throughout the warmer months (WBM 2003). During the cooler months westerly and southwesterly winds are typical with velocities similar to those experienced during the warmer months (WBM 2003). Maximum recorded wind gusts occur in August (148.3 km/hr; Bureau of Meteorology 2012) with the minimum gusts occurring in February (83.5 km/hr; Bureau of Meteorology 2012).

During the autumn and winter months the south eastern coast of Australia, particularly southern Queensland, NSW and Victoria, experience weather phenomenon referred to as East Coast Lows (ECLs). ECLs are intense low-pressure systems which often generate one or all of the following:

- strong to gale force winds along the coast;
- intense rainfall leading to flash flooding; and
- prolonged rough seas (Bureau of Meteorology 2012a).

Of the above factors, the Macquarie Rivulet and Mullet/Hooka Creek deltas are particularly venerable to impacts associated with heavy rainfall events. This is attributable to the proximity of the Illawarra Escarpment to the coastal margin resulting in intense high energy flood events. The erosive capacity of these floods combined with the erodability of the soils within the catchment (Table 2.1) and the unconsolidated nature of the floodplain and channel margin sediments can lead to the development of features such as bank collapses, channel avulsions and splays as discussed in chapters.

Table 2.1 *Soil types, frequency, landscape description, catchment and erosion potential of soils/landscapes in the Lake Illawarra catchment area. Data derived from the interpretation of the 1:100,000 soil landscape maps for Kiama (sheet 9028; Hazelton 1993) and Wollongong-Port Hacking (sheet 9029-9129; Hazelton et al. 1990).*

	Soil landscape grouping	Macquarie Rivulet	Mullet Creek	Lake Illawarra North (Hooka Creek)	Landscape	Erosion Potential
Red solonetzic krasnozems	Erosional landscape (ca)	Common			Steep to very steep hills with broad colluvial benches. Relief 60-100m	Extreme
Brown and yellow podsolic soloths	Erosional landscape (ap)	Moderate/ rare	Moderate/ rare		Short steep upper slopes with long gentle foot slopes. Relief 60-100 m	Moderate
Brown and red podzolic	Erosional landscape (bo)	Rare			Rolling low hills with benched slopes. Relief 40-100 m	Low
Prairie soil, brown krasnozems, red podzolic	Erosional landscape (sh)		Moderate		Rolling low hills with long side slopes. Relief 30-50 m	Moderate
Red and yellow podsolic	Depositional landscape (wt)	Common	Common		Long gently to moderate side slopes, undulating to rolling hills. Relief <200 m.	Moderate
Alluvial loams, siliceous sand, prairie soil, yellow podzolic	Swamp landscape (fa)	Abundant	Abundant	Abundant	Alluvial plains, floodplains, valley flats and terraces below escarpment. Relief <10 m.	Extreme
Brown and red podsolic	Colluvial landscape (ie)	Moderate/ rare	Moderate/ rare		Steep to very steep slopes on Quaternary talus. Relief 100-500 m.	Extreme
Red and yellow podsolic, yellow earths, siliceous sand	Colluvial landscape (ha)	Moderate/ rare	Moderate/ Rare		Rolling to very steep hills. Relief <300 m.	Extreme
Brown podsolic, brown earth, xanthozems, lithosols	Residual landscape (gw)		Common	Common	Undulating to step hills, rounded ridges, gently to steep slopes. Relief 10-70 m.	Extreme
Prairie soil, red and brown, krasnozems, red and yellow podsolic	Residual landscape (bk)			Common	Rolling to steep low hills	Extreme

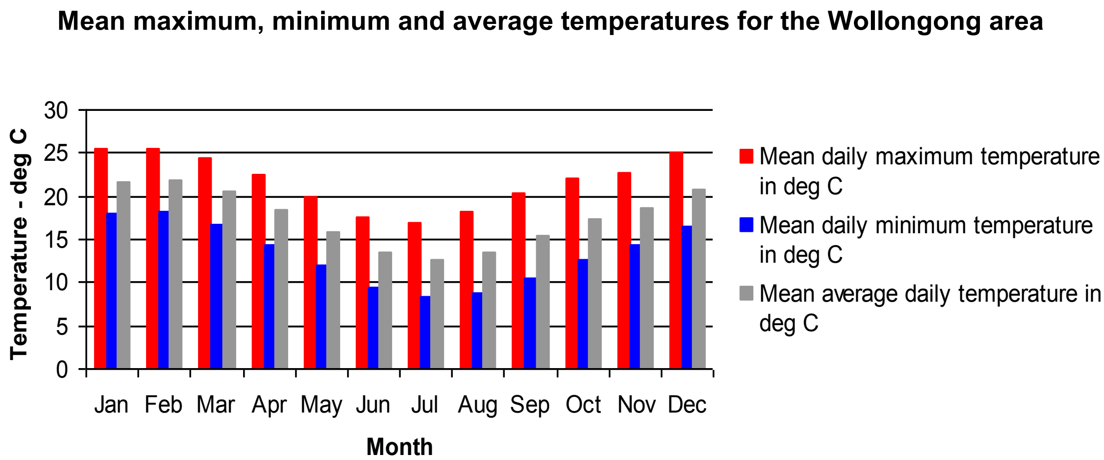


Figure 2.2: *Mean maximum, minimum and average temperatures for the Wollongong area (after Bureau of Meteorology 2012).*

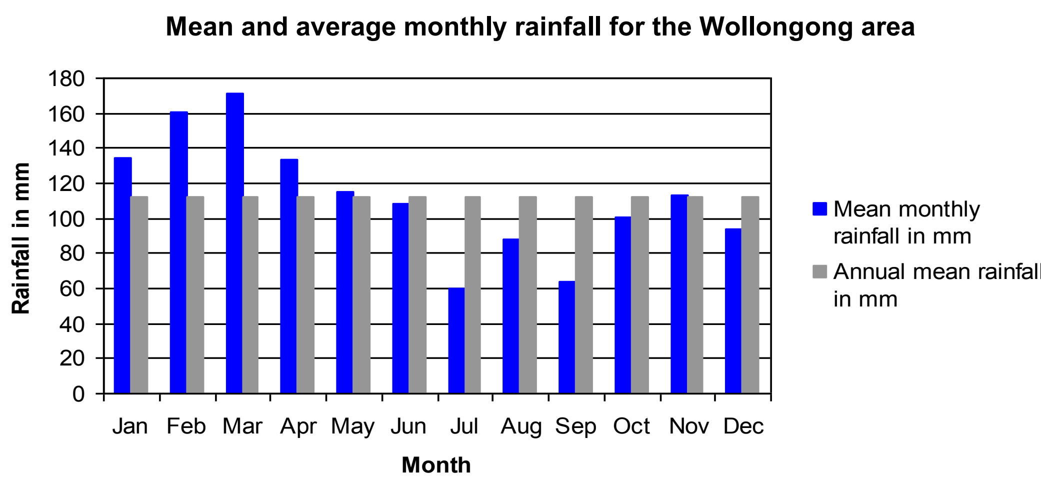


Figure 2.3: *Mean and average monthly rainfall for the Wollongong area (after Bureau of Meteorology 2012).*

2.6: Flooding

The proximity of Lake Illawarra to the steep escarpment makes it highly susceptible to both minor/moderate and major flooding. Hean and Nanson (1985) illustrated that significant floods can erode and redeposit larger than average amounts of sediment on the lower floodplains and the fluvial deltas in a short period of time. Therefore, these large scale events can have significant effects on the evolution of the lake's floodplains and deltas. Lawson and Treloar (2005) and Wollongong City Council (2012) identified

twenty eight major/severe floods and four minor/moderate flood events which occurred in the Lake Illawarra catchment area between 1919 and 2012. The major flood events and resultant lake levels >1.5 m AHD occurred in 1919, 1930, 1943, 19 January 1950, 7 April 1950, 1 May 1955, 19 February 1959, 20-21 October 1959, 25-26 March 1961, 18-19 November 1961, 11-12 June 1964, 9 November 1966, 16 April 1969, 14 November 1969, 12 March 1974, April 1974, March 1975, 23 February 1977, March 1977, March 1978, 14 February 1984, 6 August 1986, April 1988, 2 February 1990, 31 July 1990, 6-12 June 1991, 8 February 1992 and 31 August 1996. The four moderate flood events (resultant lake levels <1.5 m AHD) occurred in August 1987, August 1990, August 1998 and on the 21st March 2011. The entrance condition (open/closed) of Lake Illawarra appears to play a significant role in regional flooding. A significant number of the major floods documented by Lawson and Treloar (2005) coincide with the total closure or significantly restricted opening of the lake's entrance.

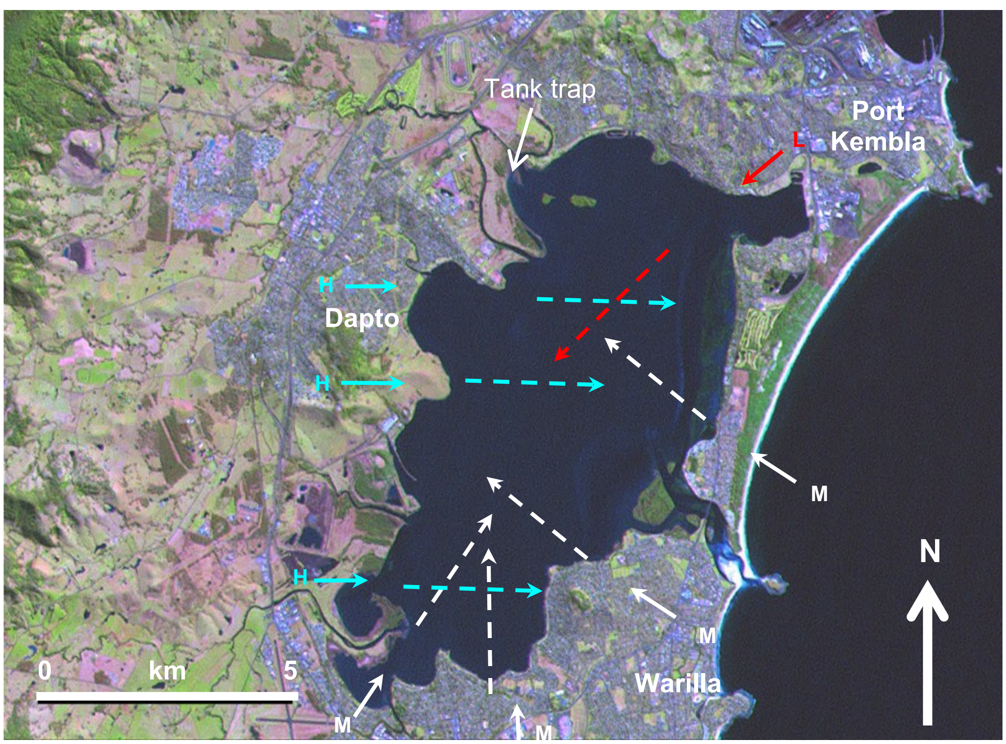


Figure 2.4: *Predominant wind directions affecting Lake Illawarra during summer (red), winter (blue) and all year round (white). The resulting travel paths of the developed wind-waves are indicated by dashed lines. Wind strength is indicated: H = high, M = medium and L = low.*

2.7: Hydrodynamics of Lake Illawarra

Lake Illawarra drains to the Tasman Sea via a long sinuous entrance channel. Tidal fluctuations within the lake are highly dependent on entrance conditions. Based on studies conducted by the Manly Hydraulics Laboratory (MHL) average lake elevations between 1993-2000 were recorded to be 0.21 AHD (WBM 2003). Using the MHL data WBM (2003) calculated approximate tidal ranges near the lake end of the entrance channel, for entrance closed (0.00 m AHD), very heavily shoaled (0.01 m AHD), heavily shoaled (0.02 m AHD), moderately shoaled (0.04 m AHD) and scoured (0.07 m AHD) conditions.

The height and period of the waves generated in the lake are dependent on the water depth, wind velocity and the length of time that it acts on the water surface. As previously noted relatively strong southerly winds are common throughout the year (Figure 2.4). The wind-waves which developed in response to these winds have the most affect on Mullet and Hooka Creek deltas in the northwestern corner of the lake. The impact of the northeasterly generated wind-waves during the summer months is minimal on all the lake deltas, due to the low wind velocity. Wind-waves generated by the strong winter westerlies have no impact on the deltas as the generated waves move from west to east across the lake.

2.8: Land use

The Lake Illawarra area was originally occupied by Aborigines of the Wadi Wadi group (Lake Illawarra Authority 2010). Dating of anthropological sites suggests indigenous settlement occurred prior to 17 ka (McDonald 1976). The overall anthropogenic impact of the local Aborigines is unknown, however it is likely to have been minimal.

Bass and Flinders in 1796 were the first documented Europeans to enter Lake Illawarra in the search for fresh water. Cedar cutters in the early 1800s are the first known Europeans to impact on the Lake Illawarra catchment area. Agriculture, primarily wheat, oats and potatoes, commenced in 1816 with the surveying and clearing of large land

grants surrounding the lake's foreshore (Lake Illawarra Authority 2010). Dairy farming replaced the growing of crops in the late 1800's. Currently, 40% or 94 km^2 of the lake's catchment area is classified as rural (Lawson and Treloar 2005; Figure 2.5).

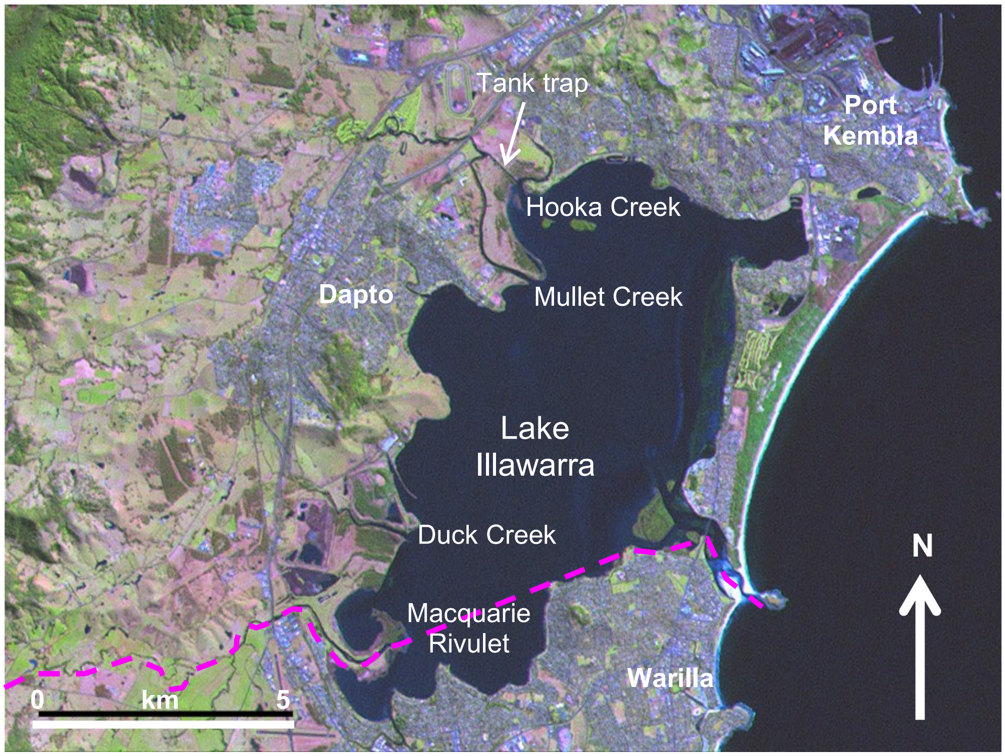


Figure 2.5: *Landsat image showing land use patterns surrounding Lake Illawarra. The bluish purple represents built up urbanised land, where as the light green, brownish green and pinkish areas are rural/cleared land. The dark green represents natural/forested land and the bluish black represents water. Note significant urban development has occurred in the West Dapto area since this image was captured. The pink dashed line illustrates the approximate boundary between the Wollongong and Shellharbour local government areas.*

The onset of industrialisation within the catchment area occurred in 1896 with the opening of the smelting works located near the mouth of Mullet Creek (Chenhall *et al.* 1995; Chiaradia *et al.* 1997). Due to a limited supply of ore the smelter ceased operation in 1906 (Chenhall *et al.* 1995; Chiaradia *et al.* 1997) and was dismantled in 1907 (McDonald 1976). It is probable smelting operations contributed to the heavy metal

contamination which can be detected in the Lake Illawarra sediments (Chenhall *et al.* 1995).

Subdivision of the large land grants for residential purposes commenced in the 1920's (McDonald 1976). Approximately 23% or 54 km^2 of the lake's catchment area is classified as urban (Lawson and Treloar 2005; Figure 2.5). However, this figure is likely to increase rapidly with the continued development of areas such as West Dapto, which is expected to contain up to 20,000 home sites within the next 40 years. Similar population growth and expansion of urban areas are being experienced, and are predicted to continue, in the Shellharbour local government area (Figure 2.5).

Anthropogenic modification of the Macquarie Rivulet and Mullet/Hooka Creek deltas tributaries extends as far back as the late 1800's. The first modifications to the tributaries were the construction of weirs (Figure 2.5). These weirs were primarily constructed to limit upstream salt water incursion and provide a fresh reliable source of water for irrigation and agricultural purposes (Hean and Nanson 1985). The presence of these structures is likely to have influenced the morphological evolution of the two deltas since they were constructed. For example, Hean and Nanson (1985) identified morphological issues such as bank slumping due to scouring and a reduction in accommodation space above the weir due to the impoundment of bedload and saltating sediment. Based on Hean and Nanson (1985), it is feasible to suggest that a reduction in accommodation space, due to sedimentation behind a fixed structure, will reduce the amount of sediment transported to the mouths of the Macquarie Rivulet and Mullet Creek.

Construction of the tank trap in 1941 by the Australian Army altered the flow path of Mullet Creek by connecting the creek directly to Koong Burry Bay via a 660 m long channel (Figure 2.5). Construction of the channel shortened the flow path increasing the hydraulic gradient. Subsequent to the channels construction Koong Burry Bay began to infill while the Mullet Creek delta experienced limited growth. These impacts are discussed in Chapter 8 of this thesis.

2.9: Chapter summary

The regional context of Macquarie Rivulet and Mullet/Hooka Creek deltas and their catchments of 96.35 km^2 and 75.2 km^2, respectively, has been documented in this chapter. Ten soil associations occur within the catchment, with 60% of them classified as being extremely erodible. Due to the orographic effect and the shape of the escarpment rainfall events are typically compartmentalized and have resulted in a number of major floods. Since European settlement large tracks of land were initially cleared for agricultural purposes and subsequently replaced with urban and industrial development. This chapter has illustrated that Lake Illawarra has been the subject of many studies, however, very little research has focussed on understanding the evolution of the lake's two major bay-head deltas, being Macquarie Rivulet delta and the Mullet/Hooka Creek delta.

Chapter 3

Previous Research

3.1 Introduction

The Holocene evolution of deltas and their associated floodplains has been affected by a combination of natural and anthropogenic processes/factors. Therefore, it is important to review and discuss the processes/factors that have affected, either partially or fully, the evolution of deltas. This chapter outlines the natural processes/factors as presented in the literature. Key elements discussed in the initial sections of the chapter include:

- Holocene sea level fluctuations;
- the classification, zonation and evolution of estuaries along the southeastern coast of Australia; and
- the classification and evolution of deltas and associated floodplains.

The deposition and environmental implications, if disturbed, of sulfidic sediments are also outlined.

3.2 Holocene sea level fluctuations in Australia and the South Coast of New South Wales

Hopley and Thom (1983), Chappell (1987), Ferland *et al*. (1995), Lambeck and Chappell (2001) and Murray-Wallace *et al.* (2005) noted that during the last Pleistocene glaciation sea level was between 120 m to 130 m below present. Early sea level research undertaken by Thom and Chappell (1975) suggested the post-glacial marine transgression in Australia terminated between 6 ka and 6.5 ka. This age range was based on a sea level envelope constructed using both fixed and relative sea level indicators. However, the dates used in the generation of this curve were not corrected for the marine reservoir effect and calibrated to sidereal years.

Thom and Roy (1985) published a revised relative sea level envelope (Figure 3.1), based on sixty nine radiocarbon dated samples older than 5 ka ^{14}C years, corrected for the

marine reservoir effect and calibrated to sidereal years. The revised curve suggested the rapid rise in sea level associated with the post-glacial marine transgression in Australia terminated between 6.5 ka and 7 ka (Thom and Roy 1985), 500 years earlier than previously published by Thom and Chappell (1975).

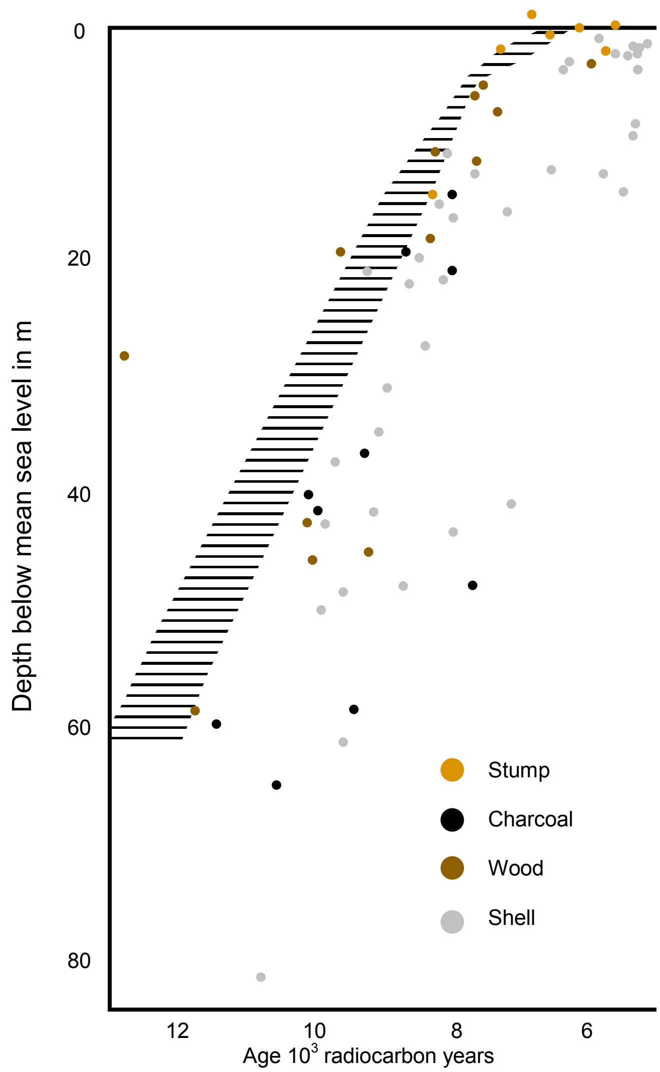


Figure 3.1: *Holocene sea level envelope for Australia based on sixty nine corrected radiocarbon dated samples older than 5 ka ^{14}C years (after Thom and Roy 1985).*

Bryant (1992) noted peak Holocene sea level in Australia ranged from 1.6 m, in the northwest to 2.4 m in the southeast above present mean sea level (Figure 3.2). These sea level variations have been attributed to the effects of hydro-isostasy (Bryant 1992). Similar isostatic effects on regional sea level have been well documented by other

authors including, but not limited to Lambeck (1993), Williams *et al.* (1993) and Haslett (2000).

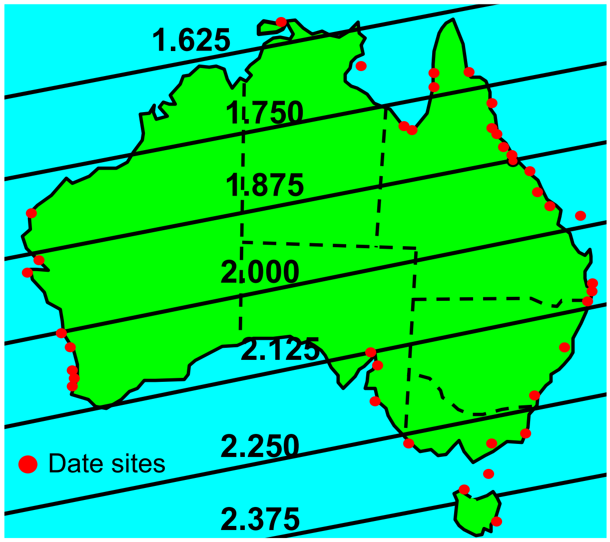


Figure 3.2: *Peak Holocene sea level across Australia. Heights indicated are in metres above present sea level (after Bryant, 1992).*

Along the southeast coast of New South Wales, several sites indicate peak Holocene sea levels reached maximum elevations in the vicinity of 2 m above present mean sea level between 7.2 ka and 7.7 ka (Jones *et al.* 1979). These conclusions were based on radiocarbon dates obtained from in situ hardwood stumps, mangrove roots and wood fragments within raised estuarine mud and barrier-beach sands exposed on McCauley's Beach south of Sydney (Jones *et al.* 1979). However, Beaman *et al.* (1994) and Larcombe *et al.* (1995) noted the use of mangrove deposits to estimate palaeosea levels has an error margin in the vicinity of ± 1.5 m. Furthermore, an exposure at Bulli Beach suggests sea level in this area reached an elevation of 1.55 m above present mean sea level (Young *et al.* 1993). This exposure contained estuarine shell (6.48 ± 0.25 ka) in conjunction with a mangrove stump (6.89 ± 0.15 ka). Farther south, estuarine deposits at Callala Beach found 1.8 m above present sea level contain 15 in situ species of estuarine macrofossils including *Anadara trapezia* and *Ostrea angasi,* which have been dated at 5.89 ± 0.05 ka (corrected and calibrated radiocarbon age; Young *et al.* 1993).

It is generally accepted that sea level rose above its present elevations during the Holocene along the New South Wales coast and then fell steadily to its present level. However, Baker and Haworth (1997, 2000a, b) and Baker *et al.* (2001a, b) suggested the subsequent highstand and fall in sea level was characterised by oscillations in the vicinity of ± 1 m.. Their conclusion was based on the analysis of fixed biological indicators particularly *Galeolaria caespitose* (calcareous tubeworm), *Tesseropora rosea* and *Chamaesipho tasmanica* (barnacles). Using the boundaries between *Galedaria caespitosa, Tesseropora rosea* and *Chamaesipho tasmanica* Baker *et al.* (2001a, b) suggested sea level can be established with an uncertainty of ± 0.1 m. However, the use of fixed biological indicators assumes wave regimes and consequent wave splash, palaeogeomorphology and associated elevated water levels in addition to climate and tidal conditions in the past were similar to those at present, as the vertical locations of intertidal organisms are significantly altered if these factors increase or decrease (Laborel and Laborel-Deguen 1995; Sloss *et al.* 2007; Lewis *et al.* in press). Lewis *et al.* (in press) also noted that encrusting organisms are more likely to preserve local variations rather than the regional sea level. ThIs has been suggested since the organisms are best preserved in sheltered settings where localised changes can occur irrespective of the regional trend.

Sloss *et al.* (2007) produced a revised sea level curve for the southeast coast of Australia. The revised curve is based on the reinterpretation of previously published and recently obtained geochronological data. The previously published data was derived from calibrated radiocarbon dating of 112 macrofossils, woody debris, mangrove roots and fixed biological indicators, whereas the recently obtained data was based on 37 calibrated radiocarbon (macrofossils, mangrove roots, organic material and carbonate beach rock) and 50 amino acid racemisation dates (macrofossils) from estuaries in southern NSW. However, care needs to be taken when using these data as palaeosea level indicators. For example, Sloss *et al.* (2007) reviewed the data published by Jones *et al.* (1979) and suggested sea level was between + 1 m and + 1.5 m above present mean sea level by 7. 4 ka (Figure 3.3). The 0.5 m reduction in the sea level to that originally

proposed by Jones *et al.* (1979) is due to the application of uncertainty terms for mangrove material and elevated estuarine water levels.

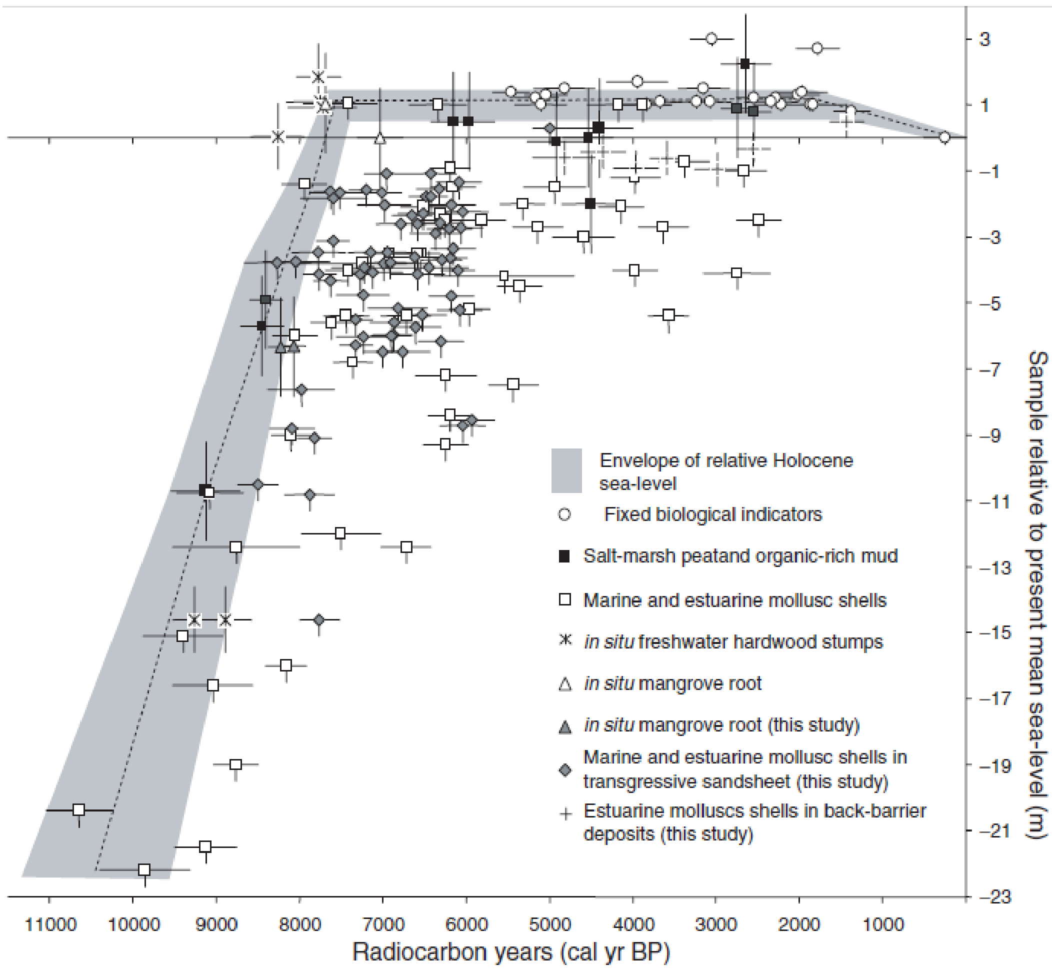


Figure 3.3: *Holocene sea level curve and envelope from* Sloss *et al. (2007) for the southeast coast of Australia.*

The revised curve/envelope proposed by Sloss *et al.* (2007; Figure 3.3) and reviewed by Lewis *et al.* (in press) indicates that sea level had reached an elevation of between -15 m and -11 m between 9.4 ka and 9 ka and then reached present sea level about. 7.9 ka to 7.7 ka. However, the validity of this age range is primarily reliant on a single radiocarbon age published by Jones *et al.* (1979). By 7.4 ka sea level along the southeast coast of Australia had reached a maximum of +1 m to +1.5 m which was subsequently maintained until approximately 2 ka Sloss *et al.*(2007) and Lewis *et al.* (in press). Significantly the maximum sea level elevation proposed by Sloss *et al.*(2007) is

consistent with previous studies including Thom and Chappell (1975), Thom and Roy (1985), Bryant *et al*. (1992), Young *et al*. (1993), Woodroffe *et al.* (1995) and Lewis *et al.* (2008). After 2 ka, Sloss *et al.* (2007) noted sea level along the southeast coast of Australia fell gradually to its present level.

The relatively static sea level suggested by Sloss *et al.* (2007) differs from the oscillating model proposed by Baker and Haworth (1997, 2000a, b) and Baker *et al.* (2001a, b) for the mid to late Holocene. Instead Baker and Haworth (1997, 2000a, b) and Baker *et al.* (2001a, b) suggest sea level oscillated up to three times during this period. However, Sloss *et al.* (2007) and Lewis *et al.* (in press) noted that a lack of data pertaining to wave regimes and consequent wave splash, palaeogeomorphology and associated elevated water levels in addition to climate and tidal conditions for the mid Holocene makes it difficult to quantify the oscillations. Furthermore, Lewis *et al.* (in press) noted the oscillating model proposed by Baker and Haworth (1997, 2000a, b) and Baker *et al.* (2001a, b) is inconsistent with the sea level data from Queensland and Bateman's Bay, NSW published by Donner and Junger (1981). The discrepancy between the Sloss *et al.* (2007) and the Baker and Haworth (1997, 2000a, b) and Baker *et al.* (2001a, b) Holocene sea level curve/envelope for southeastern Australia will remain unresolved until such time as the meaning and quality of the existing data are better understood and/or additional data are obtained (Lewis *et al.* in press).

Lewis et al. (in press) completed a detailed review and synthesis sea level data from a range of locations including Australia and New Zealand along with samples from the Northwest Shelf and, Sunda Shelf in an attempt to establish the post-glacial sea level history around the Australian margin. This study resulted in the generation of a revised post-glacial sea level envelope (Figure 3.4). The envelope suggests sea level rose at a relatively stable rate up until the onset of the 1A meltwater phase which resulted in the rate of rise increasing to around 5 cm/year between 14.3 ka and 14.6 ka (based on a 16 m rise in 300 years; Hanebuth *et al.* 2000, 2009). The data then shows a slight deceleration in the overall rate of rise up until present sea level was reached by the late Holocene. As sea level increased through the mid to late Holocene Lewis *et al.* (in press)

note the data appears to highlight regional variability and discrepancies between the nature of the Holocene highstand and subsequent fall. As such the authors split the Australian margin into distinct zones including Northern Australia, Queensland, southeastern Australia, South Australia and Western Australia. The sea level data compiled by Sloss *et al.* (2007) formed the basis of the Lewis *et al.* (in press) review for southeastern portion of the Australian coastline. Theses data have been summarised and discussed above.

One of the key findings of the review undertaken by Lewis *et al.* (2012) was that regional sea level reconstructions based on a variety of different sea level indicators is likely to produce a more credible picture of how sea level has behaved around the Australian coast. Based on the above, the sea level curve/envelope proposed by Sloss *et al.* (2007) and reviewed by Lewis *et al.* (2012) will be referred to in this study.

3.3: Estuaries

Estuaries can be found along much of the New South Wales coastline. Dalrymple *et al.* (1992) has described an estuary as: “The seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of the tidal facies at its head to the seaward limit of coastal facies at its mouth.” Dalrymple *et al.* (1992) goes onto note estuaries will only form during a transgressive event and will infill as the rate of rise slows or stabilises. However, if sea level rises the estuaries will be submerged.

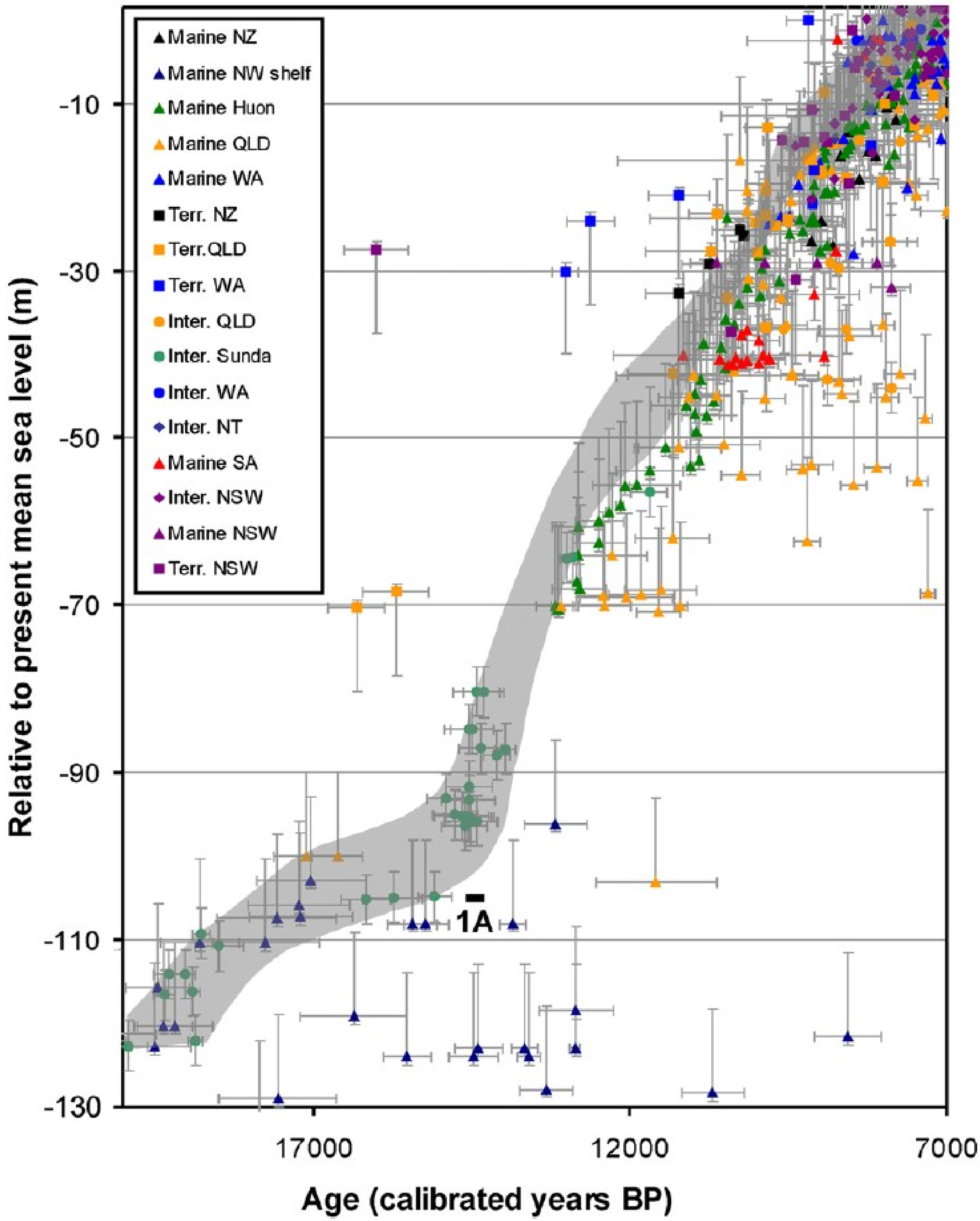


Figure3.4: *Post-glacial sea level sea level envelope up until present sea level was obtained. The envelope is based on the merger of data from Australia, New Zealand, New Guinea (Huon Peninsula) along with samples from the Northwest Shelf and, Sunda Shelf (Lewis et al. 2012).*

3.3.1: Classification of estuaries in New South Wales

Classification of New South Wales estuaries can be, and is often, based on their entrance morphology (Roy 1984). Chapman *et al.* (1982), Roy (1984), Roy and Cowell (1994) and Roy *et al.* (2001) found that three distinct estuary types occur in New South Wales. These estuary types include wave-dominated barrier estuaries (coastal lagoons), drowned river valleys (open estuaries) and saline coastal lakes. However, Yassini and Jones (1995) modified this initial classification by grouping barrier estuaries and saline coastal lakes together on the basis that their evolution and morphology are similar. They also added sheltered oceanic embayments as an additional estuary type (Figure 3.5). Furthermore, the Department of Land and Water Conservation (2003) recognised sheltered oceanic embayments as an estuary type. Roy (1984) did not recognise sheltered oceanic embayments as a type of estuary in his classification scheme as he claimed they are only estuaries in a limited sense.

Wave-dominated barrier estuaries, such as Lake Illawarra, are widespread along the south coast of New South Wales. Typically these estuaries have limited tidal ranges due to the presence of barriers enclosing their entrances, either partially (coastal lagoons, e.g. St Georges Basin) or completely (saline coastal lakes, e.g. Coila Lake). Due to the variable entrance conditions these estuaries are also referred to as intermittently closed or open lagoons (ICOL). Other characteristics of barrier estuaries are they have shallow basins, narrow sinuous entrance channels, flood tide deltas and prograding fluvial deltas (Yassini and Jones 1995).

Drowned river valley estuaries, such as the Hawkesbury River estuary, occur predominantly along the New South Wales central coast. These estuaries are characteristically deep, with steep rocky sides, have an extensive subaqueous flood tide delta sand sheet, are fully tidal, have a central mud basin and have a fluvial delta prograding into the estuarys' headwaters (Roy 1984, Yassini and Jones 1995, Kench 1999).

Sheltered oceanic embayments, such as Jervis Bay, occur along the southeastern coast of New South Wales. These estuaries develop between headlands and are permanently open to the ocean. These estuaries have fully developed tidal circulation with average depths of 20 m but occasionally are as deep as 40 m (Yassini and Jones 1995).

3.3.2: Evolution of estuaries in New South Wales

The geomorphology of New South Wales estuaries has been inherited from periods of sea level low-stands associated with Quaternary glaciation events (Roy and Peat 1974, 1975, Roy 1984, 1988, 1994, Zaitlin *et al.* 1994, Yassini and Jones 1995, Kench 1999, Roy *et al.* 2001). As a result, during periods of lower sea level rivers incised into the Ordovician to Triassic bedrock sequences and older Pleistocene sediments to form river valleys and other topographic depressions. Initiation of the latest post-glacial marine transgression resulted in the topographic depressions below sea level being inundated causing the development of estuaries (Roy and Cowell 1994). Furthermore, extensive sand bodies were transported onshore and deposited in the mouths of the depressions (Sloss *et al.* 2004, 2005). When sea level stabilised, marine and fluvial sediments began to infill the estuaries. The rate of infill of estuaries in New South Wales is highly variable and is controlled by the amount of sediment supplied to the estuary and its ability to retain sediment. As estuaries infill with sediment both morphological and ecological changes occur. The evolutionary cycle of an estuary associated with eustatic sea level fluctuations can be described simply as a cut-and-fill cycle (Roy *et al.* 2001).

Throughout the Quaternary many marine transgression/regression cycles have occurred in response to eustatic sea level changes and many cut and fill cycles have also occurred. Roy (1984) and Roy *et al.* (2001) noted the majority of estuaries in New South Wales contain preserved remnants of these palaeoestuaries. The terms ‘simple fill’ and ‘compound fill’ are used to describe the number of cut and fill cycles recorded by the estuary (Zaitlin *et al.* 1994). A simple fill estuary only records one cut and fill cycle such as the latest Pleistocene to Holocene (22 ka-present) cut-and-fill cycle. In contrast to this, compound fill estuaries record several cut-and-fill cycles that occurred prior to or during the Quaternary.

3.3.3: Estuarine evolutionary models

Several papers were published in the early 1980's (e.g. Roy 1984) outlining the evolution of three types of New South Wales estuaries. Of these three types the barrier estuary model is the most relevant to this research, as the deltas in this study are prograding into a barrier estuary. Figure 3.6 illustrates the barrier estuary evolutionary model as proposed by Roy *et al.* (2001). The model subdivides estuary evolution into four stages based on basin infill. The four stages are as follows:

- Stage 1: represents the youthful estuary where sediment infilling the basin is minimal;
- Stage 2: represents the intermediate estuary where delta progradation has commenced and partially infills the basin;
- Stage 3: represents the semi-mature estuary where extensive floodplains have developed in response to delta progradation; and
- Stage 4: represents the mature estuary where continued delta progradation has infilled the basin leaving only cut-off embayments.

Sloss (2005) studied Lake Illawarra's stratigraphy and suggested a modification of the Roy *et al.* (2001) barrier estuarine evolutionary model (Figure 3.7). The new version of the model incorporates two additional evolutionary stages. The first of these stages describes the fluvial incision which occurred in response to the Pleistocene sea level low stand. These incised fluvial channels were observed in seismic traces. It was suggested the channels may be partially infilled with coarse-grained fluvial sediments. The second additional stage describes the flooding of these incised channels by rising sea level and the subsequent deposition of a transgressive marine sand sheet between about 7.6 and 5 ka.

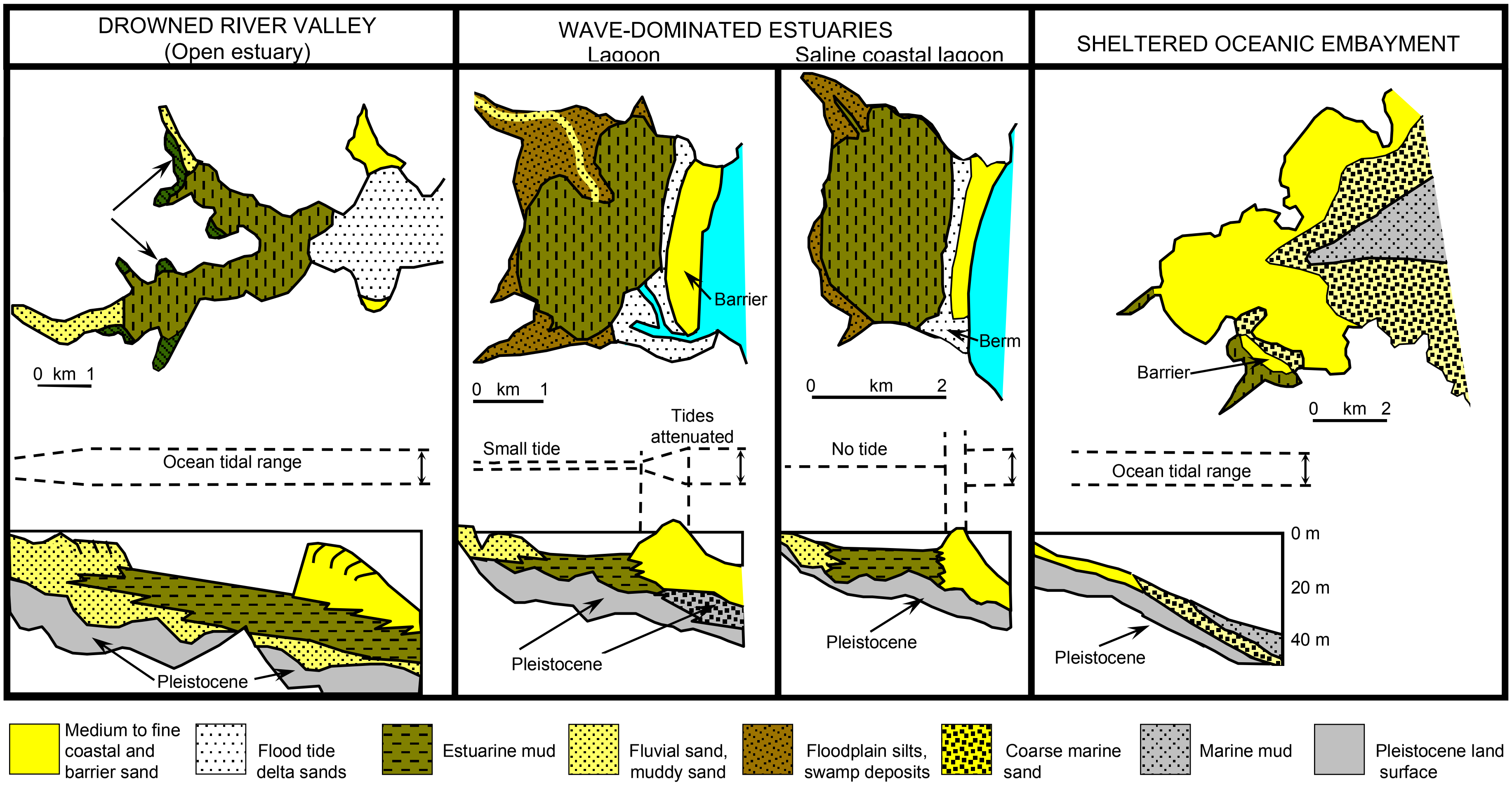


***Figure 3.5** Three distinct estuary types in New South Wales and associated facies distributions after Yassini and Jones 1995).*

Sloss (2005) suggested the Roy 1984 did not accurately reflect the Holocene evolution of wave-dominated barrier estuaries. Sloss (2005) proposed two additional evolutionary stages (Figure 3.7). The first evolutionary stage represents deposition of a basin wide marine transgressive sand sheet *ca.*7.6 ka. The lack of a barrier as indicated in the model resulted in the receiving basins experiencing marine conditions. The second evolutionary stage covers the time period between 5 ka and 7.6 ka. The stage suggests development of the Holocene barrier system reduced the influence of marine conditions within the receiving basin as evidenced by the deposition of the central mud basin facies. The remaining elements of the Sloss (2005) model are based on the four stages previously proposed by Roy (1984).

In addition to the changes proposed by Sloss *et al.* (2005, 2006a), Hopley and Jones (2006) noted that Roy *et al.* (2001) did not incorporate cut-off embayments until stage four (mature) of the model. However, there are examples along the South Coast of New South Wales, such as Tullarwalla Lagoon, St Georges Basin and Haywards Bay on the northern side of the Macquarie Rivulet delta where the development of these cut-off embayments are present in three estuaries. Hopley and Jones (2006) suggested it may be necessary to incorporate these features into the model or note their presence at earlier stages of infill than stage four as suggested by Roy *et al.* (2001).

3.3.4: Barrier estuary zonation

Zonation within an estuary arises due to the complex interaction of depositional environments, sediment types and hydrological factors (Roy *et al.* 2001). Despite the complexity of these interactions Dalrymple *et al.* (1992) noted evolutionary models indicate the spatial distribution of facies is predictable. Initial work published by authors including, but not limited to, Nichol (1991) and Dalrymple *et al.* (1992) recognised three distinct geomorphic zones within an estuary. These zones consist of a marine zone, central lagoon/mud basin and a fluvial delta zone (Figure 3.8). This zonation within an estuary is commonly referred to as a tripartite zonation. However, Roy *et al.* (2001) noted within all southeastern Australian estuaries four geomorphic zones can be recognised. The first three geomorphic zones recognised by Roy *et al.* (2001) are the

same as the tripartite zones suggested by authors such as Dalrymple *et al.* (1992). The additional zone is a riverine channel and alluvial plain zone.

The marine zone extends from the estuary's mouth landwards and includes units associated with sedimentation on the barrier and in the inlet channel. Sediment within the marine zone is comprises of moderately well sorted quartzose marine sand derived from the continental shelf (Roy *et al.* 2001). Wave energy levels within this zone are generally high (Figure 3.8). The geomorphic units occurring within the marine zone include the barrier spit, the back-barrier flat, the flood-tide delta, the tidal channel and the beach ridge (Nichol 1991).

Moving landward, the next zone is the central lagoon/mud basin. Sedimentation within this zone consists of clay sized sediment derived from the tributaries entering the estuary. As the central lagoon/mud basin is a low energy saline environment (Figure 3.8) the clay and silt-sized particles are able to settle and flocculate out of suspension. The sediment within this zone is generally dark grey to black with common organic material along with common microfossils and macrofossils (Roy *et al.* 2001, Hopley and Jones 2006).

The second most landward and the most complex zone is the fluvial delta zone. The fluvial delta zone is where tributaries interact with the estuarine environment and deposit their sediment. Sediment is highly varied, ranging from fluvial gravel and sand in the channels to mud on the delta slope and prodelta. Several geomorphological environments are present within the fluvial delta zone including river and distributary channels, mid-channel shoals, levees, crevasse splays, delta-top plain, delta slope, distributary mouth bars, interdistributary bays and fresh-water swamps (Roy and Cowell 1994). However, Dalrymple *et al.* (1992) noted bay-head delta facies are distinguishable from fluvial sediments due to the presence of tidal structures and/or brackish-water fauna. Delta morphology within this zone is variable ranging from fan-shaped deltas to elongated birds-foot deltas.

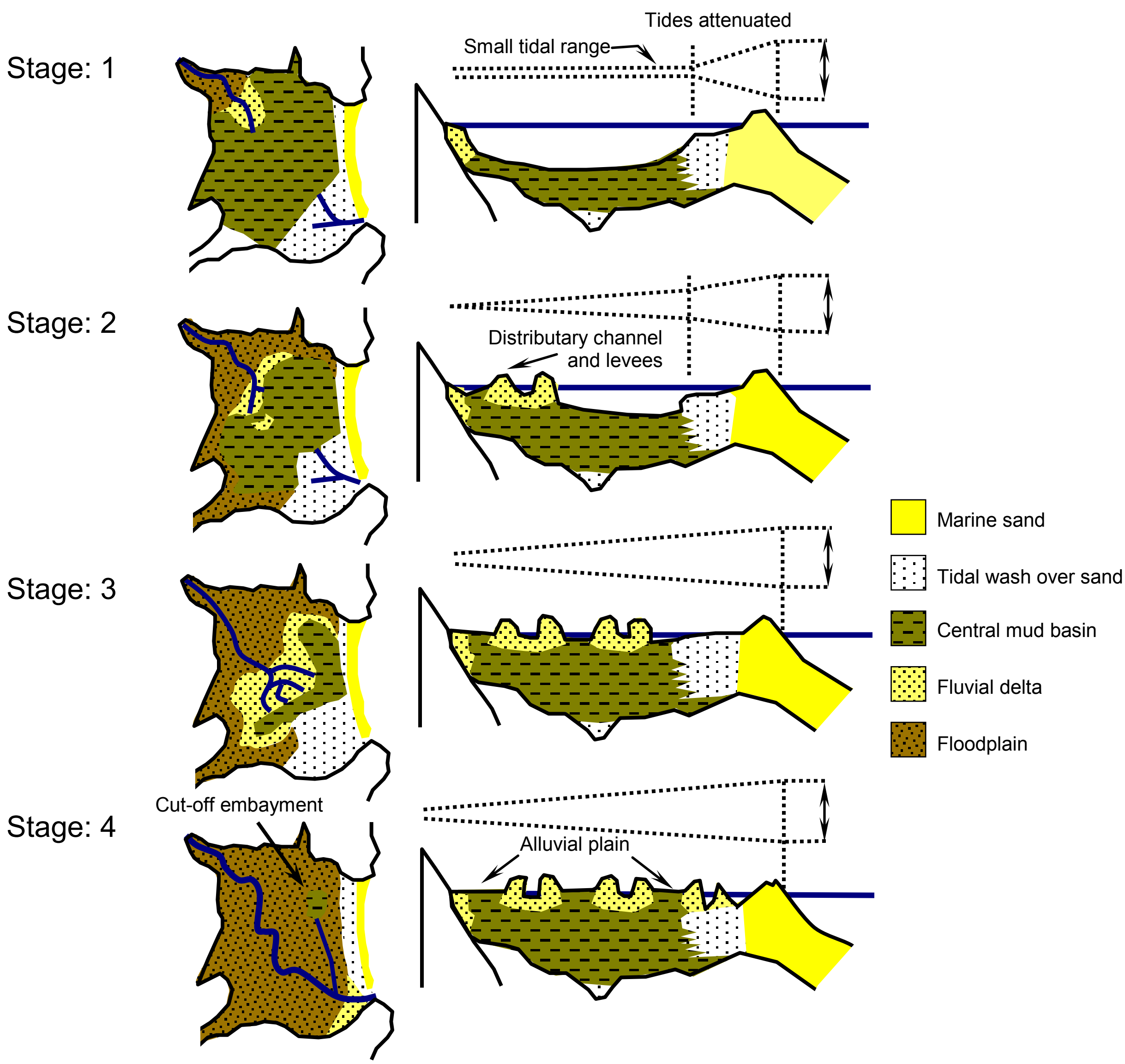


Figure 3.6: *Roy's Barrier estuarine evolutionary model (after Roy 1984).*

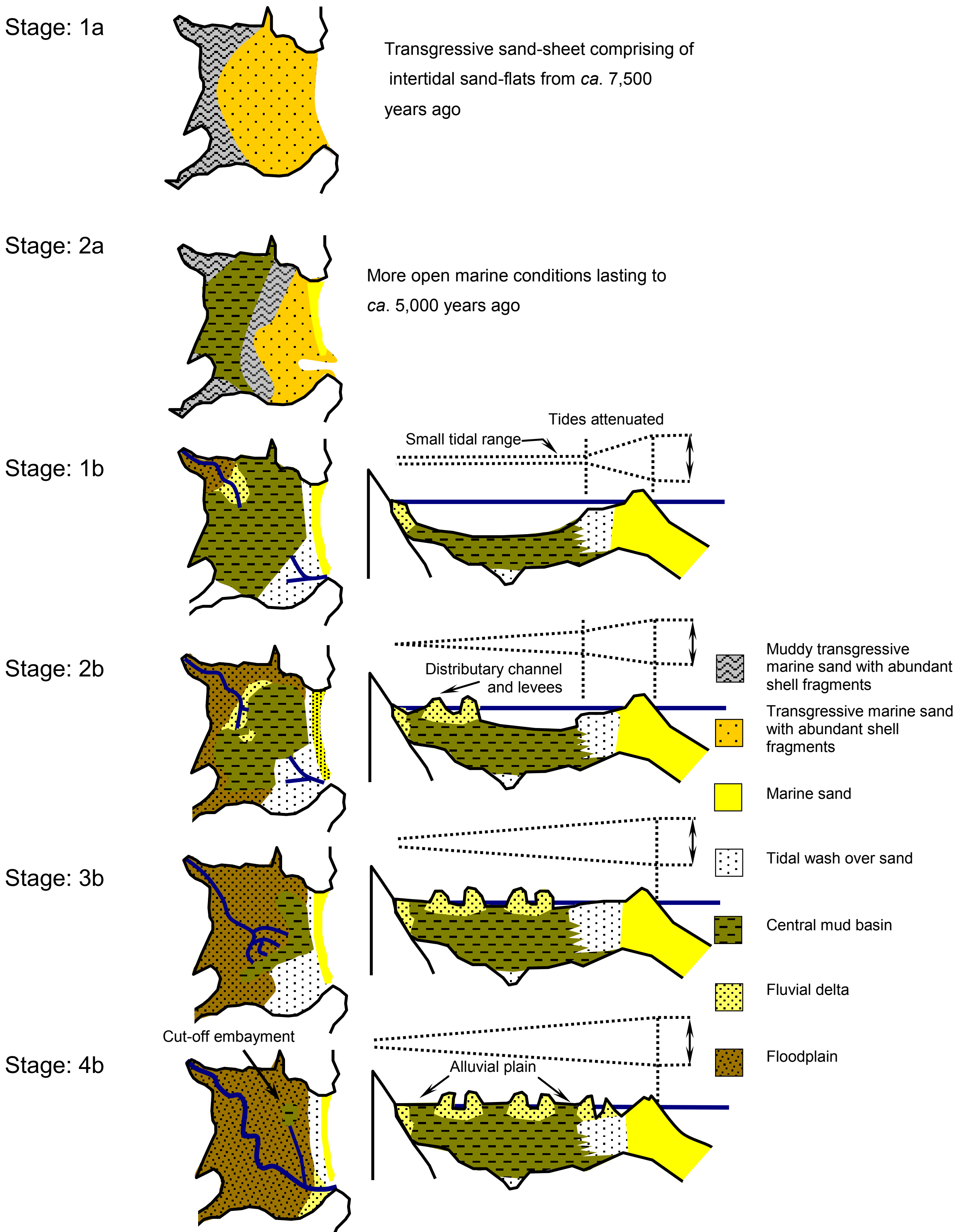


Figure 3.7: *Modified estuarine evolutionary model (after Sloss et al. 2005).*

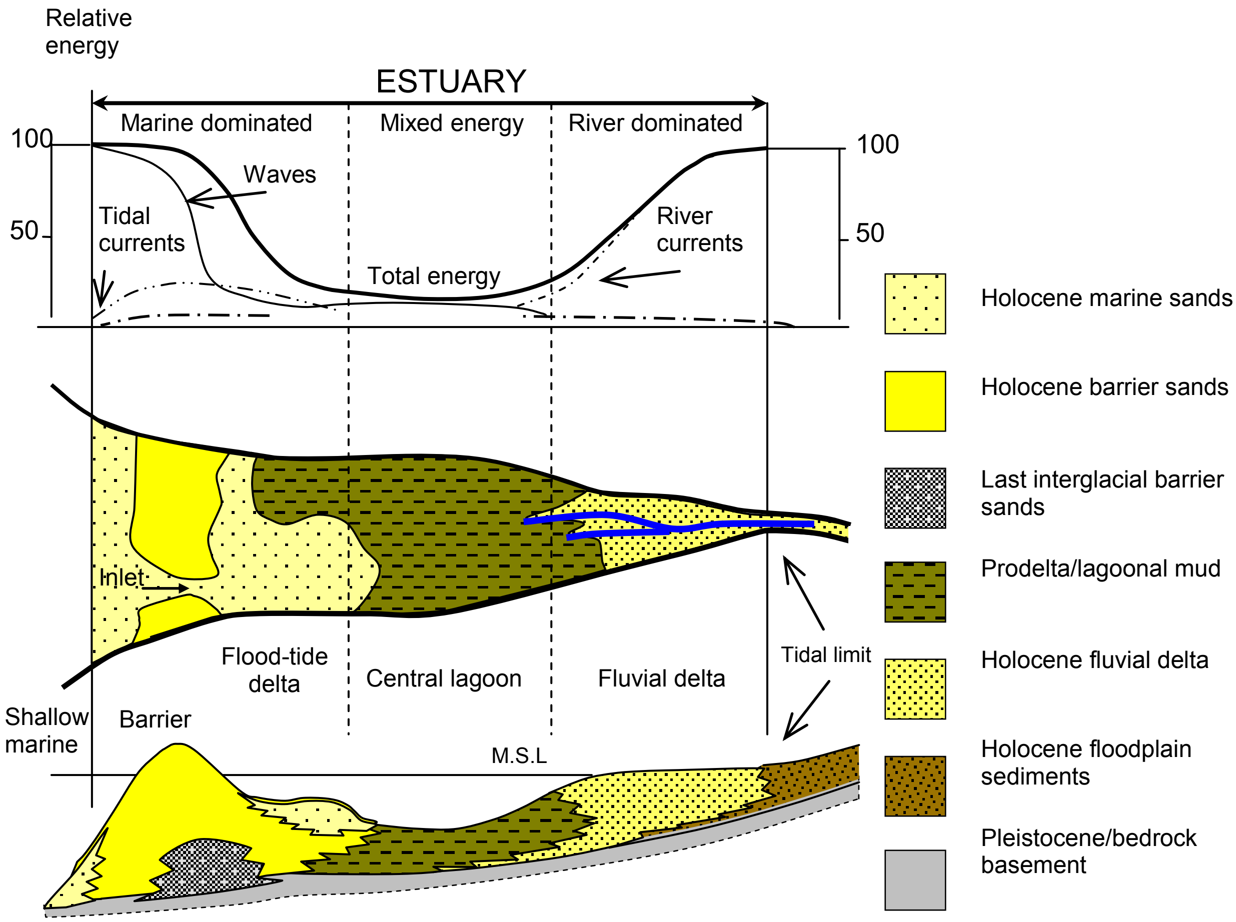


Figure 3.8: *The distribution of energy, the tripartite zones in plan view and a cross-section of the estuary within an idealised barrier estuary (after Dalrymple et al. 1992).*

The final geomorphic zone is the riverine channel and alluvial plain zone. The development of this zone is attributed to the progradation of fluvial deltas into estuaries. Roy *et al.* (2001) noted the riverine channel zone grades downstream towards the fluvial delta zone where a slight change in the channel width, salinity and sedimentary deposits occurs. Sediments within the riverine channel zone are generally sandy, however gravel may also be found. The alluvial plains consist of floodplains, back-swamps and palaeochannels (Roy *et al.* 2001). Sediments within these environments range from fluvial sand and gravel in the palaeochannels to fluvial mud and peat in the swamps.

3.4: Fluvial deltas

The term delta was first used by the Greek historian Herodotus about 450 BC, who noticed the shape of the sediment deposited at the mouth of the Nile River was similar to the Greek letter delta (Δ; Coleman 1976, Bhattacharya and Walker 1992; Sutter 1994). Today the term delta is used to describe shoreline extensions which prograde at the mouths of rivers and creeks entering water bodies, such as estuaries and oceans, where the sediment supply is greater than the rate of sediment reworking by basinal processes (Coleman 1976, Bhattacharya and Walker 1992, Sutter 1994).

3.4.1: Delta classification

The most common classification of deltas is based on their plan morphology and is often represented in a ternary diagram (Figure 3.9). Galloway's (1975) tripartite classification of delta morphology is based on the relative influence that fluvial, tidal and wave processes have on the delta. From this diagram, three broad delta classifications are recognised and referred to as fluvial/river-dominated, wave-dominated or tide-dominated deltas.

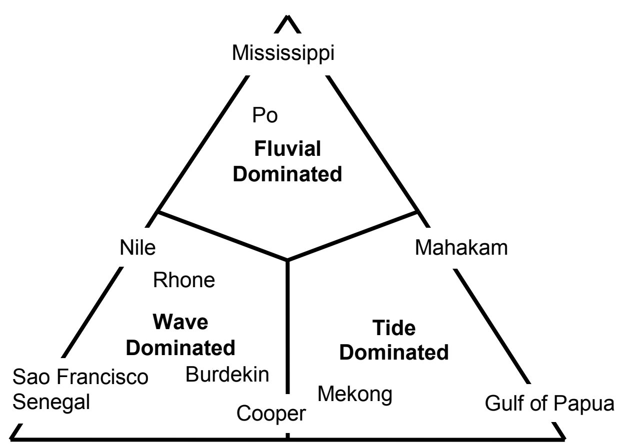


Figure 3.9: *The ternary diagram first presented by Galloway (1975) is commonly used in the classification of deltas. The classification of a delta is based on the dominant process acting on it. The classification of several large Holocene deltas is indicated (after Pigott 1995).*

Fluvial/river-dominated deltas or Gilbert-type deltas have been described as high-constructive deltas by Bhattacharya and Walker (1992) and others. These deltas are generally characterised by well developed delta plains, steeply dipping foreset beds, lower angle topset and bottomset beds and an overall digitate or birds foot morphology (Figure 3.10; Bhattacharya and Walker 1992, Davis 1994). Generally fluvial-dominated deltas develop in areas where there is a relatively large sediment supply and a calm receiving basin. The Mississippi (Gulf of Mexico, North America; Galloway 1975, Coleman and Wright 1975, Coleman 1976, Coleman 1984b, Bhattacharya and Walker 1992) and Volga (Caspian Sea; Overeem *et al.* 2003), Wandandian Creek (Hopley and Jones (2006) deltas are examples of fluvial/river-dominated deltas.

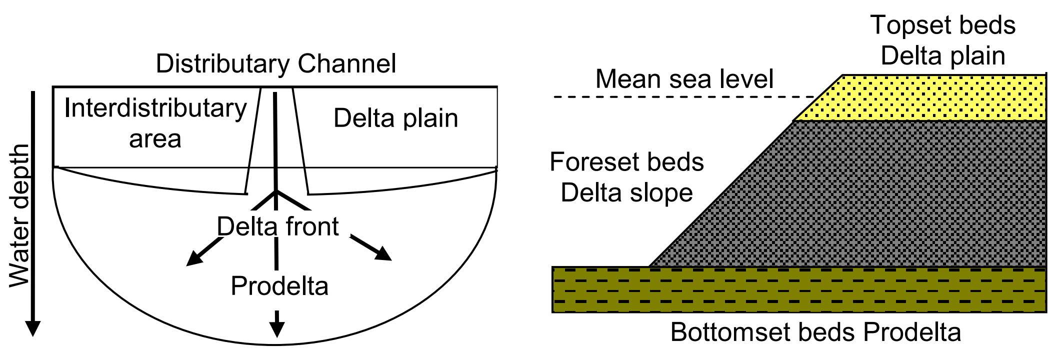


Figure 3.10: *Schematic plan view and cross-section of a Gilbert-type delta (after Haslett 2000).*

In contrast to fluvial/river-dominated deltas, wave-dominated deltas are characterised by smooth shorelines with well developed beaches and dunes and very few distributary channels (Davis 1994, Nichol *et al.*1997). It is possible to distinguish two main morphologies within wave-dominated deltas. The symmetrical capsulate morphology associated with deltas, such as the São Francisco delta (Atlantic Ocean, South America; Coleman 1976, Coleman 1984b, Davis 1994, Sutter 1994), can be attributed to the lack of a dominant longshore drift direction (Davis 1994). In contrast to the capsulate morphology some wave-dominated deltas, such as the Senegal River delta (Atlantic Ocean, Africa; Coleman 1984b, Davis 1994), develop distinctive spits. These spits are the

result of strong longshore currents which form due to waves approaching the shoreline at oblique angles (Davis 1994).

Tide-dominated deltas are common in macrotidal environments, such as northwestern Australia (Ord River delta; Coleman 1976), Papua New Guinea (Fly River delta; Dalrymple *et al.* 2003) and India (Ganges-Brahmaputra Rivers delta; Coleman 1984). These deltas are characterised by broad funnel shaped mouths oriented perpendicular to the coast and have high width to depth ratios (Davis 1994; Jones *et al.* 2003).

In addition to the above mentioned large scale deltas smaller flood and ebb tide deltas can develop in the inlet channels of coastal estuaries in microtidal environments. Generally, only the flood tide delta is preserved as the ebb tide delta is reworked by wave action in the near shore zone (Sloss 2001). Figure 3.11 illustrates the flood tide delta which is currently prograding into Lake Illawarra on the South Coast of New South Wales.

Figure 3.11: *An oblique aerial photograph (February 2001) of the flood tide delta which is prograding into the central mud basin of Lake Illawarra (after Sloss 2001).*

3.4.2: Deltaic sub-environments

The delta plain is the most landward portion of the delta and is characterised by distributary channels (both active and abandoned) and interchannel environments

(Coleman 1976, Bhattacharya and Walker 1992; Sutter 1994; Haslett 2000). The channels are lined with levees which accrete by trapping fluvial sediment during flood events (Coleman 1976, Bradshaw 1987). Some of the other geomorphological features which can occur within the interchannel environments are floodplains, swamps, marshes, crevasse channels, crevasse splays and sub-embayments. Sutter (1994) noted that delta plains can be further subdivided into upper and lower sections. The upper delta plain is the older portion of the delta and is dominated by fluvial processes (Hart 1995). In contrast to this, the lower delta plain is younger and is influenced by the incursion of saline water. Furthermore, the lower delta plain is the site where more active sedimentation occurs.

The delta slope/front is the site where both fluvial and basinal processes are important (Coleman 1976, Sutter 1994). At the delta slope sediment is delivered from the distributary channels as both suspended and bed load (Davis 1994). Typically the coarsest material is deposited in the mouth of the channels to form distributary mouth bars. Much of the remaining sediment transported by the channels is deposited lower on the delta slope and on the prodelta. Deposition on the delta slope leads to progradation of the delta, assuming the sediment accumulates at a higher rate than it is removed (Coleman 1976, Bhattacharya and Walker 1992). This leads to the characteristic coarsening-up stratigraphy observed within delta slope cores (Davis 1994).

The prodelta, located at the base of the delta slope, is where the finer material settles out of suspension. Sediment is deposited laterally and with minimal lithological variation (Sutter 1994). Due to the slow rate of deposition, the prodelta is often extensively bioturbated by the burrowing activity of benthonic organisms.

3.4.3: Holocene evolution of deltas

Modern deltas are geologically young features, ranging from thousands to hundreds of years old. Sea level changes dramatically affect the evolution of deltas as they evolve at the interface of fluvial tributaries and receiving basins such as estuaries (Davis 1994). During the last glacial period sea level in New South Wales was 120 m to 130 m below

present (Hopley and Thom 1983, Chappell 1987, Ferland *et al*. 1995, Lambeck and Chappell 2001 and Murray-Wallace *et al.* 2005). This resulted in the late Pleistocene (OI5e) high-stand deltas being abandoned and entrenched by the rivers which once supplied them with sediment.

The post-glacial marine transgression commenced approximately 18 ka (Ferland *et al.* 1995) and resulted in the coastline returning to, or close to, its original OI5e position *c.a.* 7.9 ka to 7.7 ka (Sloss *et al.* 2007; Lewis *et al.* in press). The rapid rate at which sea level rose, approximately 12-13 mm/year based on the low-stand level and the 10,000 years for sea level to reach its current level, is likely to have drowned many of the worlds deltas. However, some evolutionary studies (e.g. Nichol *et al.* 1997) have found evidence which suggests some deltas were able to regress as sea level flooded the antecedent Pleistocene land surface. As the rate of rise slowed and stabilised during the mid to late Holocene delta progradation was able to recommence (Nichol *et al.* 1997). It is important to note many of the larger continental/mega deltas found around the world, such as the Mississippi delta, have developed on ancestral deltas built up over millions of years (Coleman 1976, Coleman 1988, Davis 1994).

The Holocene evolution of deltas is attributed to the interaction of autocyclic and allocyclic processes. Autocyclic processes are an integral part of the deltaic system as opposed to allocyclic processes which are external to the deltaic system and, therefore, act independent to it (Sutter 1994). Channel switching is one of the most common autocyclic processes which occur within a delta. Allocyclic processes include climate change and sea level fluctuations. Coleman and Wright (1975) and Coleman (1976) comparison of 400 parameters indicated only a small number of autocyclic and allocyclic processes/factors were significant in the morphological evolution of deltas. These processes/factors include climate both within the catchment area and receiving basin, catchment area relief, waterway discharge, sediment yield, waterway mouth processes, marine processes (waves, currents and tides), wind, continental shelf slope, tectonics and geometry of the receiving basin. The interrelationship of the major processes/factors is illustrated in Figure 3.12. However, it must be noted the

processes/factors identified and described by Coleman and Wright (1975) and Coleman (1976) are derived from studies of larger continental scale deltas. The applicability of some of the identified factors, such as the continental shelf-slope and the five receiving basin geometries, do not necessarily apply to smaller bay-head deltas prograding into a wave dominated estuaries, such as Lake Illawarra.

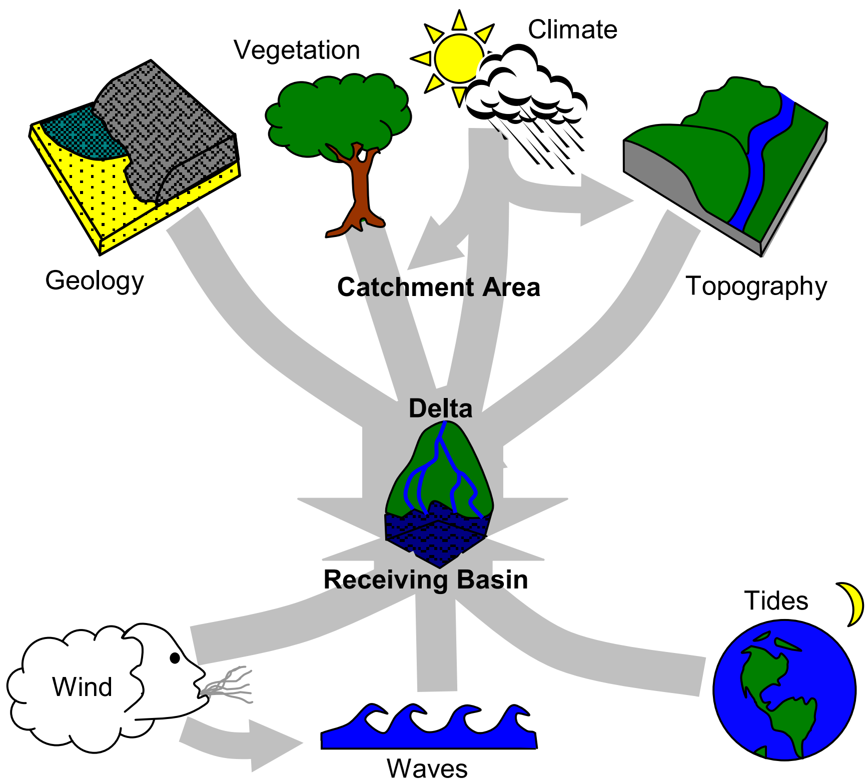


Figure 3.12: *The interrelationship of the major processes/factors which affect delta morphology (after Coleman and Wright 1975, Coleman 1976, Coleman 1980).*

3.4.3.1: Climate

Climatic variation is probably the most significant natural factor affecting delta morphology. Within the catchment area climatic conditions influence vegetation type and quantity, soil type and stability, weathering both mechanical and chemical, the amount of runoff and the amount of evaporation (Coleman and Wright 1975, Coleman and Prior 1980, 1984a, Hopley 2004). All of these inter-related factors affect the amount and type of sediment which is delivered to the delta. The affect of climate within the deltaic plains differs to the roll it plays in the catchment area. Climate conditions

associated with the deltaic plains affect the type/composition of subaerial and subaqueous deposits, the size and strength of delta shaping waves, the vegetation, and the production of evaporites and chemical precipitates (Coleman and Wright 1975).

3.4.3.2: Catchment relief, river discharge and sediment yield

Coleman and Wright (1975) and Coleman (1976) and Coleman (1984a) noted a strong relationship between catchment area relief and the net loss of sediment. The relief of a catchment area directly controls vegetation cover, stream power, sediment size and sediment sorting. Based on this, it can be stated that deltas associated with high relief catchments are likely to be larger and coarser grained whereas deltas associated with low relief catchments are likely to be smaller and finer grained.

It is generally accepted rivers with higher annual discharges generally transport and deposit larger amounts of sediment on an annual basis (Coleman and Wright 1975, Coleman 1976). However, it is important to note the annual discharge of a given river in a natural state is highly dependent upon the regional climatic conditions. Less frequent channel avulsion is likely to occur in rivers and deltas which are exposed to regular discharge patterns, as the channels are able to become hydrologically stable. In contrast to this, regions which experience significant temporal variations in discharge volumes have waterways and deltas that are often unable to adjust rapidly, resulting in the channels constantly avulsing (Coleman and Prior 1980, 1984a). Furthermore, rivers and deltas with significant temporal variations in discharge, regardless of their total annual discharge, are often characterised by coarser and more poorly sorted sediments (Coleman and Wright 1975). Systems with higher discharge volumes can often overcome the processes/factors which are operating in the receiving basin (Coleman and Wright 1975).

Approximately 95% of sediment transported to the ocean is via river channels with much of the material deposited in deltaic environments (Coleman and Wright 1975, Syvitski *et al.* 2003). Sediment yield within a given catchment is determined by many factors including, but not limited to, the size of the catchment area, climatic conditions,

catchment area relief, discharge, vegetation cover, soil types and soil erodability (Coleman and Wright 1975, Fanetti and Vezzoli 2007, Hinderer 2012). Due to the complex spatial and temporal interactions between some or all of these factors accurately quantifying catchment sediment yield, and ultimately sediment available for deposition at the delta front, is complex. Since the late 1970's empirical models have been developed to calculate the sediment yield (e.g. Universal Soil Loss Equation) and the volume of sediment potentially transported downstream to the sediment sink. However, the developed models often contain errors due to data gaps, inbuilt assumptions and the inability to capture all variables (Trimble 1999, Fanetti and Vezzoli 2007, Hinderer 2012).

A complicating factor in the establishment of sediment yield using the simplistic empirical models is a single sink is assumed, typically the receiving basin (Hinderer 2012). However, in natural systems multiple sediment sinks and sources occur along a given routing path (Allen 1997). This process is referred to as sediment cascading. Based on this, there is scope for the theoretical sediment which reaches the delta front, both in a positive and negative way, to differ from what actually reaches the delta front or associated floodplains. For example, Trimble (1999) compared the rate of vertical accretion of floodplains in a lower valley between the 1930's and the period 1975 to 1993 and found the accretion rate for the later period was approximately 3-4% of what was calculated for the 1930's. This result was unexpected as previous projections indicated sediment yields may have increased. Trimble (1999) attributed much of the observed variation to the formation of low lying vegetated floodplains which acted as sediment sinks in the upper reaches.

Not withstanding the above, Coleman and Wright (1975), Reading and Collinson (1996), Haslett (2000) and Liquete *et al.* (2005), among others, have indicated a strong relationship exists between sediment yield and delta size (Table 3.1). Specifically, the table indicates deltas evolving at the mouths of sediment laden waterways with large catchments typically have more extensive plains. It is important to note these findings are based on large continental scale deltas. However, this relationship appears to hold

true for deltas such as the Hawkesbury River delta (Nichol *et al.* 1997) and Shoalhaven River delta (Umitsu *et al.* 2001) where abundant sediment supply derived from large catchment areas has enabled the deltas to prograde rapidly, infilling their respective receiving basins. In smaller catchments the reduced progradation rate has lead to large portions of the estuaries into which they are prograding unfilled e.g. Wandandian Creek Hopley and Jones (2006). As these smaller bay-head deltas are prograding into relatively shallow and sheltered waterways, the progradation rate is likely to reflect reduced sediment yields from the smaller catchments.

Table 3.1: *Demonstrates the relationship between sediment yield and delta size for a select sample of continental scale deltas (Reading and Collinson 1996; Haslett 2000).*

Delta	Sediment Load/Yield (10^6 tons yr^{-1})	Delta Plain Area (km^2)
Ganges-Brahmaputra	1,670	105,641
Yangtze	478	66,669
Po	71.7	13,398
São Francisco	6	734

3.4.3.3: River mouth processes

The interaction between river water and the waters of the receiving basin exert significant control over the deposition of sediment within the deltaic environment. The interaction results in the expansion and diffusion of the outflowing water and a reduction in its ability to transport sediment. Three distinct interactions are recognised based on the density differences between the two water bodies. Homopycnal flows occur when density contrasts between the two water bodies is minimal, such as in lagoonal environments (Figure 3.13). Homopycnal flows often result in intense mixing of the waters and the rapid deposition of transported sediment, particularly the coarser grained bedload (Sutter 1994, Reading and Collinson 1996, Haslett 2000). These flow conditions result in the formation of deltas characterised by low angle topset and bottomset beds and steeply dipping foreset beds. Hyperpycnal flows are often generated by flood events. In this situation the outflowing water is denser than the

water within the receiving basin (Figure 3.13). Sedimentation occurs more distal to the waterways mouth as the incoming water flows as a density current beneath the basin waters (Sutter 1994, Reading and Collinson 1996, Haslett 2000). Due to the distal deposition of this sediment progradation of the delta is inhibited (Reading and Collinson 1996). Hypopycnal conditions occur predominantly when the receiving basin is relatively saline, such as in a saline lake like Lake Illawarra, resulting in the less dense outflowing water extending as a buoyant plume (Figure 3.13; Sutter 1994, Reading and Collinson 1996, Haslett 2000). Typically the coarser material is deposited close to the shoreline with the fine sediment transported and deposited offshore.

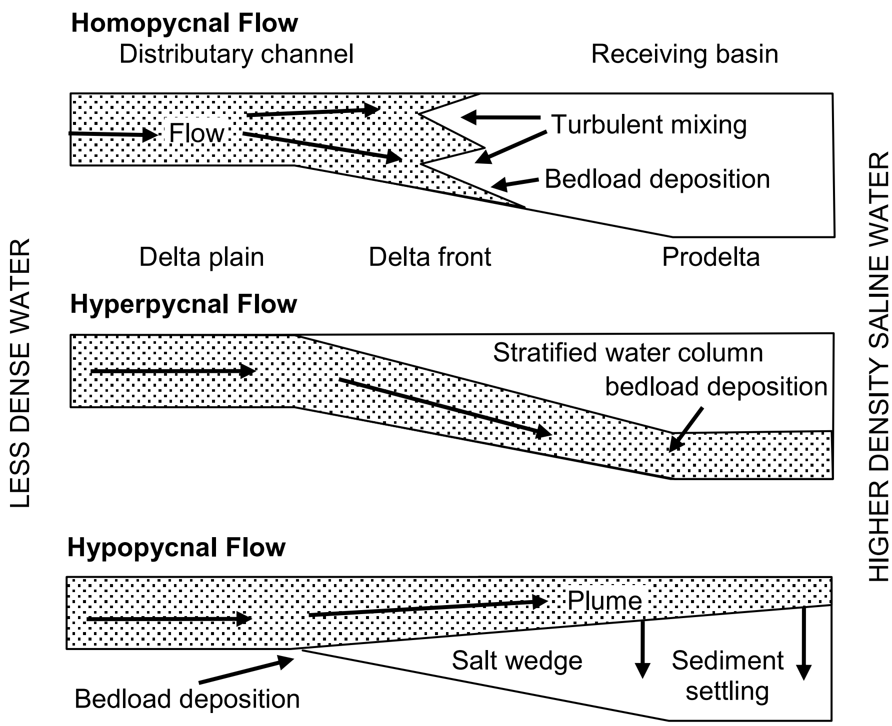


Figure 3.13: *Delta hydrodynamics based on density differences between outflowing water and the receiving basin (after Haslett 2000).*

Three major types of channel mouths and bars can be recognised. The configuration of the channel mouths and bars can be attributed to the differing ratios of inertia, friction and buoyancy between the inflowing sediment laden water and the receiving basin which occur at the mouths of waterways. Inertia-dominated channel mouths develop where steep foreset beds enable both the outflowing water and the receiving basin water to mix adequately in both horizontal and vertical space (Sutter 1994, Reading and

Collinson 1996). Radial lunate bars proximal to the mouth of the channel are characteristic features of inertia-dominated systems (Figure 3.14a). Friction-dominated mouths occur in shallow water where the frictional interaction between the outflowing water and the sediment interface results in the deposition of midground bars (Figure 3.14b). The triangular shape of the bars is the result of the incoming waters only being able to expand horizontally (Sutter 1994, Reading and Collinson 1996). The formation of these midground bars results in channel bifurcation and leads to the development of classical birdsfoot styled deltas, such as the Mississippi. When the receiving basin is relatively deep and the outflowing water is less dense, buoyancy-dominant channel mouths occur. Due to the increased depth of water the affect of friction is significantly reduced which enables the outflowing water to expand as a narrow plume (Sutter 1994, Reading and Collinson 1996). Deltas developed in these conditions are characterised by elongate subaqueous levees which extend considerable distances into the receiving basin (Figure 3.13c). However, is important to note in reality channel mouths often display a combination of mouth and bar types.

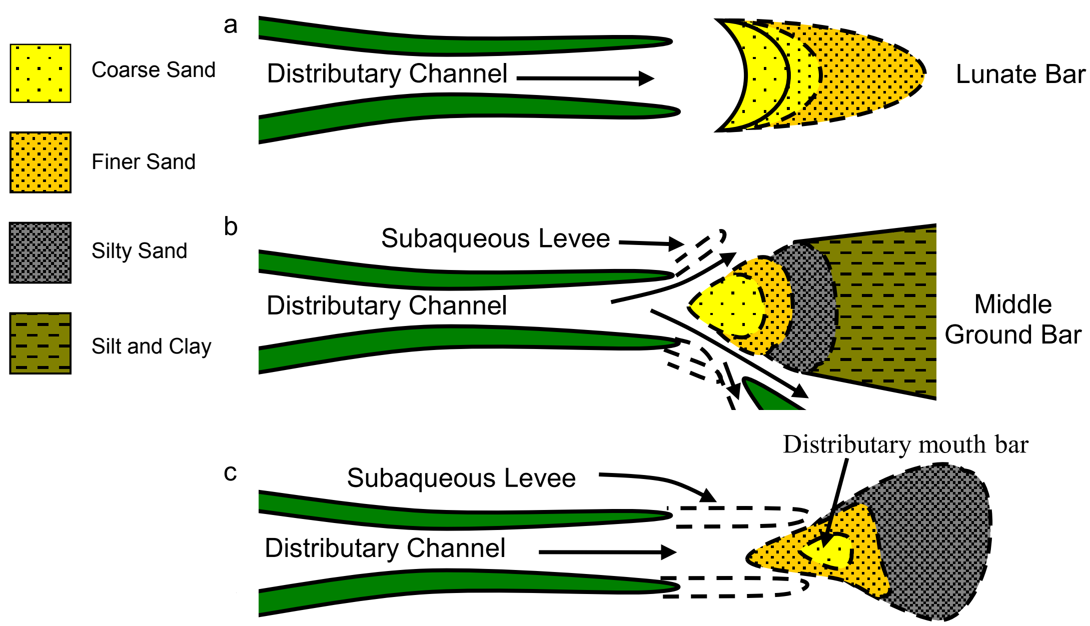


Figure 3.14: *Idealised characteristics of waterway mouths and bars: (a) inertia-dominated (b) friction-dominated (c) hypopycnal or buoyancy-dominated (after Sutter 1994).*

The three main types of distributary channel morphologies identified in deltaic environments include bifurcating (Figure 3.15a), rejoining (Figure 3.15b) and single (Figure 3.15c) channels. Deltas with bifurcated channels have multiple closely spaced channel mouths with a conjoined delta plain. Coleman and Wright (1975) noted bifurcated channels develop in areas associated with high rates of subsidence, low wave energy, small tidal range, low offshore slope and finer grained sediment. Examples of these bifurcated deltas include the Mississippi and the Volga. Rejoining channel morphology has a web like appearance attributable to the complex rejoining of channel bifurcations. The Niger delta's distributary channels are examples of rejoining channel morphology. Rejoining channel morphology develops in areas with large tidal ranges, moderate wave energy and steep offshore slopes and where river outflows fluctuate (Coleman and Wright 1975). The final channel type is quite simple as it consists of minimal channels originating close to a common point at the delta head. Common features associated with these types of deltas include lunate bars, high wave action, large tidal ranges, steep offshore slopes and long linear sand bodies (Coleman and Wright 1975). The Mekong and São Francisco deltas display this type of channel morphology.

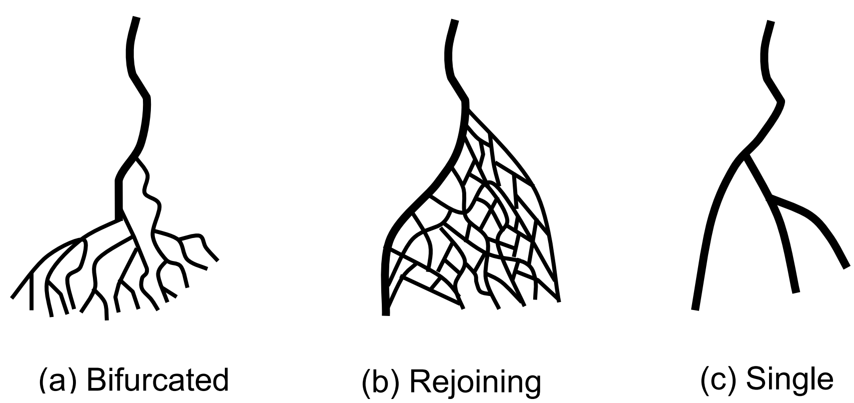


Figure 3.15: *Delta distributary channel morphologies (after Coleman and Wright 1975).*

3.4.3.4: Marine processes: waves, currents and tides

Coleman and Wright (1975), Coleman (1976), Coleman (1984a) and Reading and Collinson (1996) noted that wave direction and strength impacts on coastline

development particularly. The introduction of sediment to the coast by large rivers often disturbs the balance between the deltas subaqueous topography (bathymetry) and the wave regime. The net effect is that wave-dominated deltas generally have a diverse range of sand body configurations. In areas where near shore wave power is high, deltaic sediments are typically well-sorted sands with a high permeability (Coleman and Wright 1975). Furthermore, the mineralogy of the river sand is often altered as it mixes with the oceanic sediments and in some instances only marine sediments are present. In contrast to this Coleman and Wright (1975) noted that deltaic sediments deposited in areas with low near shore wave power are often poorly-sorted with low permeabilities.

Longshore or littoral currents in the near shore zone are driven by several factors including, but not limited to, waves, tides and wind (Coleman and Wright 1975, Reading and Collinson 1996). These currents control longshore sediment transportation. The relative strengths of these currents affect the overall morphology of the delta and its associated sand bodies. In systems where longshore currents are strong sediment transported to the delta is redirected in the direction of the current to form spits oriented parallel to the coast line (Coleman and Wright 1975, Davis 1994). In contrast to this, systems with weak longshore currents typically build symmetrical capsulate lobes (Davis 1994).

The influence of tides on delta morphology is mostly evident in macrotidal environments, such as in northern Australia. Deltas developing in these environments are characterised by pronounced landward tapering of the river mouth (e.g. Ord River delta; Coleman 1976, Coleman and Prior 1980, 1984b). Flood-tide flow velocities and turbulence are at their greatest at mid tide and result in the entrainment of sediment. This sediment is then transported inland on the rising tide prior to deposition in crevasse splays and overbank splays (Coleman and Wright 1975, Davis 1994). Like the flood tide, ebb tides are at their strongest during mid tide. This means sediments deposited on the splays during the flood tide are not re-suspended and transported seaward. However, some bank and channel sediment is entrained prior to its deposition on the mouth bar when the velocity and turbulence of the tide decreases (Coleman and

Wright 1975). As a result of these depositional processes sand bodies developed in macrotidal environments are typically elongated and form parallel to the river banks (Coleman 1976, 1980, Davis 1996). Furthermore, during the slack water stage sediment can be deposited to form sandy bars, such as point and mid-ground bars. Deltaic sedimentary processes in microtidal areas differ from those described above. Due to the limited tidal exchange, the majority of the suspended and bedload sediment is kept mobile and does not accumulate in the distributary channel(s).

Marine processes such as those discussed above have the capacity to influence the evolution of bay-head deltas prograding into wave dominated barrier estuaries/ICOLs, such as Lake Illawarra. The influence of these processes is likely to be greatest during the early phases of barrier development i.e. stages 1a and 2b Figure 3.7. Once the barrier has developed the influence of wave action, littoral currents and tides is significantly reduced. However, as the deltas prograde infilling the receiving basin, stage 4b Figure 3.7, a direct connection between the delta and the ocean is re-established. The establishment of this connection will increase the influences of marine processes have on future delta evolution.

3.4.3.5: Wind

Wind conditions can exert significant controls on the morphology of deltas, particularly deltas with low lying subaerial floodplains. Some of the processes which occur in response to wind include the following:

- generation of longshore currents;
- generation of wind waves; and
- aeolian transport (Coleman and Wright 1975, Coleman and Prior, 1980, Reading and Collinson 1996).

As longshore currents have been previously described, in section 3.4.3.6, they will not be rediscussed.

Wind waves are generated by friction as wind blows over water. The height and period of wind waves generated is affected by the depth of the water, wind speed and the

length of time the wind acts on the water's surface. Wandandian Creek delta, St Georges Basin (Hopley and Jones 2006) is an example of a bay-head delta, within a wave dominated estuary, where wind waves have influenced the morphology of the delta lobe.

3.4.3.6: Continental shelf-slope

Coleman and Wright (1975) and Coleman (1980) noted that continental shelf-slope exerts a significant control over delta development where the shelf-slope gradient is relatively low (0.003º to 0.480º). The shelf-slope's primary controlling factor is related to the power of the waves reaching the shore line. On lower gradient slopes the shallower water reduces the wave strength and thus promotes increased progradation rates as sediment reworking is minimised. In addition to controlling wave power, shelf-slope gradient can influence distributary patterns. Coleman and Wright (1975) observed three main patterns. Firstly, in areas with very low slopes, low wave power and in a microtidal environment the deltas distributary patterns consisted of many lobes derived from bifurcated channel switching. The Mississippi Delta is an example of this type. Channel switching associated with the second pattern occurs upstream of the channel mouth and consists of major channel abandonment and the formation of a new channel. This pattern is observed in areas with shelf-slopes in the vicinity of 0.089º, such as the Bay of Bengal (Ganges-Brahmaputra Delta). The final pattern Coleman and Wright (1975) described is referred to as alternate channel extension. The Danube Delta is a typical example of this form of distributary pattern. In this case several channels are operational; however, it is generally only one which transports significant quantities of sediment. As a result of this, one channel progrades rapidly whilst the others remain relatively stable and often develop beach ridges. When the hydraulic gradient of the rapidly prograding channel decreases, the sediment load will transfer to one of the other channels resulting in it prograding. Despite what has been described above, processes associated with the continental shelf slope are unlikely to play a significant role in the evolution of the Macquarie Rivulet and Mullet/Hooka Creek deltas. This is attributable to the fact that the deltas are currently prograding into a sheltered barrier estuary where the bathymetric shape is independent of the shelf slope.

3.4.3.7: Receiving basin

Both the tectonic stability and geometry of the receiving basin can influence the rate and morphology of prograding deltas. Progradation of deltas into rapidly subsiding areas results in pronounced thickening of deltaic sands (Coleman and Wright 1975). Furthermore, basin subsidence can result in lobe stacking as is observed in the Mississippi delta (Coleman and Wright 1975). Coleman and Wright (1975) and Coleman (1976, 1980) recognised five receiving basin geometries. The first basin described is essentially an open narrow trough between land masses, such as the Sea of Japan and Straits of Malacca. In this situation sediment is supplied to the basin from both of the landmasses. Due to the basin being relatively narrow, tidal currents are typically strong. These strong currents rework the deltaic sediments into shore-aligned spits. Narrow U-shaped basins, such as the Bay of Bengal and Persian Gulf, are the second type identified and described by Coleman and Wright (1975). In this instance, deltas are characterised by large linear tide aligned bars at the mouth of the river. The Niger and Yangtze deltas are examples of the third type of receiving basin and are generally fluvial dominated with large swampy areas within the upper parts of the deltaic plain (Coleman and Wright 1975). This morphology occurs as the main receiving basin is topographically lower, due to downwarping, than the shoreline yet the depositional site is seaward of this point. In these instances the delta progrades onto a tectonically stable platform (Coleman 1976). The São Francisco is an example of a delta prograding into a basin displaying characteristics associated with the fourth type of basin geometry. In this instance the basin is located near an active zone of subsidence within a large oceanic basin. Deltas prograding into these basins are characterised by a morphology indicative of a high wave energy environment (Coleman and Wright 1975). Coleman and Wright (1975) noted in these types of basins where subduction is occurring, the delta morphology differs on either side of the subduction zone. Coleman (1976) noted deltas prograding into type 4 receiving basins will never fill the basin due to the active subsidence. The final receiving basin geometry is characterised by a semi or fully enclosed basin with active and rapid subsidence occurring proximal to one side of the basin, such as the Black Sea and Gulf of Mexico (Coleman and Wright 1975, Coleman

1976). Despite the extensive research conducted by Coleman and Wright (1975) the identified receiving basin geography and tectonics do not adequately reflect the typical receiving basin geometry and tectonic stability associated with ICOLs/barrier estuaries, such as Lake Illawarra. This issue will be addressed in Chapter 10.

3.4.4: Floodplain depositional processes

Floodplains are topographically flat areas lining waterways, composed largely of horizontally bedded unconsolidated sediments deposited by overbank flows from the related waterway (Nanson and Croke 1992, Alexander and Marriott 1999). Nanson and Croke's (1992) literature review, in conjunction with field observations, described six processes which resulted in the development of floodplains. These processes can act independently or together to produce a variety of floodplains. The six processes identified include:

1. lateral point-bar accretion;
2. overbank vertical accretion;
3. braided-channel accretion;
4. oblique accretion;
5. counterpoint accretion; and
6. abandoned-channel accretion.

The lateral accretion of point-bars is often viewed as the primary factor in floodplain development in meandering systems (Figure 3.16). This process involves the progressive deposition of coarser grained sediments on point-bars extending from the convex bank (Dietrich 1987). Deposition of sediment is the result of helical and divergent flows and resulting sheer stress patterns (Nanson and Croke 1992). Accretion of the point-bar in conjunction with the erosion of the opposite bank results in the development of new floodplain as the channel migrates. The laterally accreted point-bar deposits are often overprinted by subsequent overbank sediments. Furthermore, Nanson and Croke (1992) noted the resulting floodplain morphologies can range from relatively flat to others which are steeper and have well developed scroll patterns.

Overbank vertical accretion of a floodplain occurs during periods of flood, when sediment laden water breaches the waterway's banks. Sedimentation occurs in response to the decrease in floodwater turbulence as it spreads across the floodplain (Nanson and Croke 1992, Collinson 1996, Alexander and Marriott 1999). This form of floodplain development is generally associated with low gradient and low power streams which are unable to erode banks and migrate. Levees and crevasse splays are morphological features associated with overbank vertical accretion (Figure 3.16). Levees develop in response to the subaqueous and subaerial vertical accretion of the delta plain parallel to the distributary channel. Crevasse splays are lobes of coarser material which extend finger like from the levees across the floodplain (Collinson 1996).

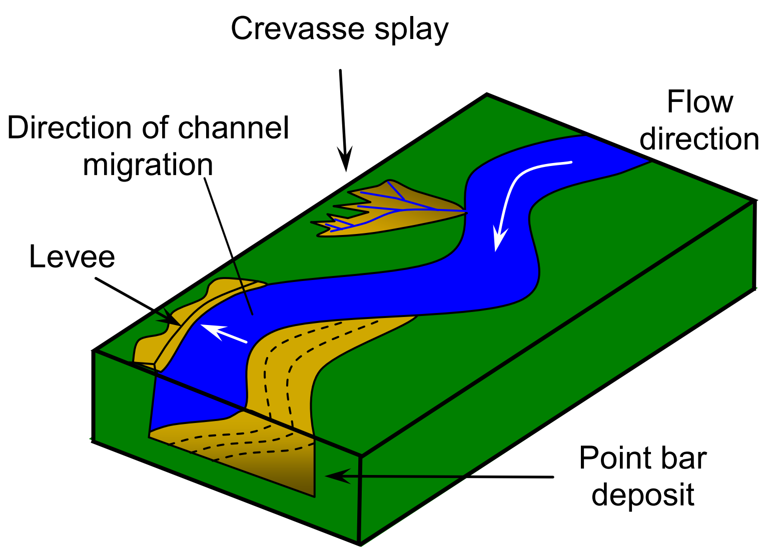


Figure 3.16: *Diagrammatic representation of point bar, crevasse splay and levee deposits associated with a meandering waterway.*

Nanson and Croke (1992) noted there are three processes which can result in floodplain development via the accretion of braided channels. Firstly, the stabilisation of abandoned braided bars and the channel bed due to the migration of the primary channel. Secondly, the formation of elevated braid bars due to continued incision of the channel. Finally, the development of elevated bars during large flood events. However, this form of floodplain development is not applicable to this study.

Brierley and Fryies (1995) and Page *et al.* (2003) defined oblique accretion as the lateral accretion of fine-grained sediment by the progradation of a relatively steep convex bank in association with channel migration. These fine-grained drapes contrast with the coarser-grained gently dipping point bar topography which can underlie them. This form of accretion typically occurs in systems with high suspended sediment loads (Nanson and Croke 1992). Sedimentary deposits associated with this kind of accretion are well developed along many inland Australian rivers and coastal waterways with confined catchments.

Floodplain formation associated with counterpoint accretion occurs in three stages (Nanson and Page 1983). The first stage involves the formation of a zone of separation, attributed to the widening of the channel in conjunction with point bar development. The second stage is initiated once the separation zone is established. This stage is characterised by the deposition of a longitudinal bar in the slack-water area. The final stage is marked by continued sedimentation on the bar resulting in it eventually forming a bench. Sediments associated with these forms of deposits contain a high proportion of fine-grained suspended sediments and organic matter (Nanson and Croke 1992).

Abandoned channel accretion is the final floodplain depositional process described by Nanson and Croke (1992). This is a process by which abandoned channels are infilled with sediment during flood events. The progressive infilling of the abandoned channel results in a fining-upwards stratigraphy. A fining-upward stratigraphy associated with abandoned channel accretion, was by noted Hopley and Jones (2006) in their study of the Wandandian Creek delta, a bay-head delta prograding into St Georges Basin, NSW, a wave dominated estuary similar to Lake Illawarra.

3.5: Previous research into the evolution of bay-head deltas, prograding into broad shallow wave-dominated barrier estuaries on the southeast coast of Australia

The evolution of mega or continental scale deltas, such as the Mississippi, Volga, Po, Rhine and Yellow, is well understood. However, there have been a limited number of studies into the evolution of smaller scale bay-head deltas prograding into broad

shallow wave-dominated estuaries, such as Lake Illawarra, is limited. Furthermore, where these studies have occurred the results are often based on a limited amount of subsurface data and supporting geochronological data. Not withstanding the above mentioned limitations the following section provides an overview of several previous studies into the evolution of bay-head deltas within this tectonic setting. The deltas discussed include Macquarie Rivulet and Mullet/Hooka Creek deltas (Lake Illawarra), Shoalhaven River delta (Shoalhaven River), Tomerong Creek and Wandandian Creek delta (St Georges Basin).

3.5.1: Mullet/Hooka Creek and Macquarie Rivulet delta, Lake Illawarra

In recent years there have been several studies published by Sloss (2001, 2005) and Sloss *et al.* (2004, 2004a, 2005, 2006a) regarding the evolution of Lake Illawarra and its deltas. It is important to note that the Sloss *et al.* papers mentioned above are based on the findings from his Honours research (Sloss 2001) and later PhD research (Sloss 2005). This research was based on the analysis of vibracores, seismic traces and geochronological data. The following section provides an evolutionary summary of the Mullet/Hooka Creek and Macquarie Rivulet delta based on the research undertaken by Sloss (2005).

Sloss (2005) findings regarding the evolution of Mullet Creek and Hooka Creek deltas was based on the analysis of three subaqueous cores two terrestrial cores and interpretation of a west to east seismic trace located proximal to the current opening of Mullet Creek (Figure 3.17, Figure 3.18). Sloss (2005) notes the presence of a marine transgressive sand containing fauna such as *Anadara trapezia* overlying the Pleistocene substrate within the Mullet/Hooka Creek area. Geochronological analysis of Anadara *trapezia* from the sites yielded mid Holocene ages 5000±220 (Hooka Creek) and 5570±240 (Mullet Creek) and were believed to indicate more open marine conditions existed within the estuary until at least this time. The basal transgressive sand unit is inturn overlain by a reduced estuarine mud facies indicating deposition occurred within a calm environment. Sloss (2005) suggested the reduced energy levels within the basin reflected the emergence of the Holocene barrier. Ages obtained from the facies

indicated deposition commenced *ca.* 4.15 ka. Sloss (2005) suggests at least two distinct phases of delta progradation occurred within the Hooka Creek area. However, due to a lack of specimens suitable for dating the ages of these two pulses have been inferred based on dates obtained from the estuarine mud facies. These ages suggest deposition of the basal fluvial pulse occurred post 3.8 ka and the upper pulse occurred post 2.9 ka. The lake of suitable specimens for geochronological analysis within the Mullet Creek fluvial facies prevented the establishment of a precise depositional timeframe. Instead, the depositional age was inferred based on ages obtained from the underlying estuarine mud facies which suggested progradation was occurring by 2.5 ka.

Research undertaken by Sloss (2005) indicated the evolutionary path of Macquarie Rivulet is similar to that of the Mullet and Hooka Creek deltas as illustrated in Figure 3.19 (Sloss 2005). The transgressive marine sand directly overlies the antecedent Pleistocene substrate and forms the basal Holocene unit within the Macquarie Rivulet study area. This unit is then overlain by the westerly thinning cohesive estuarine mud facies. Ages obtained from amino acid racemisation dating of macrofossils such as *Notospisula trigonella,* indicated that facies deposition commenced *ca.* 5 ka within the study area. An age obtained from VC 9 (Figure 3.19) indicates fluvial progradation commenced approximately 2,600 years ago which corresponds well with ages derived from Mullet and Hooka Creek deltas. Sloss (2005) noted the distal portion of the delta is relatively recent with delta progradation occurring in the last 350-400 years.

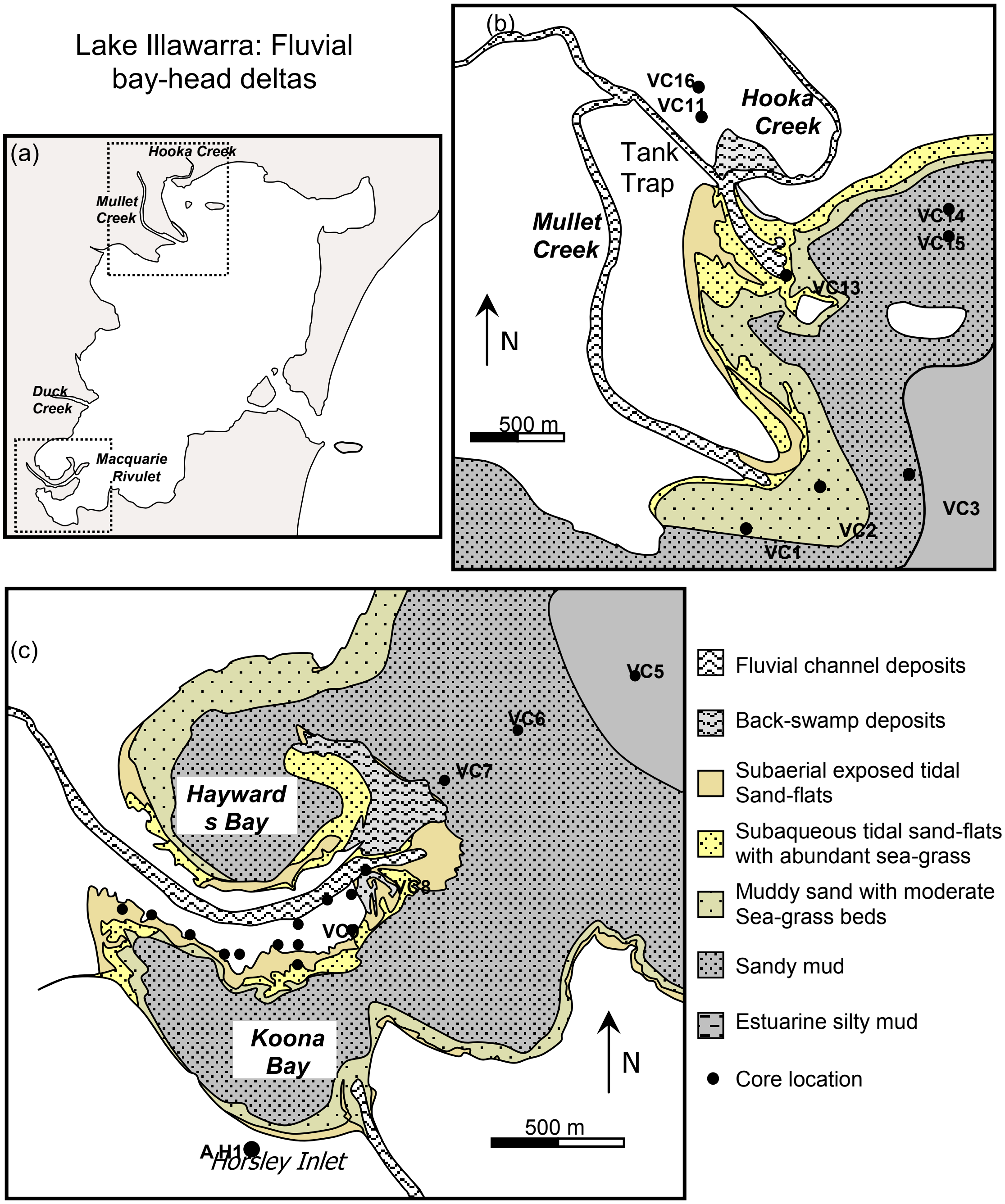


***Figure 3.17**: Facies divisions and core locations for the Hooka and Mullet Creeks region and the Macquarie Rivulet region (Sloss 2005).*

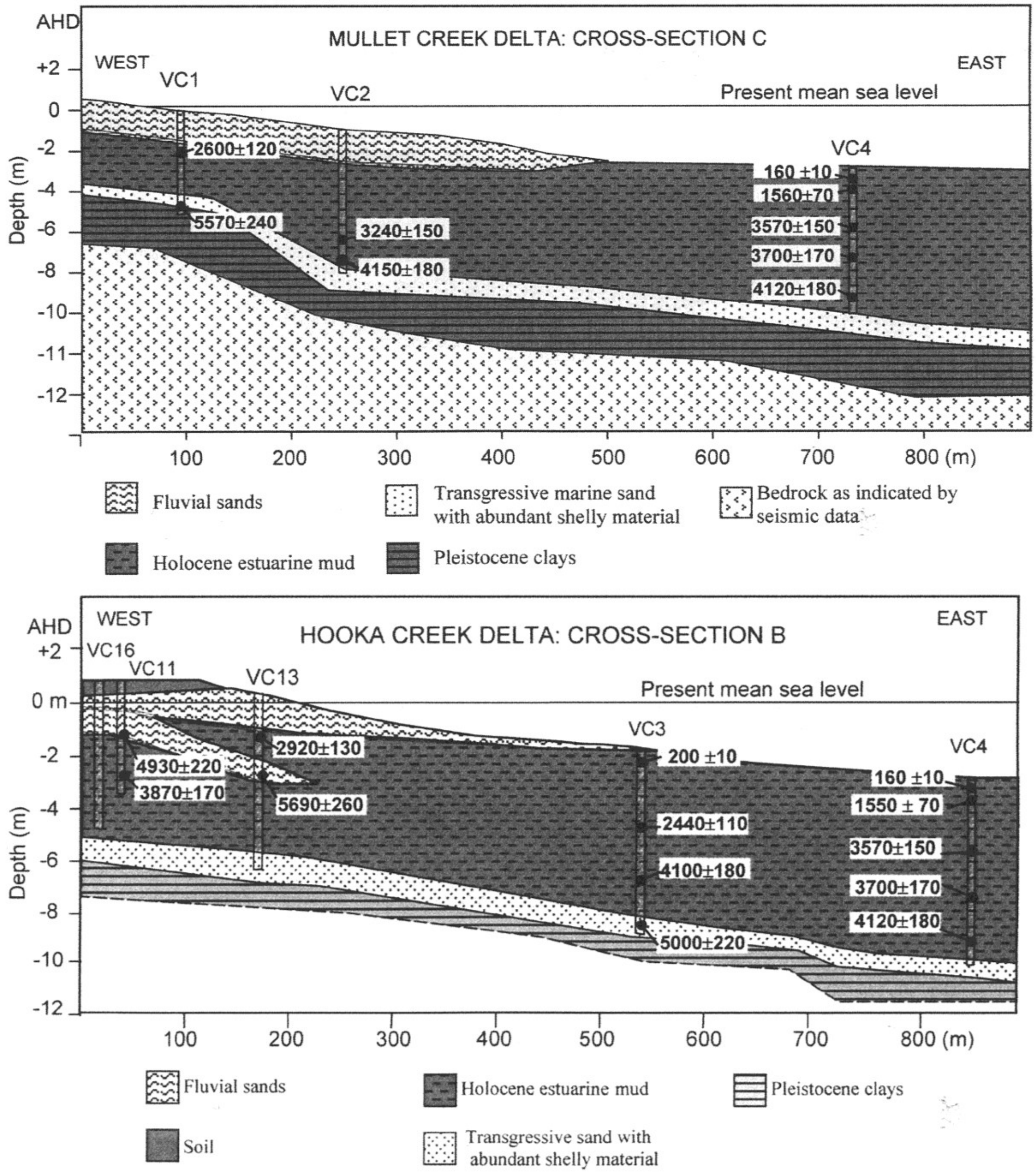


Figure 3.18: *Cross sections developed by Sloss (2005) to illustrate the evolution of Mullet and Hooka Creek deltas. Core locations incorporated into the sections are indicated on Figure 3.17.*

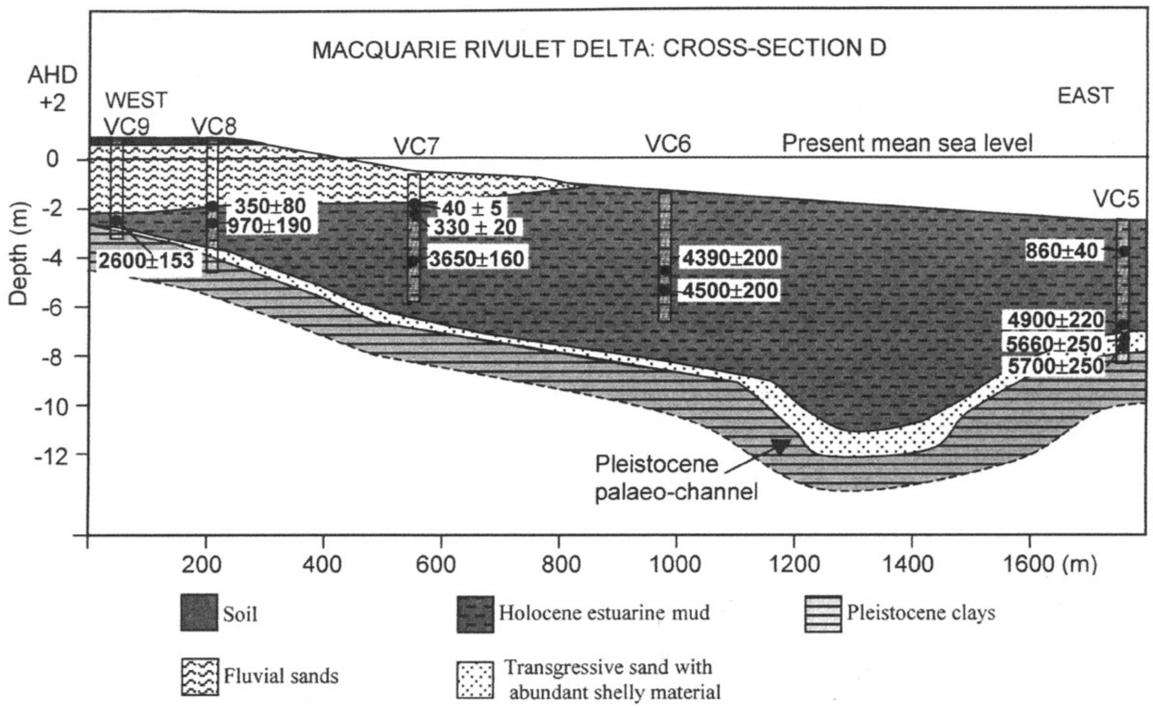


Figure 3.19: *Cross section developed by Sloss (2005) to illustrate the evolution of the Macquarie Rivulet delta. Core locations incorporated into the sections are indicated on Figure 3.17.*

3.5.2: Shoalhaven River delta, Shoalhaven River

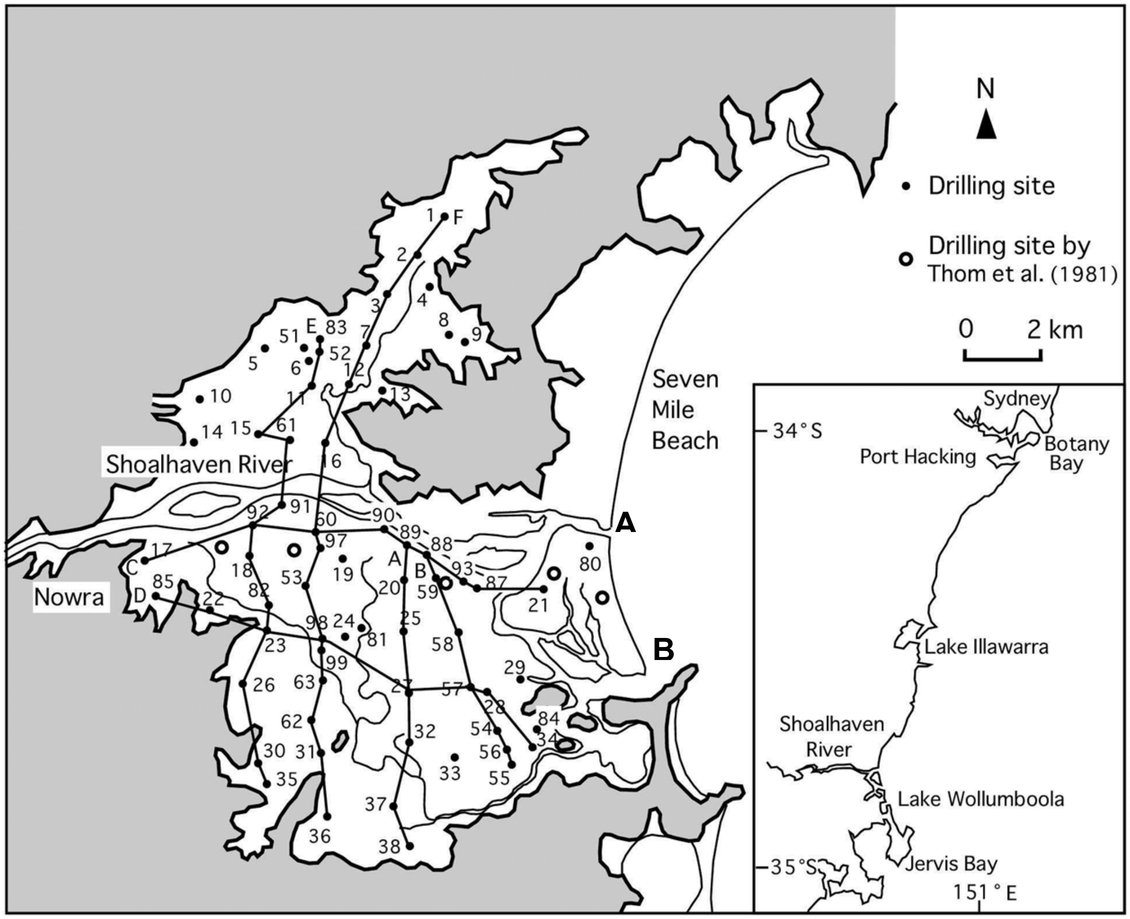
Umitsu *et al.* (2001) built on previously published research (Wright 1970, Roy 1984a, Young *et al.* 1996) established the morphological and sedimentological evolution of the Shoalhaven River deltaic-estuarine plains (Figure 2.1). The study assessed the evolution of the plains based analysis of aerial photographs, an extensive coring program (Figure 3.20) and supported by 39 radio carbon ages along with mollusc and diatom analysis. Umitsu *et al.* (2001) note the inherited morphology of the Pleistocene receiving basin has influenced the morphological evolution of the Shoalhaven River delta throughout the Holocene. Early research published by Wright (1970) indicates fluvial sediments were being deposited on the Seven Mile beach-ridge plain approximately 6,000-6500 years ago. During this period Roy (1984a) suggested the Shoalhaven River flowed in a southeasterly direction with the entrance channel being located proximal to Crookhaven Heads (Figure 3.20). However, later research by Young *et al.* (1996) suggested the river exited north of Crookhaven Heads in the vicinity of Shoalhaven Heads (Figure 3.20).

Furthermore, Young *et al.* (1996) noted Crookhaven and Eelwine Creeks represent crevasse splays. However, Umitsu *et al.* (2001) found no evidence to support Young *et al.* (1996) findings. Instead they have suggested the early evolutionary phase of the Shoalhaven River was consistent with a fluvial dominated birdsfoot delta prograding into a shallow embayment. As the embayment infilled Umitsu *et al.* (2001) noted the lower reach of the Shoalhaven River appears to have meandered with the channel exiting near Crookhaven Heads *ca.* 2 ka. Post this date the river appears to have breached the Holocene barrier in the vicinity of Shoalhaven Heads. At present the Shoalhaven Heads opening is closed with the river discharge flowing through Crookhaven Heads.

3.5.3: Tomerong Creek and Wandandian Creek deltas, St Georges Basin

Tomerong Creek and Wandandian Creek deltas are actively prograding into north eastern and wester limbs of St Georges Basin, approximately 200 km south of Sydney (Figure 2.1, 3.21). Bradshaw (1987) conducted an initial assessment of the Holocene evolution of St Georges Basin. More recently Sloss (2005), Sloss *et al.* (2006a), Hopley (2004) and Hopley and Jones (2006) conducted detailed studies establishing the evolution of the Tomerong Creek and Wandandian Creek deltas respectively.

During the late Pleistocene low-stand, the palaeo-Tomerong and Wandandian Creeks incised into the OIS 5e Pleistocene alluvium and bedrock as they flowed to the late Pleistocene coastline (Bradshaw 1987). Where exposed weathering of the OIS 5e Pleistocene alluvium combined with the presence of vegetation enabled the development of rudimentary soils. These weathered Pleistocene sediments are then overlain by the Holocene sedimentary successions.



F***igure 3.20:*** Map illustrating the drill hole and section locations used to establish the evolution of the Shoalhaven River (Umitsu *et al.* 2001). A= Shoalhaven Heads, B= Crookhaven Heads

As with Lake Illawarra, a marine transgressive sand sheet comprised of clean medium-grained shell-rich sand underlies the Tomerong Creek delta (Figure 3.22, Sloss 2005, Sloss *et al.* 2006a). Coring undertaken by Sloss (2005) and Sloss *et al.* (2006a) indicates this transgressive sheet becomes progressively muddier and eventually lenses out towards the current mouth of Tomerong Creek. Instead, core EB4 (Figure 3.22) indicates that the underling OIS 5e sediments are overlain by estuarine muds. These muds grade in a southerly direction into a thick back barrier muddy sand facies with deposition commencing *ca.* 6 ka. Sedimentary successions associated with the progradation of the Tomerong Creek delta overlay the estuarine muds in the north and the backbarrier muddy sands towards the south of Erowal Bay. These successions are characterised by the deposition of the organic rich prodelta muds which are inturn overlain by the fluvial delta deposits (Figure 3.22). Significantly, these studies do not

provide sufficient detail on the sedimentological characteristics of these two facies to adequately compare them to the facies identified within the Wandandian Creek delta area as discussed below. Furthermore, a lack of material suitable for dating within these facies restricted the ability of Sloss (2005) and Sloss *et al.* (2006a) to directly assign a depositional age for the facies. Despite this the authors indicated the delta progradation commenced *ca.* 2.5 ka based on underlying ages.

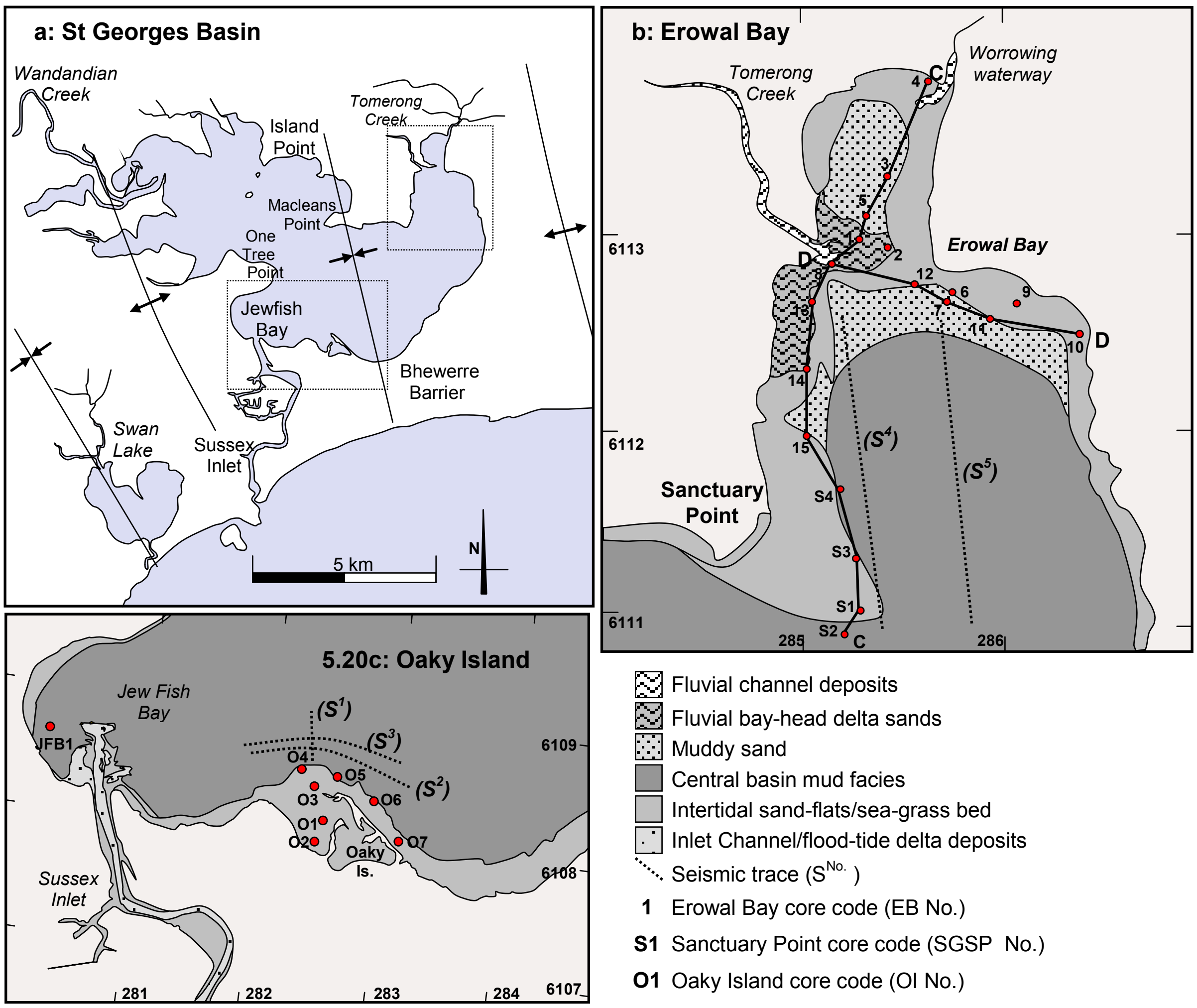


Figure 3.21: *(a) Location map and structural setting of St Georges Basin, and contemporary facies distribution and core locations for (b) Erowal Bay and (c) Oaky Island region (Sloss 2005).*

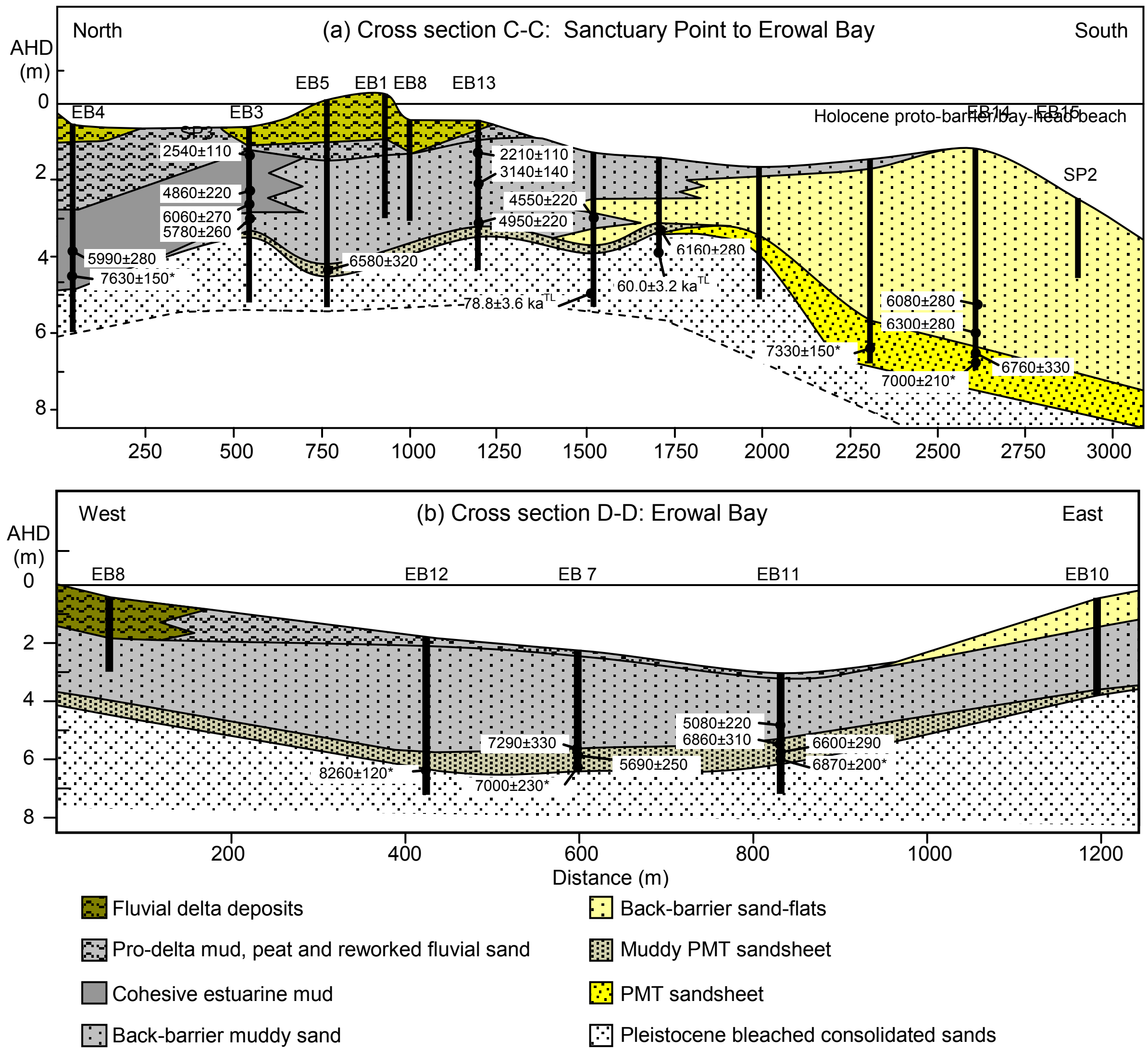


Figure 3.22: *Cross-sections C-C from Sanctuary Point to Erowal Bay in the eastern limb of St Georges Basin showing the facies associations in the Holocene sedimentary succession disconformably overlying a late Pleistocene transgressive sandsheet; and 7(b) cross-section D-D east to west across Erowal Bay showing the facies associations in the Holocene sedimentary succession disconformably overlying late Pleistocene deposits (Sloss 2005).*

Hopley (2004) and Hopley and Jones (2006) identified nine sedimentary facies within the 16 vibracores, two drill holes and two push cores collected during the study (Figure 3.23). The identified facies combined with 14 AAR, AMS and ^{14}C dates enabled the

authors to reconstruct the Holocene evolution of the delta. A summary of their findings is detailed below.

The results of their study indicated the palaeo-Wandandian Creek incised into the Snapper Point Formation and Wandrawandian Siltstone resulting a relatively deep and steep sided palaeochannel at least on its northern margin during the Pleistocene low stand. This palaeochannel was partially infilled with medium-grained fluvial sand, which in some areas has been deeply weathered to form a palaeosol. A notable absence in the Wandandian Creek cores/drill holes was the transgressive sand sheet that was recorded by Bradshaw (1987, 1993) to cover much of St Georges Basin. The absence of this basal facies within the study area was attributed to the presence of a linear bathymetric high, evident in bathymetric survey data, located to the east of the delta. Instead the basal transgressive Holocene mud (prodelta/lagoonal mud facies) directly overlies the mottled light grey silty Pleistocene sediments and fluvial channel deposits; accumulation commenced at approximately 7 ka. The fine-grained nature of the prodelta/lagoonal muds and the absence of the transgressive sand sheet indicates that deposition of the muds occurred in a calm lagoonal environment, which probably developed behind a barrier to the east of the study area.

Initial progradation of the Wandandian Creek delta into the study area commenced at *ca.* 4 ka in the westernmost portion of St Georges Basin with the deposition of the delta-front sandy silt facies. This facies is then overlain by the coarsening-upward prograded sand facies. Progradation into the St Georges Basin area was facilitated by the lowering of regional sea-level by about 1.5 m after 2 ka. As sea-level fell to its present level and the accommodation space further up Wandandian Creek reduced, the rate of delta progradation was likely to have increased.

Located between the delta-front sandy silt facies and the prograded sand facies at depths between -4 m and - 1.7 m (AHD) is the palaeoswamp facies. Of the identified facies the depositional environment of this facies is the most perplexing. However, it is likely that the facies represents the infilling of abandoned channels following avulsion of

the active channel. The sedimentological characteristics and the extensive amounts of organic matter in this facies suggest that it was deposited in a backswamp environment. However, dating of the facies (910±150 yr BP; Table 6.5), combined with regional sea-levels, suggest that the facies would have been deposited subaqueously in water depths similar to or slightly higher than at present.

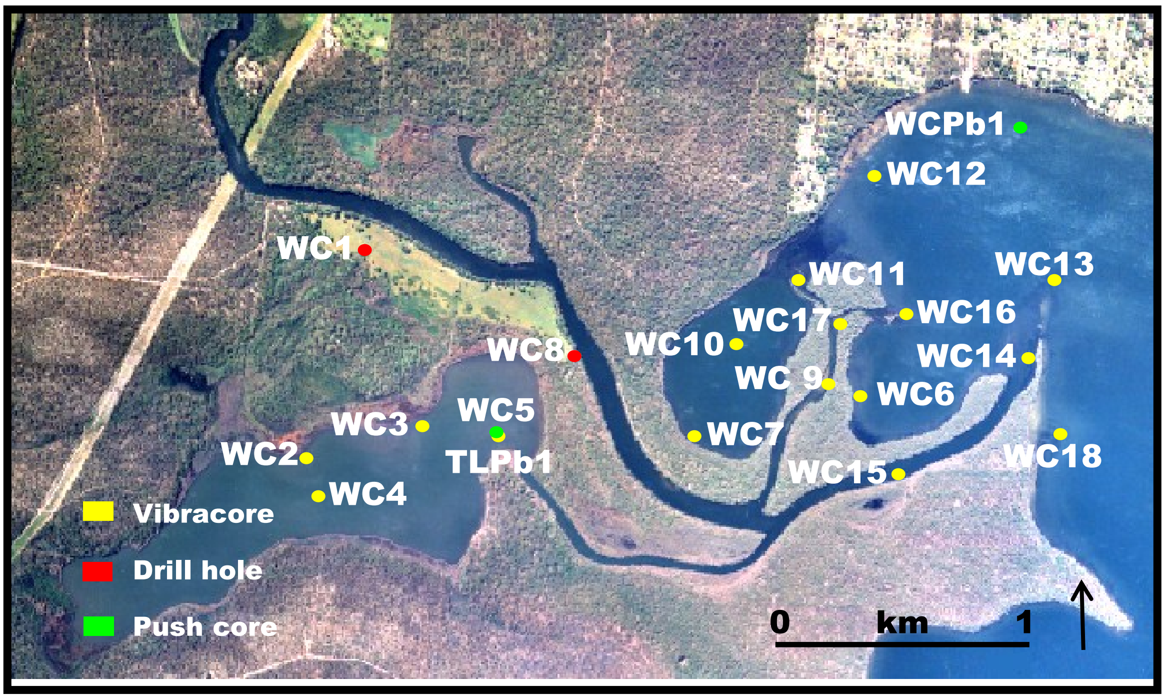


Figure 3.23: *Location of the sixteen vibracores, two drill holes and two push cores (Hopley 2004).*

The upper delta plain overlies the subaqueous units outlined above and is characterised by well developed floodplains, levees, mouth bars and backswamps. Formation of the backswamp features is primarily the result of overbank deposition during flood events. These features are characterised by a fining-upwards stratigraphy.

The anthropogenic modifications of the Wandandian Creek catchment area since European settlement have had minimal affect on sedimentation and progradation rates of the delta. However, dredging activities during the 1970's, proximal to the deltas

bifurcation, would have resulted in a short term reduction in bedload transport restricting delta progradation.

3.5.4: Wapengo Creek delta, Wapengo Lagoon

Wapengo Lagoon, located on the far south coast of N.S.W has evolved within the metasedimentary rocks of the Lachlan Fold Belt (Figure 3.24). The Lagoon is permanently connected to the Tasman Sea via a 2.5 km long sinuous channel. Within the lagoon the marine influenced, central basin and the fluvial zones are readily discernable. The morphological and sedimentological evolution of the lagoon was established by Nichol (1991a) based on the analysis of hammer and vibracores (Figure 3.25).

Nichol (1991a) noted the most predominant feature of the Wapengo delta is the single intertidal levee extending some 350 m into the central basin defining a single predominantly straight channel. Nichol (1991a) suggests early in the evolutionary history the delta was characterised by two channels flowing around a mi-channel island/shoal with the northwestern channel eventually infilling and being abandoned.

Nichol (1991a) noted the evolution of the Wapengo delta is characterised by the infilling and eventual abandonment of a prior channel. The basal facies within the study are characterised by massive beds if silty sand, which Nichol (1991a) suggests were deposited bedload aggradation. This basal unit is intern overlain by coarse sand and gravel units associated with the progradation of the delta through the development of levees and mid-channel shoals/islands. These levee sequences are inturn overlain by the fining upward overbank deposits.

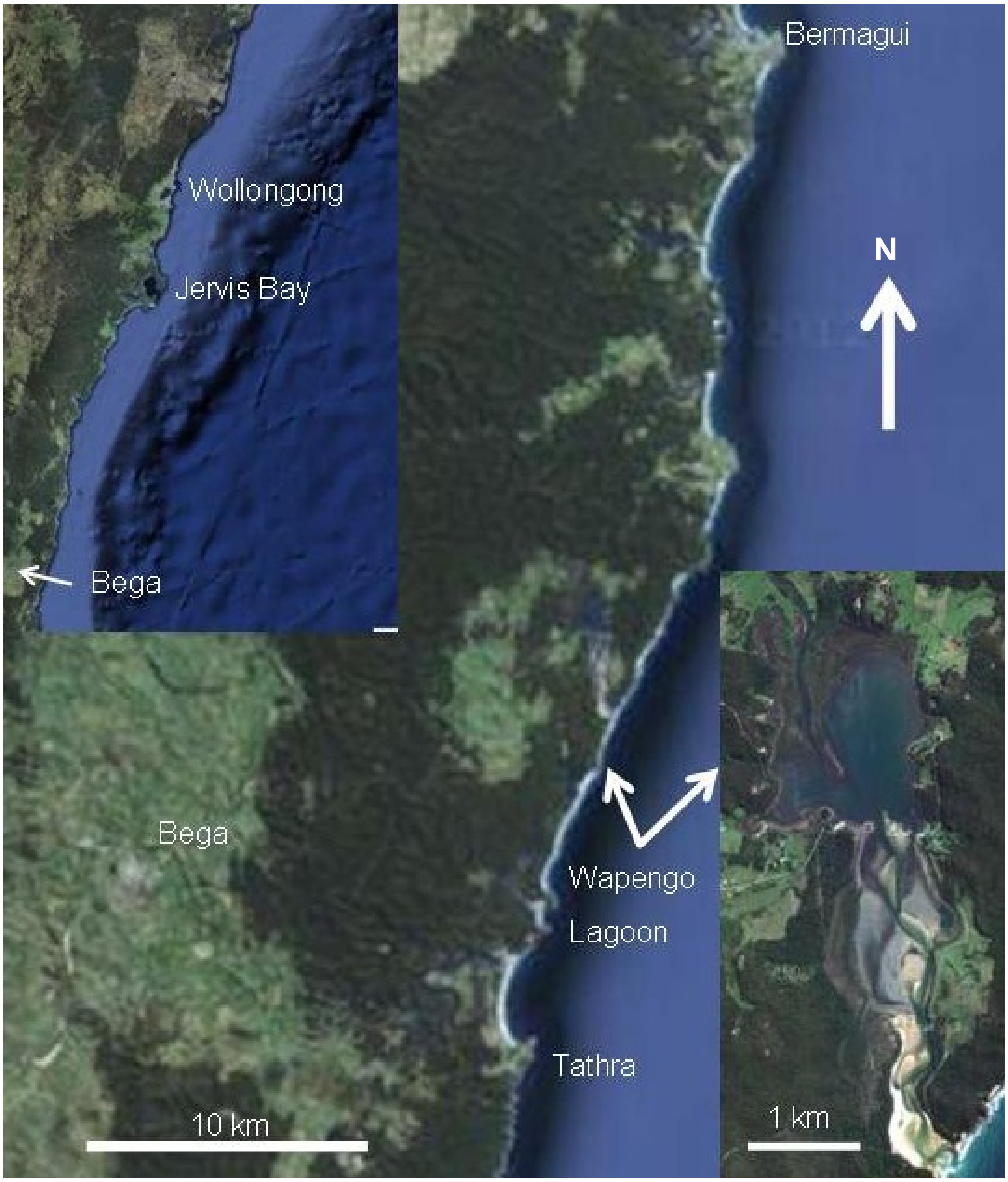


Figure 3.24: *Composite map illustrating the location of Wapengo Lagoon on the far South Coast of NSW and a close up aerial view of the lagoon. Images: Google Earth accessed 2013.*

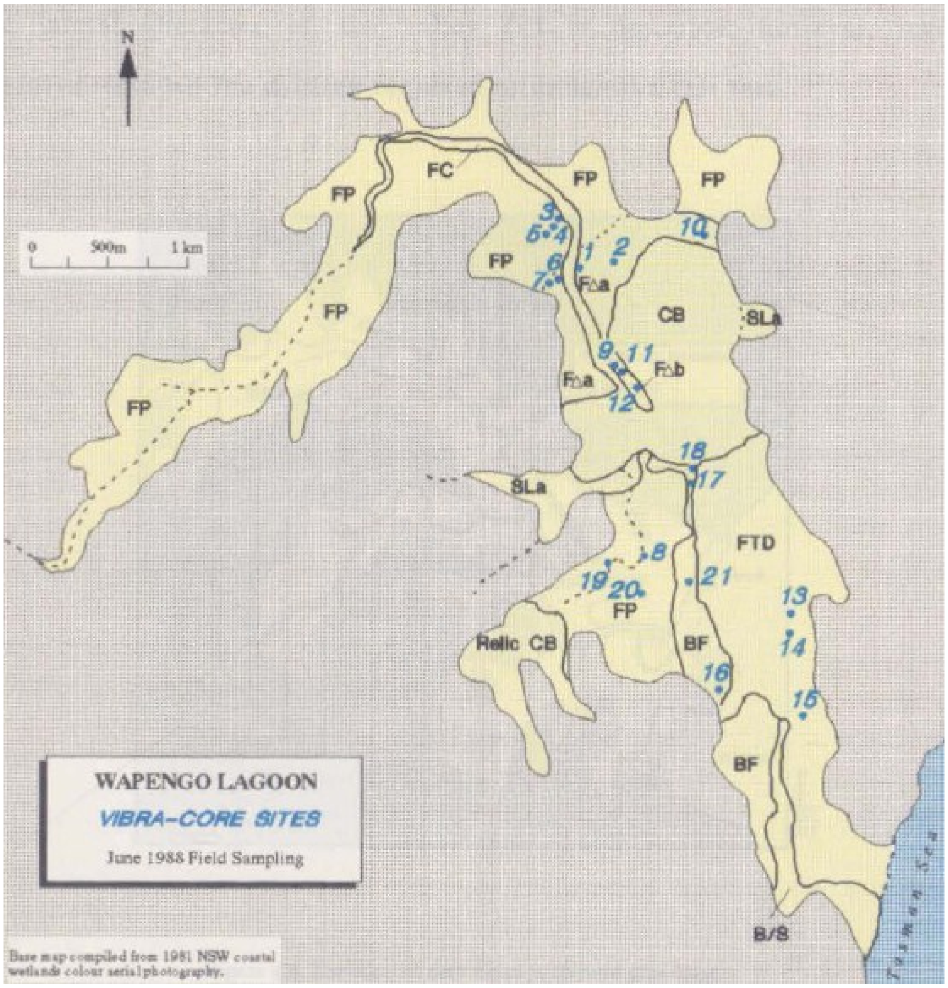


Figure 3.25: *Wapengo Lagoon vibracore locations (Nichol 1991a).*

The sedimentary record within the cores near the current channel lack signs of lateral migration. As such Nichol (1991a) suggested the Wapengo Creek channel position has remained relatively stable. As such the delta has evolved based on vertical accretion followed by overbank depositional processes. Cores taken from locations away from the channel were characterised by well defined sequence of massive coarsening upward beds representing off channel bedload accretion associated with tidal inundation. These beds are overlain by thick fining upward units representing extended periods of low energy deposition away from the main channel.

Other than the bedding described above X-ray analysis of core VC2 (Figure 3.25) revealed thin alternating beds of coarse and fine sediment. The coarse beds have been interpreted to represent periods of high energy deposition associated with the initial

flood pulse and the finer sediments associated with the floods subsidence. Significantly, the sedimentary structures observed within the Wapengo cores lack sedimentary structures associated with tidal influences.

3.5.5: Summary comments regarding the previous studies

The sections above have provided an overview of previous studies which have assessed the evolution of bay-head deltas which have evolved within a wave-dominated barrier estuary environment. In all but one of the studies described above (Wandandian Creek delta; Hopley and Jones 2006) the evolution of the fluvial deltas was established while undertaking a broader assessment of the evolution of the estuary in its entirety. As such the evolutionary history of the deltas presented by the various authors is generally based on a limited number of cores and dates. Thus the limited data restricts the studies capacity to accurately reconstruct the evolution of the deltas.

Specifically, the studies presented above generally describe the sedimentological evolution of the bay-head deltas based on the simplistic facies model of fine grained basal mud overlain by coarsening upward fluvial sand and fining upward floodplain sediment. However, the focused study of the Wandandian Creek delta published by Hopley and Jones (2006) showed that the sedimentological evolution of bay-head deltas is more complex than presented in the other studies. The key difference between the Hopley and Jones (2006) study and the others discussed above is the increased number and spatial distribution of subsurface samples utilised by Hopley and Jones (2004). The increased number and spatial distribution of cores increased the studies chances of intersecting the increased number of facies as intersected by Hopley and Jones (2006). Based on the results of previous studies described above, the high spatial resolution approach adopted in this study provides an excellent opportunity to accurately reflect the complexities of bay-head delta evolution within a wave-dominated barrier estuary.

3.6: Acid sulfate soil

The proximity of the Illawarra Escarpment to the coastline limits the amount of space available to accommodate the Wollongong/Shellharbour regions rapidly expanding

population as discussed in Chapter 2. Due to the land shortage development of and adjacent to the Macquarie Rivulet delta has commenced, there is also the potential for development to occur on the Mullet/Hooka Creek floodplain. The lower reaches of deltaic floodplains are typically underlain by estuarine mud, which contains sulfidic minerals, such as pyrite (White and Melville 1996). When sulfidic minerals remain waterlogged in anoxic conditions, the soil is generally referred to as potential acid sulfate soil. However, if they are exposed, the sulfidic minerals will begin to oxidise and actual acid sulfate soils will form. The resulting acid can then move through groundwater systems.

3.6.1: Formation of acid sulfate soils

Estuarine mud underlies many of the coastal floodplains associated with the progradation of deltas into estuarine basins. Typically the mud contains iron sulfides, primarily in the form of pyrite (White and Melville 1996, Lin *et al.* 2004, Rosicky *et al.* 2004a, b, Wilson 2005). Pyrite formation within the mud is due to bacteria, such as *Desulfovibrio* sp.**,** converting sulfate within the saline water that combines with ferrous iron in the sediments to form iron disulfide under anoxic conditions (Wilson 2005). White and Melville (1996) listed five conditions which are necessary for the formation of sulfides within the sediment:

- a supply of sulfate, generally sourced from sea water;
- decomposed and decomposing organic material within the sediment;
- an adequate source of iron;
- anoxic conditions; and
- tidal flushing to remove soluble reaction products.

Pyrite within the estuarine mud sequences is generally stable unless it is exposed to oxygen. Once exposed the pyrite within the sediment begins to react with oxygen to form sulfuric acid. However, within the mud it is possible to observe partially oxidised products of the reaction. These products include jarosite which takes the form of light yellow mottles in the sediment. Ward *et al.* (2004) noted that pyrite oxidation can occur in the absence of oxygen if Fe^{3+} is present in the soil solution. Furthermore, as the

acidity of the solutions drops below pH 3.5 the rate of oxidation will increase due to the stabilisation of the Fe^{3+}.

White and Melville (1996) noted for every one tonne of completely oxidised pyrite within the mud, approximately 1.6 tonnes of pure sulfuric acid is produced. However, the rate and amount of acid released from the mud is dependent on the neutralising capacity of the sediments in which it was produced. This capacity is often referred to as the acid neutralising capacity or ANC of the sediment. The ANC of the sediment is determined by several factors including but not limited to the carbonate/shelly fraction within the sediment and clay. Gypsum crystals are common precipitates in carbonate rich muds (Figure 3.26). White and Melville (1996) noted that mud with higher clay contents appears to have a greater neutralising capacity than mud with lower clay contents.

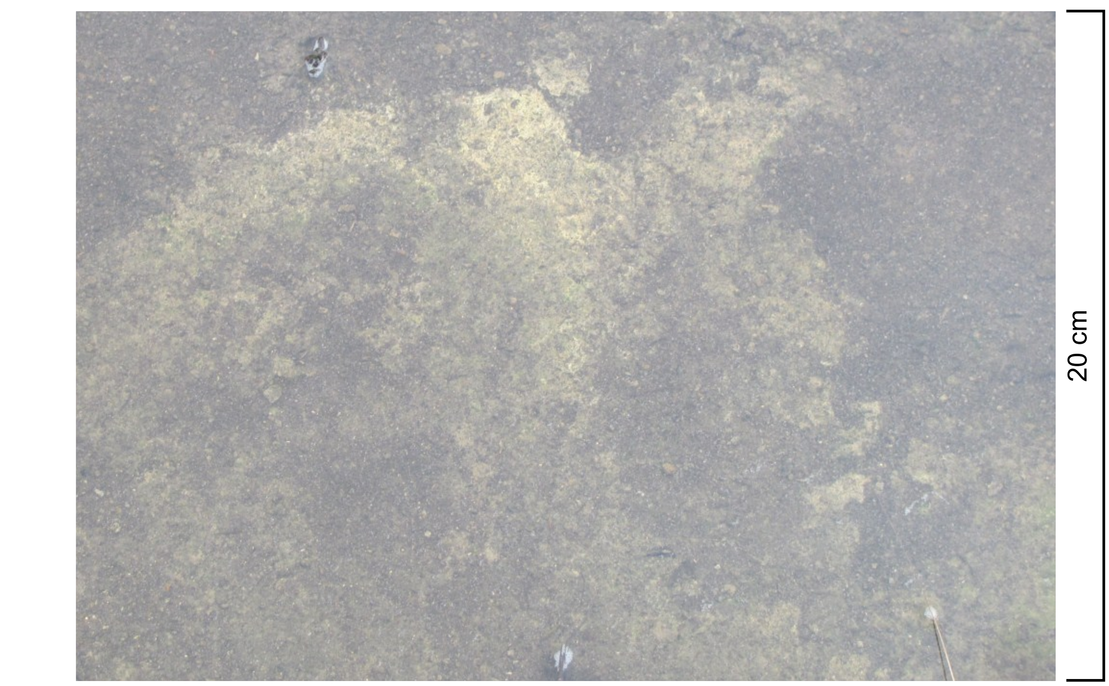


Figure 3.26: *Gypsum precipitate on the base of a natural drainage channel Mullet/Hooka Creek floodplain.*

3.6.2: Impacts of acid sulfate soils and acidic runoff

Acid sulfate soils and the associated acidic runoff have significant environmental and economical consequences. The diverse effects of the acidification of the soil and water can be observed in both the natural aquatic and terrestrial environments along with effects on man made structures.

From an aquatic perspective the acidification of the water can result in the development of fish diseases (red spot disease), fish kills, reduction in the number of fish fry and an overall decline in fish growth rates (White and Melville 1996; Sammut 2000). As the sulfuric acid flows through the ground it is able to dissolve and transport minerals such as iron, aluminium and cadmium (White and Melville 1996; Macdonald *et al.* 2004). Once the acidic ground water enters the main waterway, with a pH >4 the dissolved iron within the water precipitates to form iron floc. The smothering of aquatic plants within the channel is one of the main effects of floc formation (Figure 3.27). The dissolved aluminium within the acidic waters acts as a flocculating agent by clumping sediment particles causing them to sink to the bottom and kill many aquatic plant species. The resulting clear water increases the water temperature, reduces protective cover from predatory birds and animals and increases the development of melanomas in fish (Sammut 2000).

Figure 3.27: *Iron floc smothering aquatic plants in a natural drainage channel Mullet/Hooka Creek floodplain.*

As previously noted, the acidic ground water is able to dissolve and transport various minerals. The dissolution of these minerals makes the elements available to plants in toxic quantities. Typically, the increased acidity and the increased absorption of these elements only permit the growth of acid tolerant plants such as smartweed. In some extreme cases of acidification large areas of land can be scalded (White and Melville 1996, Sammut 2000, Rosicky *et al.* 2004a, b).

Currently, a large proportion of the Mullet/Hooker Creek floodplain, which is identified as a PASS site, is in private ownership and is used for grazing beef cattle (Figure 3.28). Animals grazing in areas where mineral contamination of the pasture is high can absorb and store these elements, especially heavy metals, potentially passing them minerals onto humans when the animal products are consumed, i.e. meat and milk (White and Melville 1996). Although the exact impacts to human health are unclear it has been suggested the following impacts could occur:

- stunted growth, impaired mental development and poor general health;

- heavy metal poisoning;
- dermatitis, caused by contact with contaminated material; and
- respiratory problems due to the sulfur dioxide gas (White and Melville 1996).

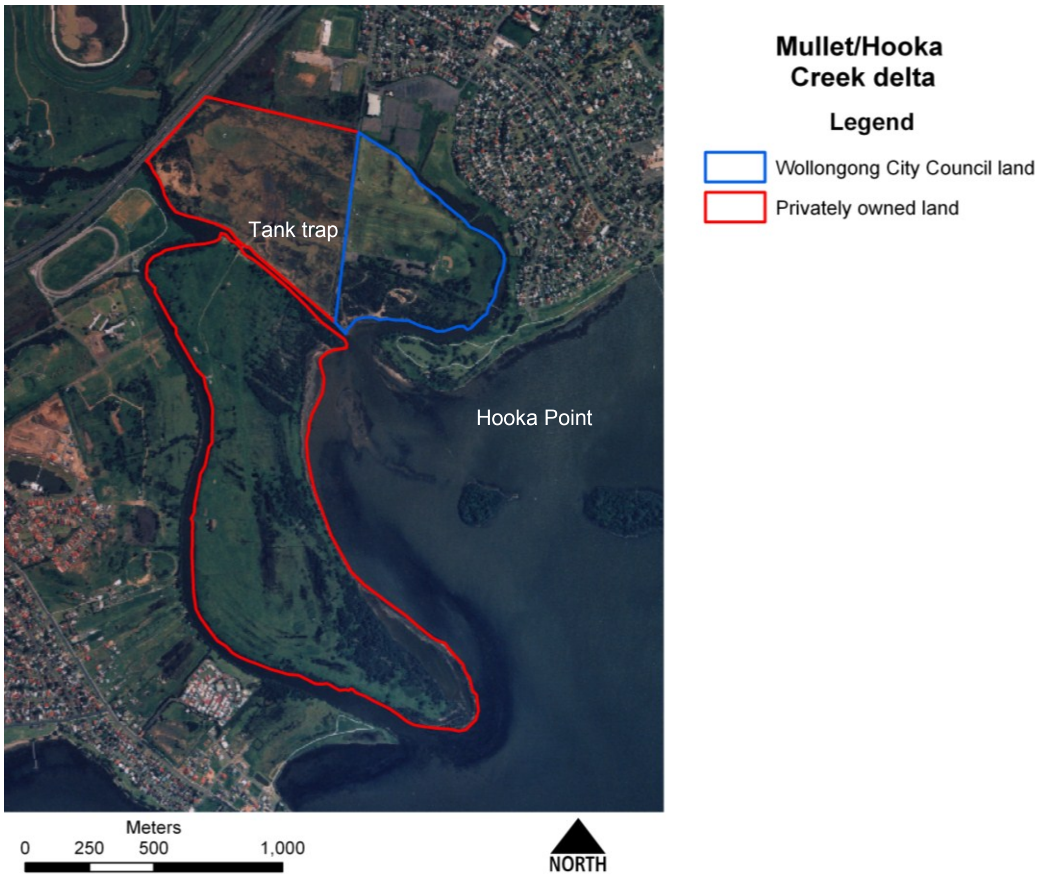


Figure 3.28: *Aerial photograph showing delineating land ownership for the Mullet/Hooka Creek study site. 2006 background image refer to Table 8.1 for details.*

Furthermore, sulfuric acid associated with acid sulfate soils can have significant impacts on man-made structures. The acid has the ability to corrode concrete, iron, steel and some aluminium alloys (Sammut 2000). This poses a potential risk to the existing stormwater and sewerage pipe infrastructure, bridges and jetties and to future built infrastructure within the two study areas. These risks if realised can result in need to undertake expensive rectification works. For example, the Tweed Shire Council has replaced corroded cast iron water pipes at a cost of approximately $4 million (White and Melville 1996).

3.7: Chapter summary

The modern Macquarie Rivulet and Mullet/Hooka Creek deltas have evolved due the complex interactions of natural (autocyclic and allocyclic) and anthropogenic processes/factors. This chapter has outlined these processes/factors as presented in the literature. The Quaternary period is characterised by a series of marine transgression/regression cycles, each of which have directly impacted on the evolution of deltas. Sloss *et al.* (2007) produced a Holocene sea level reconstruction based on an assessment of pre-existing and new data suggesting that the sea reached present sea level between 7.9 and 7.7 ka and continued to rise a farther 1.5 m by 7.4 ka which persisted until 2 ka. After 2 ka sea level gradually fell to the current elevation. The research conducted by Sloss *et al.* (2007) has recently been reviewed by Lewis *et al.* (in press) and incorporated into a broader study of sea level around the Australian coast

Lake Illawarra, into which the two deltas are prograding, is classified as a barrier estuary or intermittently closed or open lagoon (ICOL). The lake's evolution conforms to the generic models of wave-dominated barrier estuary evolution proposed by authors such as Roy (1984), Roy *et al.* (2001) and Sloss *et al.* (2005, 2006a). At present the lake would be classified as a stage 2 or intermediate estuary. Furthermore sediment distribution within the lake is consistent with the tripartite zonation as described by Nichol (1991) and Dalrymple *et al.* (1992), i.e. the marine dominated zone, central mud basin and the fluvial dominated zone. In this study the primary focus is on the fluvial delta zone.

Extensive research by Coleman and Wright (1975) and Coleman (1976) has shown that delta evolution is a response to over 400 parameters. However, only nine of the 400 parameters assessed were found to have significant implications for delta development. The identified parameters include catchment relief, climate, continental shelf-slope, marine processes (waves, currents and tides), receiving basin, river discharge, river mouth processes (flow, channel mouth/bars and distributary channel morphology), sediment yield and wind. It is important to note not all of the identified parameters impact on the evolution of bay-head deltas such as Macquarie Rivulet and Mullet/Hooka

Creek deltas that are prograding into tectonically stable wave-dominated barrier estuaries.

Floodplain formation in the delta region is attributable to a combination of processes including lateral point-bar accretion, overbank vertical accretion, braided-channel accretion (not applicable to this study), oblique accretion, counterpoint accretion and abandoned-channel accretion. The resulting Holocene alluvium often caps potential or actual acid sulfate soils formed by the oxidation of minerals such as pyrite within the estuarine sediments. If not managed appropriately, the resulting acid can have significant environmental and economical consequences.

This section has also illustrated that a limited amount of research into the evolution of bay-head deltas has occurred along the southeast coast of Australia. Furthermore, where the evolution of these deltas has been established, it is generally not the primary focus of the study. Instead these studies have focussed on establishing the broader evolution of the estuary. As such the evolution of the deltas is poorly evaluated and presented by the authors. This lack of information justifies the high resolution nature of the study presented in this thesis.

Chapter 4

Subsurface Sampling, Sedimentary Analysis and Results

4.1: Introduction

Establishing the evolutionary history of both ancient and modern (Holocene) deltas is quite complex. This is attributed to the many and varied interactions between autocyclic and allocyclic processes occurring across varied temporal scales. A combination of various subsurface sampling, sedimentological, geophysical, geochronological and geographic information system (GIS) techniques were utilised to acquire the required information for the current study. Detailed sedimentological and faunal analysis facilitated the identification of discrete facies and associated environments of deposition. Facies mineralogy was established using X-ray diffraction (XRD) analyses. Amino acid racemisation (AAR) was the primary geochronological method used to establish the evolution of the deltas. To complement the AAR and ^{14}C dates, ^{210}Pb dates were obtained to establish recent sedimentation rates.

4.2: Site access

Permission to conduct coring/sampling of the subaerial portions of Macquarie Rivulet delta and associated floodplains was sought from the land owners, Winten Property Group. Initially the property developers were reluctant to provide access to the site. This was based on a perception the work would damage the environment resulting in negative publicity for them. This was resolved by the development of an Environmental Management and Rehabilitation Plan (Volume 2, Appendix 1) and a data sharing arrangement with the relevant parties. The plan was subsequently submitted to the then Department of Natural Resources (now Department of Environment and Climate Change and Water) by the Winten Property Group. After a review of the submitted work the department granted permission under Part 3A of the Rivers and Foreshores Improvement Act 1948 (Volume 2, Appendix 1).

Permission to undertake coring/sampling of the subaerial portions of Mullet Creek was sort from the private land owners and Wollongong City Council (Figure 3.20). Site access was granted based on the provision of the Environmental Management and Rehabilitation Plan prepared for the Macquarie Rivulet site and a data sharing arrangement.

Collection of subaqueous cores/samples for both Macquarie Rivulet and Mullet/Hooka Creek deltas was facilitated by the use of a 5 m long aluminium motor boat. The boat was also used as a working platform for the collection of the cores. Launch sites included the Oak Flats boat ramp, to access cores proximal to the Macquarie Rivulet delta, and from the Berkeley boat ramp and a beach launch site for Mullet/Hooka Creek delta (Figure 4.1).

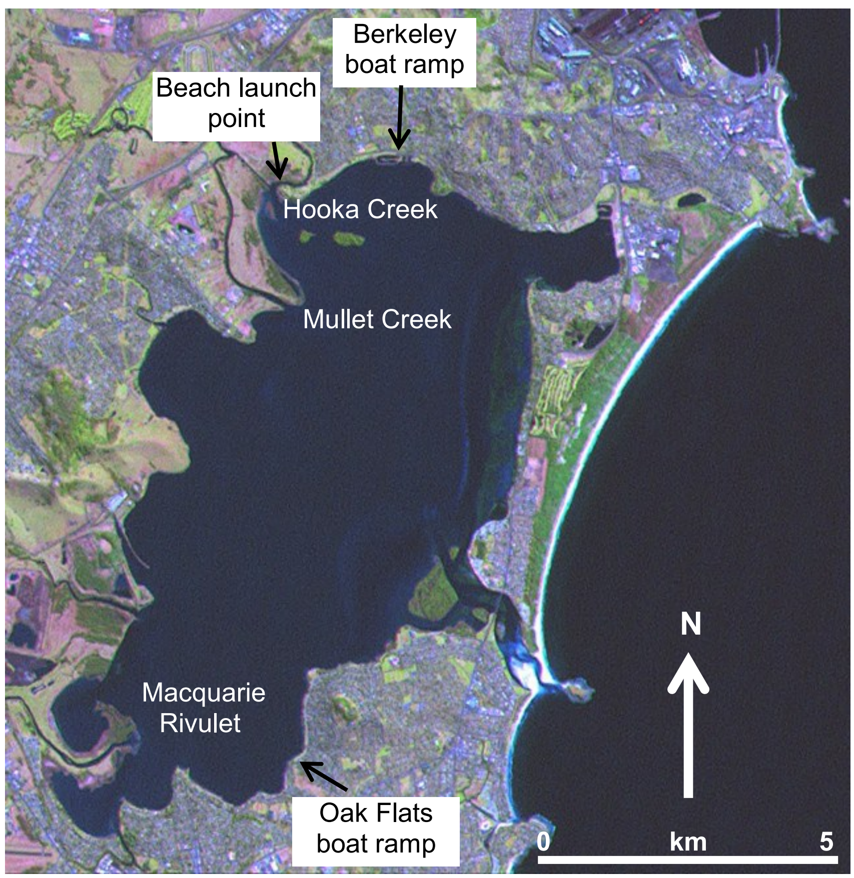


Figure 4.1: *Location of boat launch sites for the collection of subaqueous cores.*

4.3: Core, drill hole, push probe locations and topography

Core, drill hole and push probe locations were spatially selected using aerial photographs, field observations and topographic maps to ensure a comprehensive coverage of the Macquarie Rivulet and Mullet/Hooka Creek deltas. When selecting locations, consideration was also given to sampling locations included in previous studies to maximise the available subsurface stratigraphic data. A total of 147 cores/drill hole locations have been included in this study, 74 from Macquarie Rivulet (Table 4.1, Figure 4.2) and 73 from Mullet/Hooka Creek (Table 4.2, Figure 4.3). Appendix 3 provides additional core related information such as compaction and amount of material augured prior to coring. A total of 20 push probes were collected from the Mullet/Hooka Creek area (Table 4.3, Figure 4.4). Due to the depth to the Pleistocene bedrock in the vicinity of Macquarie Rivulet it was not possible to use the probe technique.

Table 4.1: *Macquarie Rivulet delta core locations for map sheet 9028-1-S (Kiama 1:25,000 map sheet). Core coordinate system is Australian Geodetic Datum (AGD) 1966.*

MR	Easting	Northing	MR	Easting	Northing	MR	Easting	Northing
1	0298513	6174333	26	0297345	6175050	51	0299162	6175387
2	0298204	6174195	27	0297135	6175121	52	0298902	6175431
3	0297828	6174397	28	0299292	6174726	53	0298034	6175324
4	0297626	6174640	29	0299142	6174668	54	0298292	6173656
5	0297657	6174773	30	0299002	6174545	55	0298254	6173471
6	0298033	6175387	31	0298935	6174493	56	0299156	6175969
7	0297875	6175421	32	0299500	6174800	57	0298169	6174440
8	0297930	6175371	33	0299100	6174700	58	0298209	6174641
9	0297797	6175318	34	0298839	6174365	59	0298288	6174814
10	0298628	6174415	35	0298758	6174230	60	0298324	6175017
11	0297953	6175223	36	0298876	6174557	61	0298351	6175167
12	0297860	6175151	37	0299200	6174600	62	0297969	6175445
13	0297785	6175132	38	0299300	6175600	63	0296855	6175088
14	0297715	6175111	39	0298220	6174000	64	0299025	6176034
15	0297738	6175054	40	0298550	6174120	65	0299228	6174339
16	0297575	6175068	41	0298230	6174100	66	0298979	6174087
17	0297488	6174816	42	0298480	6174000	67	0298168	6175228
18	0298371	6174247	43	0298650	6174351	68	0298077	6175204
19	0298045	6174234	44	0297960	6174180	69	0298934	6175653
20	0297904	6174343	45	0298630	6174030	70	0298762	6175669
21	0297764	6174468	46	0297580	6174230	71	0298613	6175020
22	0297679	6174555	47	0297660	6174230	72	0298881	6174886
23	0297563	6174684	48	0297930	6174120	73	0298200	6174142
24	0297500	6174894	49	0297880	6174120	74	0298355	6174004
25	0297655	6174930	50	0298671	6175452			

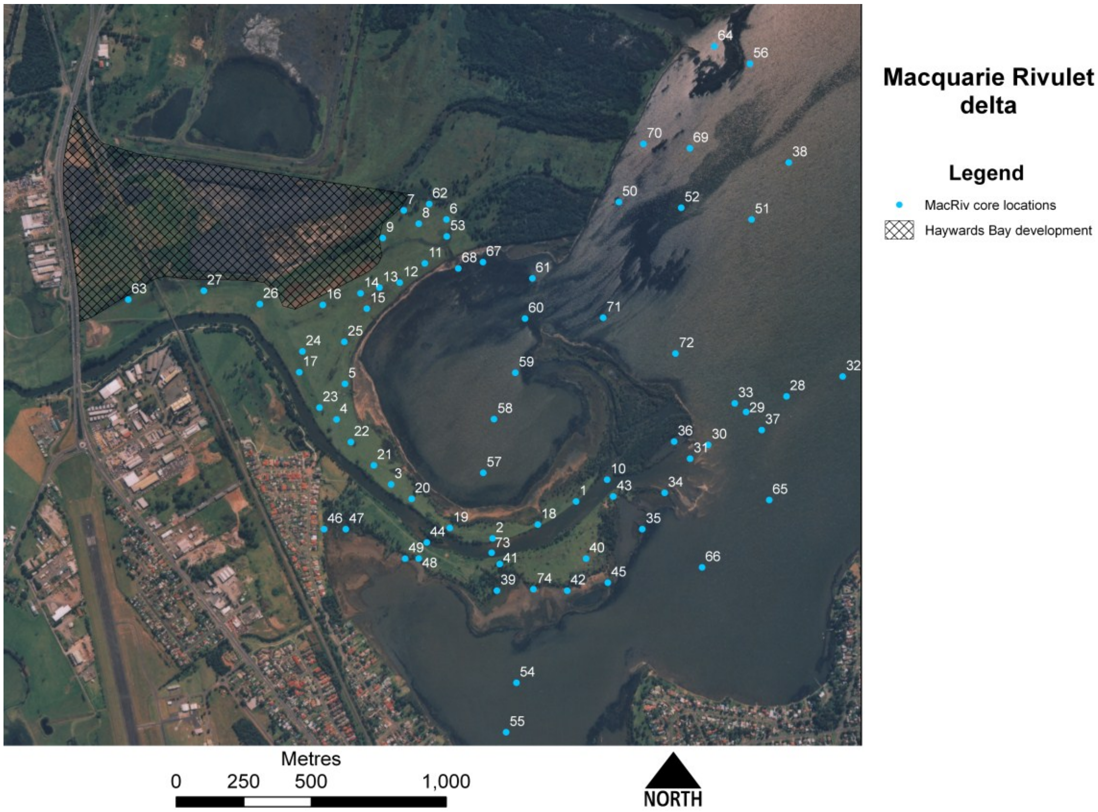


Figure 4.2: *Map showing the location of the 74 Macquarie Rivulet delta core/drill holes. 2002 background image from Hopley et al. (2007), refer to Table 8.1 for details.*

Table 4.2: *Mullet/Hooka Creek delta core locations for map sheet 9029-2-S (Wollongong 1:25,000 map sheet). Core coordinate system is Australian Geodetic Datum (AGD) 1966.*

MC	Easting	Northing	MC	Easting	Northing	MC	Easting	Northing
1	0301274	6180099	26	0300609	6180468	51	0301472	6181811
2	0301146	6180131	27	0301216	6181225	52	0301319	6181993
3	0300984	6180199	28	0301185	6181095	53	0301179	6182152
4	0300746	6180354	29	0301106	6180778	54	0301030	6182183
5	0300341	6180504	30	0300993	6180858	55	0301184	6182016
6	0300523	6180606	31	0301084	6181006	56	0301119	6181878
7	0300827	6181655	32	0300681	6180673	57	0300861	6182071
8	0300840	6181903	33	0300426	6181908	58	0300608	6182259
9	0300803	6180706	34	0300180	6181781	59	0300542	6182138
10	0300484	6180843	35	0300365	6181715	60	0300332	6182193
11	0300489	6181072	36	0300550	6181642	61	0300258	6182094
12	0300705	6181207	37	0300919	6181451	62	0300460	6181995
13	0300605	6181231	38	0300798	6181539	63	0301221	6180858
14	0300505	6181265	39	0300631	6181815	64	0300912	6180780
15	0300428	6181286	40	0300899	6182337	65	0301013	6180662
16	0300382	6181276	41	0300696	6182378	66	0300986	6181080
17	0301490	6179780	42	0300481	6182435	67	0301062	6181344

MC	Easting	Northing	MC	Easting	Northing	MC	Easting	Northing
18	0301910	6179900	43	0300273	6182355	68	0300808	6181192
19	0300935	6181199	44	0300429	6182304	69	0300203	6182171
20	0301438	6181137	45	0300916	6181597	70	0300254	6182192
21	0300900	6182199	46	0301119	6181631	71	0300311	6182112
22	0301591	6180560	47	0301279	6181645	72	0300542	6181897
23	0301589	6179997	48	0300964	6181821	73	0301086	6181250
24	0300340	6181580	49	0301042	6182044			
25	0300868	6180273	50	0301429	6181697			

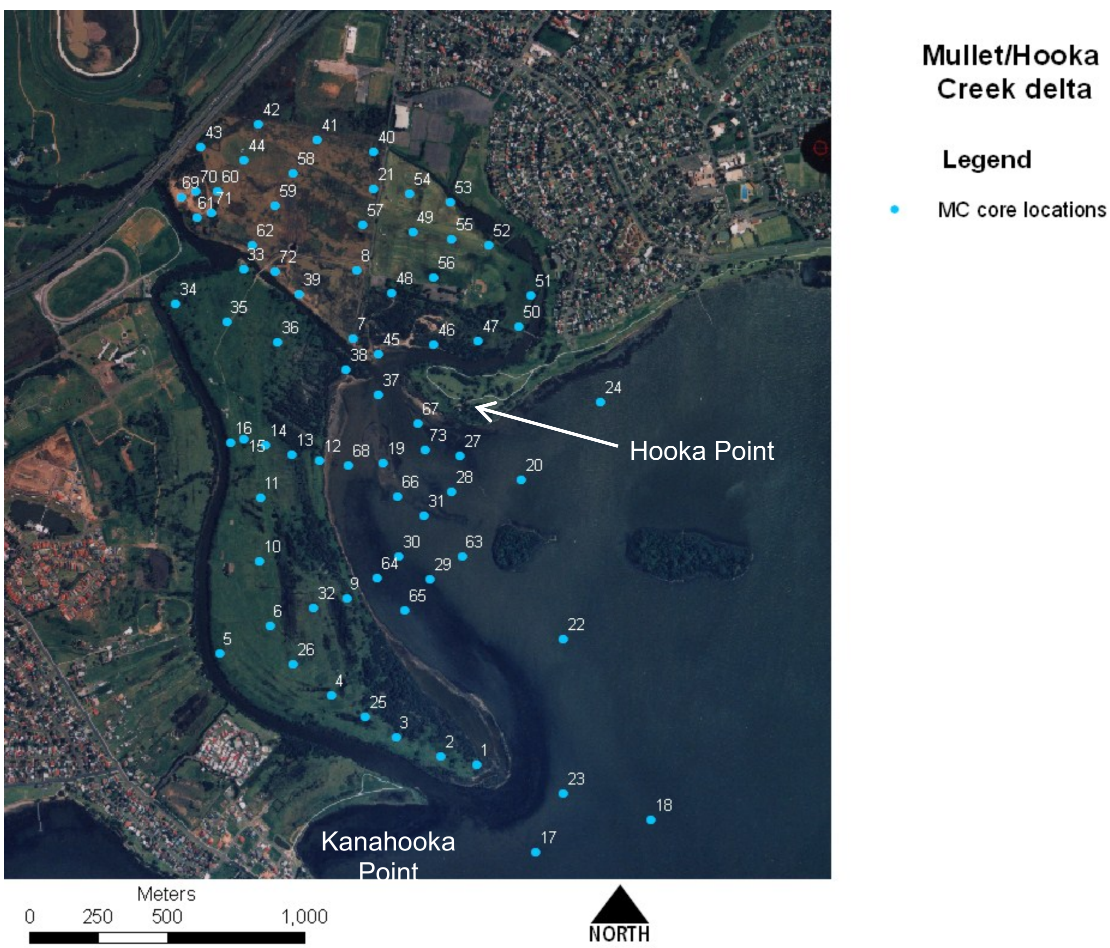


Figure 4.3: *Map showing the location of the Mullet/Hooka Creek delta core/drill holes. 2006 background image from Hopley and Jones (2007), refer to Table 8.2 for details.*

Table 4.3: *Mullet/Hooka Creek delta push probe locations for map sheet 9029-2-S (Wollongong 1:25,000 map sheet). Core coordinate system is Australian Geodetic Datum (AGD) 1966.*

Push	Easting	Northing	Depth to refusal	Push	Easting	Northing	Depth to refusal
1	301878	6181024	-2.75	11	301496	6181063	-1.7
2	301774	6181091	-2.7	12	301593	6186975	-1.6
3	301699	6181094	-2.9	13	301878	6181087	-2.85
4	301429	6180382	-6.5	14	301223	6180765	-4.45
5	301818	6180698	-6.5	15	301324	6180821	-3.6
6	301169	6180677	-4.2	16	301286	6180676	-6.5
7	301246	6180569	-6.5	17	301741	6181193	-2.5
8	301477	6181328	-1.2	18	301761	6181311	-2.25
9	301577	6181531	-2.8	19	301785	6181447	-3
10	301667	6180889	-3.55	20	301815	6181565	-1.45

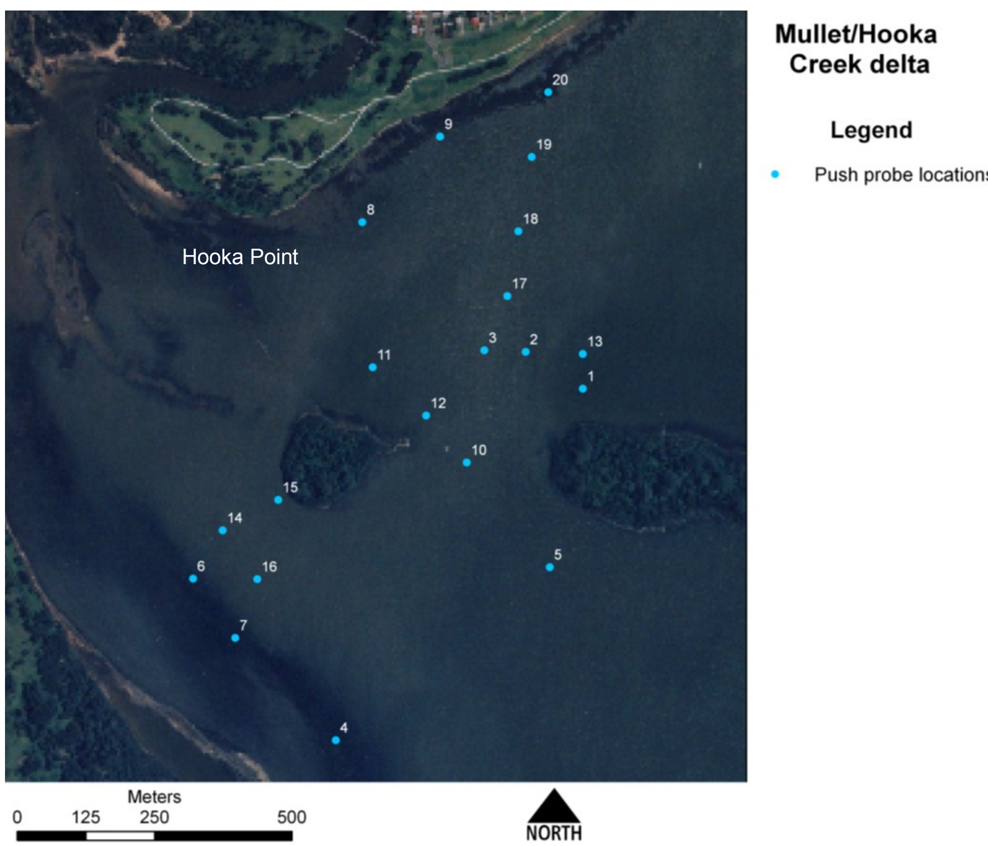


Figure 4.4: *Map showing the location of the Mullet/Hooka Creek delta push probes. 2006 background image from Hopley and Jones (2007,) refer to Table 8.2 for details.*

The topographic elevation of collected cores, with respect to Australian Height Datum (AHD) was established using a combination of methodologies. The primary methodology was the extraction of elevation's from high resolution airborne laser mapping (LiDAR) data sets (Figures 4.5 and 4.7). The LiDAR data discussed in this report was captured in 2005 by AAMHatch using a 25,000 Hz laser scanner calibrated to a rapid static GPS base station. Data accuracies are reported to be 0.15 m in the vertical and 0.06 m in the horizontal. The collected point data is spatially referenced to the GDA94 (horizontal) and AHD (vertical) datum's applying the MGA Zone 56 projection model and the Ausgeoid98 geoid models, respectively. Captured data was provided to Wollongong City Council as DXF files. Supplementary survey data was collected using a calibrated Leica TC307 total station.

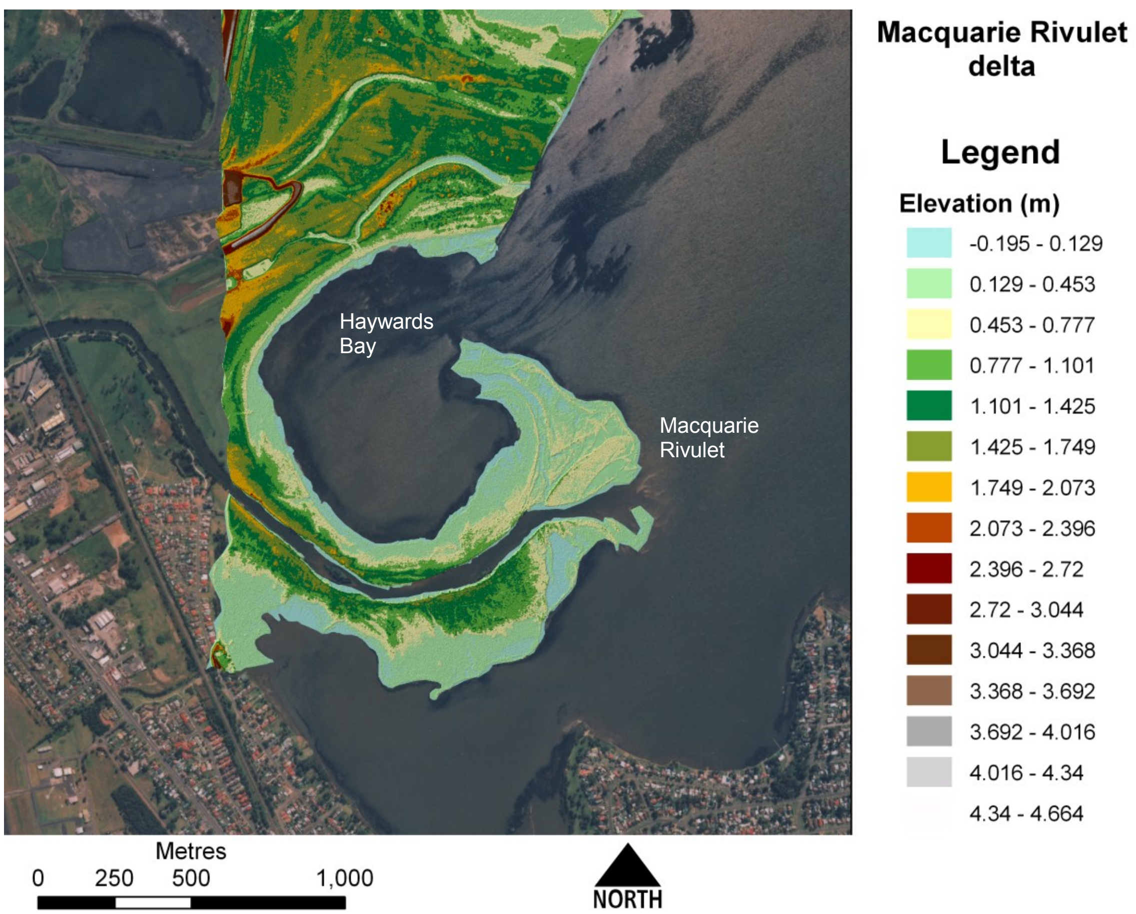


Figure 4.5: *Extent of LiDAR coverage used as a topographic benchmark for Macquarie Rivulet delta cores/drill holes. Coloured surface is an interpolated TIN model produced in*

Arc GIS, based on the available LiDAR data points. Elevation datum is AHD. 2002 background image from Hopley et al. (2007), refer to Table 8.1 for details.

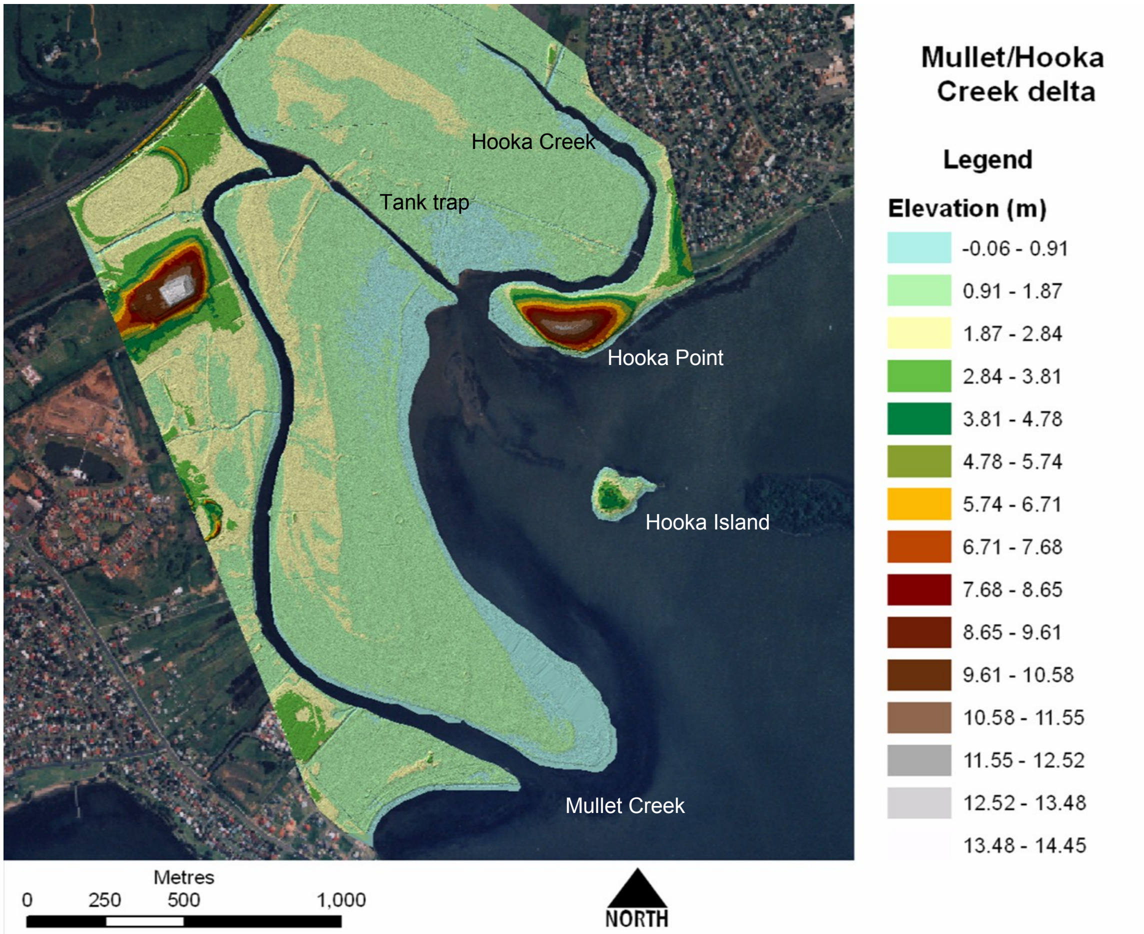


***Figure 4.6:** LiDAR coverage used as a topographic benchmark for Mullet/Hooka Creek delta cores/drill holes. Coloured surface is an interpolated TIN model produced in Arc GIS, based on the available LiDAR data points. Elevation datum is AHD. 2006 background image from Hopley and Jones (2007,) refer to Table 8.2 for details.*

4.4: Subsurface coring/sampling

Three coring/drilling techniques were used to obtain the subsurface stratigraphic information required to assess the evolution of the deltas. The techniques included sonic coring, petrol-powered vibracoring from a boat and screw auger drilling. Each of the coring/drilling techniques utilised are explained in more detail below. The location of all utilities was identified, using the dial before you dig service, prior to any subsurface coring or drilling occurring (Volume 2, Appendix 2)

4.4.1: Sonic push coring

The sonic push coring technique used in this study was developed due to the poor penetration and high levels of compaction resulting from the use of a conventional petrol-powered vibracoring on the subaerial portions of the delta. The technique was also developed to facilitate the collection of a continuous core which could not be achieved using a solid auger drilling technique. This technique is based on the principles incorporated into sonic drill rigs, however, it utilised the Universities pre-existing equipment.

Initially the upper compact floodplain profile (approximately 1 m) is removed using a solid auger fitted to the University of Wollongong's drill rig. As the technique evolved the solid auger was replaced with a hand held auger head connected to a modified two stroke engine. This modification increased the speed at which this upper compact material was removed while increasing the accuracy of the down-hole sedimentological description. The use of a hollow head also facilitated the collection of samples with minimal contamination.

Once the upper compact material was removed a 9 m long aluminium tube (core barrel) is inserted into the hole. The use of the core barrel enabled the collection of relatively undisturbed sediment samples, which provided the high resolution stratigraphic data required to undertake this study. Furthermore, it was found filing a taper around the end of the core barrel, inserted into the ground, improved penetration and reduced the compaction ratio. A petrol-powered vibracoring head was then fitted to the core barrel and moved horizontally backwards and forwards while penetrating the ground. When penetration slowed significantly, the hydraulic head of the drill rig was used to apply downward force to the vibracore head, while it is vibrating (Figure 4.7). The downward hydraulic force applied to the core increased as ground resistance increased. Coring ceased when ground resistance was greater than the weight of the drill rig. For example, when cores penetrated highly resistant Pleistocene material the hydraulic system was unable to push the head down resulting in the hydraulics lifting the drill rig. It was found the combination of the vibrations and the downward force increased the depth of

penetration up to 8.5 m below ground level. It is probable this technique would be able to penetrate further if the aluminium barrels used were longer or could be connected.

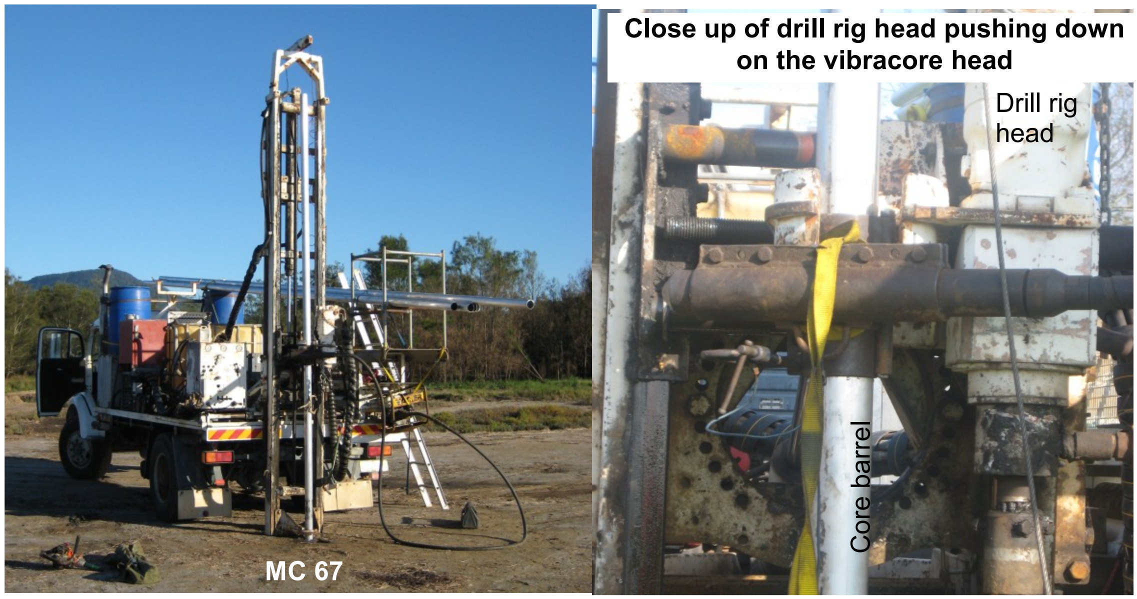


Figure 4.7: *The hydraulic head of the drill rig is used to apply downward force to the vibracore head while it is vibrating. Photo on the left shows a close up of the relationship between the drill rig head, vibracore head and core barrel.*

Prior to extraction, the ground level was marked on the barrel and the compaction ratio was calculated. Core barrels, which did not penetrate into the Pleistocene, were then filled with water and a plug inserted to create a vacuum, minimising loss of sample. The core barrel was twisted several times to break away the core base. Lifting brackets were then applied and the core extracted using the drill rigs hydraulic winch (Figure 4.8). Due to the length of the cores, extraction required several resets. All cores, once extracted, were cut into manageable lengths, no more than 4.5 m long, and stored in the School of Earth and Environmental Sciences, University of Wollongong, cool room until they were split for analysis. Storage of cores in a cool room significantly slows the rate at which the core samples degrade.

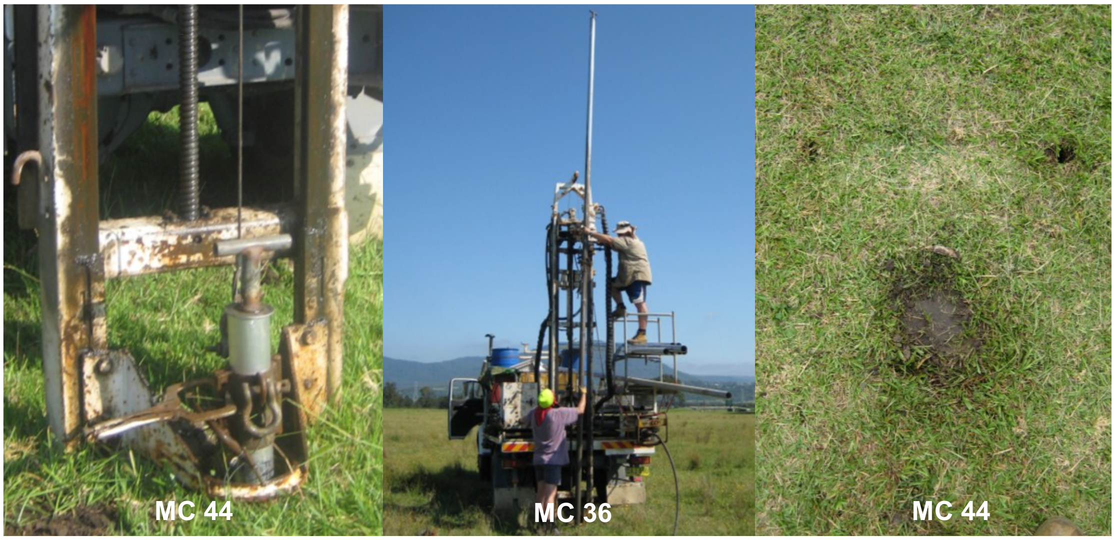


Figure 4.8: *Core extraction. Photo on the left shows cut core with lifting brackets and core plug fitted. Photo in the centre shows a 9 m long core barrel being extracted using the drill rig's hydraulic winch. The photo on the right shows the ground impacts post core extraction and back filling.*

4.4.2: Petrol-powered vibracoring from a boat

Petrol-powered vibracoring was used to collect subaqueous cores. This technique was selected as it can be used to retrieve continuous cores of relatively undisturbed sediment up to 9 m in length. The technique can be used in water up to 3 m deep.

The School of Earth and Environmental Sciences, University of Wollongong, aluminium boat was used as a working platform for the collection of the subaqueous cores, with the exception of MC67 as water depth did not permit access by boat. In this instance all of the equipment was carried to the site from the shoreline. Once the core location has been identified a 5 m high aluminium quadrapod was lowered into the water and the boat tied to it. As with the sonic coring technique, a nine metre long aluminium core barrel was used to collect the sample. Core barrels are vibrated into the sediment using the vibracore head as shown in Figure 4.7. As penetration slows, due to increased ground resistance, the vibracore head was stood upon and rotated to apply the downward pressure to continue penetration (Figure 4.9). At the point of refusal the core was cut at water level, compaction measurements taken, the barrel void filled with

water and plugged for removal. Cores were extracted using lifting brackets bolted to the barrel and a chain block suspended from the quadrapod. Retrieved cores are cut into manageable lengths, no more than 4.5 m long, for transport and storage in the School of Earth and Environmental Sciences, University of Wollongong, cold room.

Figure 4.9: *Collection of subaqueous cores using a petrol powered vibracore. Note the image on the left shows the vibracore head being stood upon to provide the downward pressure required to penetrate the sediment. The right hand image shows the retrieval of a core.*

4.4.3: Solid auger drilling

The solid auger drilling technique was utilised when it was not possible to retrieve cores using the sonic coring technique. The inability to retrieve the cores was due to the coarse nature of the sediment preventing further penetration and the ability to create a suitable vacuum for extraction. Solid auguring was used to collect the subsurface data for Mullet Creek cores 34 (basal 2 m), 61, 62, 69, 70, 71 and 72.

Solid auger drilling was completed using a Melville Engineering hydraulic truck mounted drill rig (Figure 4.10). The rig was fitted with 3 m long, 75 mm diameter screw auger rods. Due to the nature of the sediment the walls of the auger holes were prone to collapse. As a result the full 3 m rod length was drilled into the ground prior to removal for sampling. The quality of the samples retrieved was lower than samples collected using the other two methodologies, due to sample travel and contamination as the rods were removed. To minimise sample travel the drill rotational and downward travel speeds were continually adjusted based on the down-hole resistance. Additional 3 m long rods were added as required. Drilling continued until the Pleistocene basement was reached.

4.5: Core logging, sediment sampling and stratigraphic cross/long sections

Sampling methods varied depending on the coring/drilling technique used. Cores collected using the sonic coring or vibracoring technique were split using a circular saw to facilitate the production of visual stratigraphic logs (Volume 2, Appendix 5). These logs detail changes in facies, colour, composition and texture; the presence of macrofossils and any signs of bioturbation. After the visual logs were completed sediment samples were typically taken at 10 cm intervals and at facies boundaries along with the removal of material suitable for geochronological analysis. However, additional samples were taken at 5 cm intervals from representative sections of facies to provide the detailed data required to establish facies sedimentology.

The sampling and logging technique used for solid auger drilling was significantly different to the techniques described above. Prior to sampling the external layer of sediment on the auger rod is removed to minimize contamination i.e. samples were in situ and not transported during the drilling process. Sediment samples were taken at 50 cm intervals and at facies boundaries after removal of the contaminated layer. All macrofossils present were removed and identified to ascertain population trends within the facies, to confirm depositional environments and for geochronological analysis.

***Figure 4.10**: Configuration of the School of Earth and Environmental Sciences, University of Wollongong, truck mounted drill rig when fitted with solid augers.*

Cross- and long-sections have been constructed to assist with the interpretation of the deltas stratigraphical and morphological evolution. Each section was produced by the extraction of a high resolution topographic surface from the available LiDAR with spatially correct core locations. The subsurface facies evident in the intersected cores were then extrapolated to form the continuous surfaces illustrated in the cross/long sections in Chapters 6 and 7. Figures 4.12 (Macquarie Rivulet) and 4.13 (Mullet/Hooka Creek) show the location of the various sections.

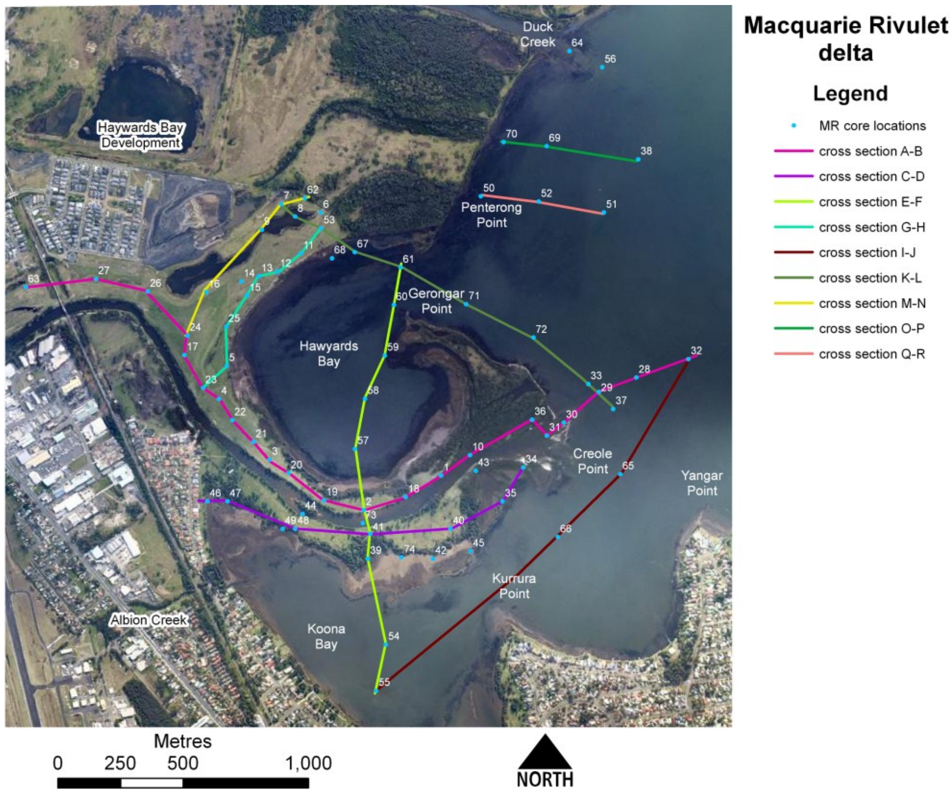


Figure 4.11: *Map showing the location of the long/cross-sections from Macquarie Rivulet. 2002 background image from Hopley et al. (2007,) refer to Table 8.1 for details.*

4.6: Sediment analysis

Several sediment analyses were undertaken during the completion of this thesis. The colours of the collected samples were assessed using the Munsell soil colour chart. This assessment was conducted at the time of splitting the cores to ensure oxidisation of the sediment was minimised. Grain size and associated sedimentological characteristics, such as sorting, skewness, kurtosis, the number of modes per sample and the corresponding grain size for the modes was achieved using a Malvern Mastersizer 2000 laser particle size analyser. Coarse-grained samples were first passed through a 1.6 mm wet sieve as the Mastersizer is unable to analyse sediment >-1 ϕ (2 mm). The wet-sieved fraction was then dried and measured using nested sieves at 0.5 ϕ increments. The averaged results obtained for the identified facies are outlined in Table 4.4.

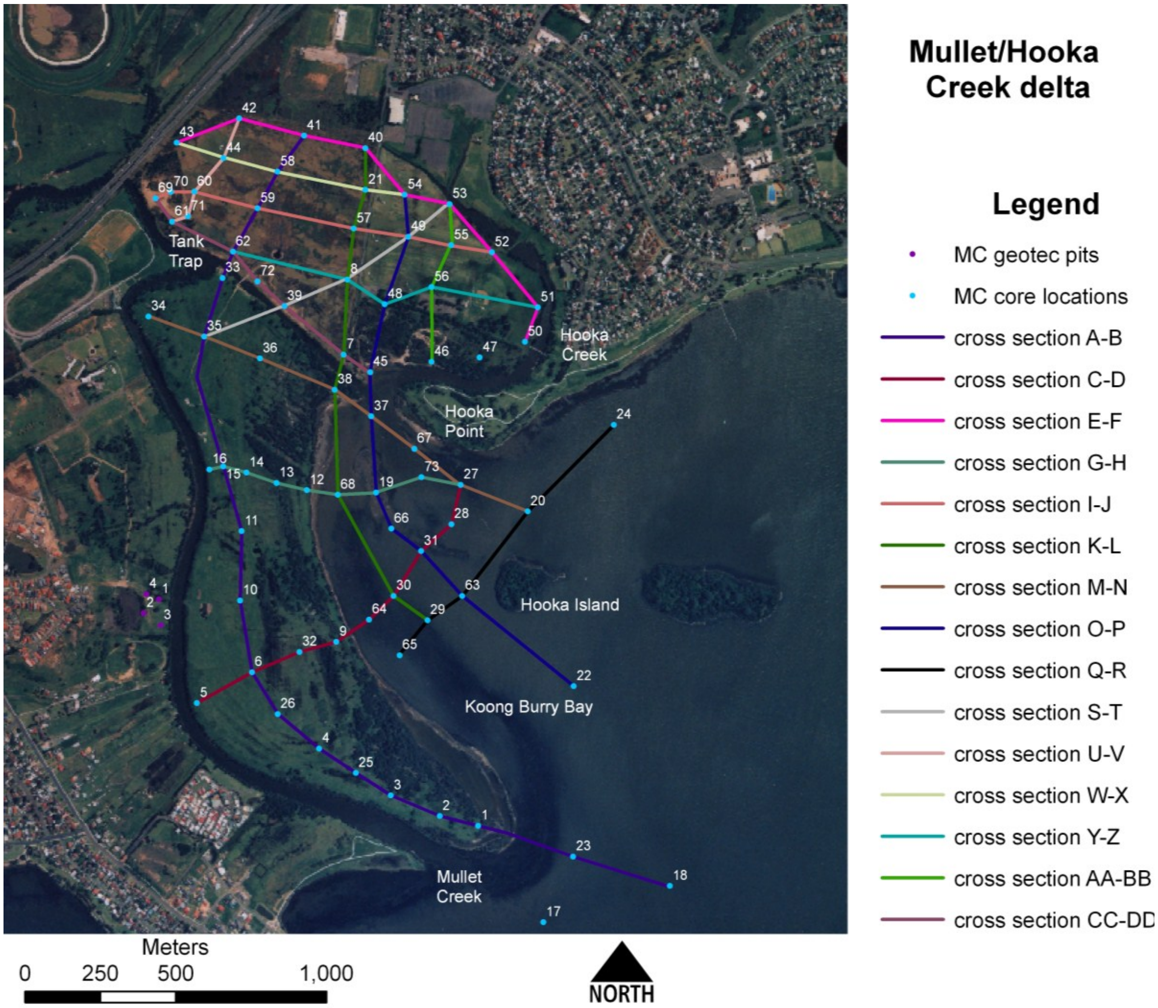


***Figure 4.12**: Map showing the location of the long/cross-sections from Mullet/Hooka Creek. 2006 background image from Hopley and Jones (2007), refer to Table 8.2 for details.*

X-ray diffraction (XRD) analysis was conducted on 35 representative samples. The analysis provided the primary mineral composition within the various facies (Table 4.5). Samples were dried for a period of 24 hours at a stable temperature of 50°C. Once dried, samples were crushed using a mortar and pestle. The XRD analysis was completed using a PW1130 copper tube, a Spellman DF3 generator and SIE 112 software. The angles of diffraction used for each of the analyses ranged from 4° to 70° 2θ. The resulting diffraction traces were then analysed using Traces, UPDSM and SIROQUANT software to aid in the identification of the minerals present in the samples.

Table 4.4: *Summary of the averaged mean grain size, sorting, skewness, modes and colour. Note the Pleistocene channel fill descriptions are based on visual in field assessments.*

Facies	Grain size	Sorting	Skewness	Colour	Coarsening direction
Pleistocene	very fine sandy silt	poorly sorted	coarse skewed	light grey with common orange, red mottles and rare olive mottles	N/A
Pleistocene Palaeosol	very fine grained sand	very poorly sorted	fine skewed	Orange brown to light blue grey	N/A
Pleistocene channel fill	very fine silty sand	very poorly sorted	fine skewed	Olive yellow brown with common red mottles	N/A
Near shore muddy sand	very silty fine sand	very poorly sorted		Greenish black muddy sand to sandy mud	N/A
Transgressive bay fill	very fine silty sand	very poorly sorted	strongly fine skewed	variable rages from dark brown greys to dark purple greys	N/A
Regressive delta	silty very fine sand to very coarse sand	very poorly to poorly sorted	fine to coarse skewed	greyish brown to very dark grey brown	Fines upwards
Palaeochannel	muddy fine grained sand to clean coarse sand	very poorly to poorly sorted	fine to coarse skewed	pale yellowish white to very dark greenish brown	Coarsens upwards
Prodelta/lagoonal mud	silt	very poorly to poorly sorted	fine skewed to near symmetrical	dark olive brown to black	N/A
Distal delta	sandy silt	very poorly to poorly sorted	strongly fine to fine skewed	dark olive to greyish black	Coarsens upwards
Fluvial sands	very fine sand to very coarse sand	moderately to poorly sorted	strongly fine to fine skewed	pale yellowish white to very dark greyish brown	coarsens upwards
Floodplain/levee	Fine to medium sand , silty sand to sandy silt	poorly sorted	strongly fine skewed to near symmetrical	buff yellow to brownish black	fines upwards
Bay infill	sandy silt to silty sand	very poorly to poorly sorted	strongly fine to fine skewed	dark olive to greyish black	fines upwards

Table 4.5: *Facies mineralogy as determined by the XRD analysis.*

Facies	Sample	Chi square	Albite (wt %)	Aragonite (wt %)	Calcite (wt %)	Chlorite (wt %)	Gypsum (wt %)	Illite (wt %)	Kaolinite (wt %)	Labradorite (wt %)	Mixed layer illite (wt %)	Orthoclase (wt %)	Pyrite (wt %)	Quartz (wt %)
Pleistocene	MC9: 5.3 m	4.9	10			0.1		8.2	7.3		0.3		0.3	73.9
	MC 60: 4.6 m	4.66	4.9				0.5	7	6.8		0.3	0.7	0.3	79.5
	MR 39: 5.7 m	3.51	5.9	2.1		0.9		9.7	12	1	5.3		0.4	62.6
	MR 53: 2.6 m	3.54	5.2	1.6				7.2	9.7	2.5	5		0.2	68.7
	Ave	**4.15**	**6.50**	**1.85**		**0.50**	**0.50**	**8.03**	**8.98**	**1.75**	**2.73**	**0.70**	**0.30**	**71.18**

Facies	Sample	Chi square	Albite (wt %)	Aragonite (wt %)	Calcite (wt %)	Chlorite (wt %)	Gypsum (wt %)	Illite (wt %)	Kaolinite (wt %)	Labradorite (wt %)	Mixed layer illite (wt %)	Orthoclase (wt %)	Pyrite (wt %)	Quartz (wt %)
Regressive delta	MC 12: 6.2 m	4.26	1.5					2.1	1.5	0.1	0.2	3.8	1	89.7
	MC 39: 5.0 m	3.45	6.3	1.7				2.7	7.6	1	4.6		0.2	76
	MC 67: 6.2 m	4.1	1.8					2.5	0.9		0.2	2.3	0.4	92
	Ave	**3.94**	**3.20**	**1.70**				**2.43**	**3.33**	**0.55**	**1.67**	**3.05**	**0.53**	**85.90**
Near shore muddy sand	MC 32: 3.9 m	4.23	6.7					4.8	4.1		0.2		0.5	83.7
	MC 64: 2.7 m	3.37	10.8	1.6				1.2	4.1	1.3	4.3		0.4	76.3
	MR 50: 0.75 m	4.78	27.8	2.6	0.2	0.2	4.3	0.5	3.7		3.2			57.4
	MR 19: 2.8 m	4.59	4.2	0.8				4	1.9		0.2		0.6	88.2
	Ave	**4.25**	**14.27**	**1.67**		**0.20**	**4.30**	**1.90**	**3.23**		**2.57**		**0.50**	**73.97**
Transgressive Bay Infill	MC 42: 3.0 m	3.35	1.5	2.1				9.5	9.7	2.7	4.1		0.1	70.3
	MC 46: .3.2 m	3.48	4	3.1		1.1		9.7	10	1.6	5.7		0.1	64.6
	MC 47: 1.5 m	3.15	3.7	0.9		0.8		7.7	6.9	1.9	5.8		0.2	72.2
	Ave	**3.33**	**3.07**	**2.03**		**0.95**		**8.97**	**8.93**	**2.07**	**5.20**		**0.13**	**69.03**
Palaeochannel	MC 38: 6.0 m	3.66	16.6	2.1		1.9		4.4	7.7	0.5	10.4		3	55.8
	MC 67: 4.2 m	3.77	6.7	4.6	0.5	2		2.9	5.6	2.2	8.5	0.1	0.3	66.6
	MR 22 2.45 m	4.19	10.2					3.3	3.9		0.2		0.9	81.4
	Ave	**3.87**	**11.17**	**3.35**	**0.50**	**1.95**		**3.53**	**5.73**	**1.35**	**6.37**	**0.10**	**1.40**	**67.93**
Prodelta/ lagoonal mud	MC 37: 2.0 m	5.39	36.7	3.4	38.1			0	8.2	0.5	2.9	8.7		
	MC 37: 2.9 m	4.29	41.9	5.4	26.4			0.4	9	0	5.4	9.3		
	MC 37: 3.4 m	3.45	49.9	2.3	14.8			0	9.7	1.7	5.4	14		
	MC58: 4.0 m	3.71	13	0.4				4.3	9.2		10.4		0.8	62
	MR 10: 3.0 m	5.22	15.3	0.6	.	0.9		3.9	8.1	11.2	10.9		0.6	48.5
	MR 39: 4.7 m	4.15	14.4	2.7		1.4		6.9	9.5	1.2	10.7	1.5	1	50.8
	MR 53: 2.6 m	4.16	20	1.5	0	0.6		6.6	11	0.9	3			56.4
	Ave	**4.34**	**27.31**	**2.33**	**19.83**	**0.97**		**3.16**	**9.21**	**2.58**	**6.96**	**8.40**	**0.80**	**54.43**

Facies	Sample	Chi square	Albite (wt %)	Aragonite (wt %)	Calcite (wt %)	Chlorite (wt %)	Gypsum (wt %)	Illite (wt %)	Kaolinite (wt %)	Labradorite (wt %)	Mixed layer illite (wt %)	Orthoclase (wt %)	Pyrite (wt %)	Quartz (wt %)
Distal delta	MC 26: 3.0 m	3.57	13.1					3.7	5.1		7.1	0.3	1	69.7
	MR 31: 0.85 m	4.49	9.1	7.6		2.9			3.6	0.3	4.4		1.6	70.6
	MR 73: 1.5 m	5.26	28	1.2			1.2	0.8	3.2		5.4		0.6	59.6
	Ave	**4.44**	**16.73**	**4.40**		**2.90**	**1.20**	**2.25**	**3.97**		**5.63**	**0.30**	**1.07**	**66.63**
Fluvial sands	MC 34: 1.2 m	3.68	1.5					3	1.5		0.2	1.2		92.5
	MC 64: 0.2 m	5.65	18.6						2.4	1.1	0.2	12		66.2
	MC 64: 1.4 m	5.38	20.6	0.4			4.5		2.4	0.2	2.6		0.7	66.2
	MR 11: 0.7 m	3.9	19.7	1.9		0.9		2.6	2.1		5.2			65.8
	MR 31: 0.4 m	4.83	20.5	1.8				0.6	1.9		2.8			72.3
	Ave	**4.69**	**16.18**	**1.37**		**0.90**	**4.50**	**2.07**	**2.06**	**0.65**	**2.20**	**6.35**	**0.70**	**72.60**
Bay Infill	MC 30 0.05m	5.63	25.2	0.4	0.5		5.3	0.6	5.1		4.7			58.1
	MC65: 0.05 m	3.81	17.7	1.2				3.4	3.7	0.8	5		0.1	68.1
	MR 61: 0.05 m	4.28	16.9	3.7	0.1	0.4	6.4	2.1	5.7	2.2	5.2			57.4
	Ave	**4.57**	**19.93**	**1.77**	**0.30**	**0.40**	**5.85**	**2.03**	**4.83**	**1.50**	**4.97**		**0.10**	**61.20**

4.7: Macrofossil analysis

Macrofossil distribution is influenced by factors such as salinity, sedimentation rates and energy levels. Thus, macrofossils can aid in the determination of palaeoenvironments and assist in establishing the evolutionary history of natural features such as Macquarie Rivulet and Mullet/Hooka Creek deltas. However, when using biological indicators, such as macrofossils, to determine palaeoenvironments consideration must be given to reworking and transportation prior to incorporation into the sedimentary succession.

A visual macrofossil analysis was conducted on the 147 cores/drill holes collected or reviewed as part of this thesis. Analysis involved the identification of the various species observed and documenting factors such as depth of occurrence, facies, relative abundance, condition of valves (i.e. signs of reworking or predation) and if valves are

articulated or disarticulated, etc. After the visual assessment was completed, macrofossils deemed suitable for geochronological analysis were removed, cleaned and stored for future analysis.

4.8: Geochronology

Facies geochronology was established to assist with the Holocene evolutionary reconstruction of the Macquarie Rivulet and Mullet/Hooka Creek deltas. Stanley (2001) demonstrated the risks of applying a single geochronological approach in deltaic environments. Specifically, he showed that less than one quarter of the radiocarbon (^{14}C) dates reviewed were within ± 500 years of the expected age. This study has addressed this issue by taking a multi-method approach. Specifically, geochronological ages referred to in this study are based on a combination of amino acid racemisation (AAR), ^{14}C and ^{210}Pb derived ages. The geochronological techniques used in this study are detailed below.

4.8.1: Amino acid racemisation

Proteins, found in all living and deceased organisms, are large molecules made up of many peptide chains with each chain made up of linked amino acids (Bradley 1985). In the case of carbonate shells such as *Notospisula trigonella* and *Anadara trapezia* the proteins combine to form a membrane in which the calcium carbonate crystallizes (Miller and Brigham-Grette 1989). The crystallised calcium carbonate forms a protective layer over the membrane preventing degradation of the proteins while the organism is alive.

Amino acids within living organisms exclusively assume the levorotatory (L)-configuration as a result of biochemical processes (Murray-Wallace 1993). Post-mortem chemical reactions break down the large proteins into peptide chains and amino acids (Miller and Hare 1980; Miller and Brigham-Grette 1989; Wehmiller and Miller 2000; Sloss *et al.* 2006a). This is synchronous with the conversion of amino acids from the L- to the dextrorotatory (D)-configuration in a regular, predictable fashion over time to an

equilibrium point where the D/L ratio = 1 (Miller and Clarke 2007). The rate at which this conversion occurs is dependent on post-mortem temperature, moisture levels of sediments and taxonomic variations.

A brief summary of the amino acid racemisation techniques used in this study is now outlined. AAR analysis was conducted on selected *Notospisula trigonella* and *Anadara trapezia* valves from Macquarie Rivulet and Mullet/Hooka Creek deltas (Tables 4.6 and 4.7). Specimens dated were typically articulated with minimal visible signs of reworking. The selected specimens were initially cleaned using a dental drill to remove any large contaminants and the outer layer of calcium carbonate, care was taken not to heat the samples. The larger *Anadara trapezia* valves had their umbo removed for analysis prior to further cleaning. Samples were washed three times in an ultrasonic bath containing clean distilled water for a period of five minute per rinse prior to being etched with 0.0033 ml of 2M HCl for every 1 mg of sample mass. Post-etching samples were soaked for 2 hours in H_2O_2 to further reduce the likelihood of sediment and organic contamination.

Cleaned samples were then digested in 8M HCL at a rate of 0.02 ml per 1 milligram of sample. Once fully digested the vials were purged in N_2 for 10 seconds each to prevent oxidation of organic material within the acid solution, prior to undergoing hydrolysis for a period of 22 hours at 110°C. After hydrolysis, samples were dried in a vacuum-tight dessicator and rehydrated with a solution containing 0.01M L-homoargenine. The D/L ratios of the rehydrated samples were obtained using a reverse-phase, high-performance liquid chromatograph (HPLC) with three analyses per sample. The averaged D/L ratio was then calculated using the calibration curves for *Notospisula trigonella* and *Anadara trapezia* derived by Sloss *et al.* (2004a) to determine the numeric age of the sample (Table 4.6 a and b).

Table 4.6a: *Amino Acid Racemisation results from Notospisula trigonella and Anadara trapezia specimens from Macquarie Rivulet delta. Ages associated with core codes marked with # or * were* previously established *by Sloss et al. (2005)*) and Cork (2010), respectively.

Location	Core	Sample depth (CM AHD)	Core Start (cm AHD)	Sample core depth (cm)	Facies	Specimen	Articulate/ disarticulate	Age	Error (±)
Macquarie Rivulet	MR 11	-130	100	230	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4700	60
Macquarie Rivulet	MR 11	-146	100	246	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	6760	110
Macquarie Rivulet	MR 12	-115	110	225	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	8060	140
Macquarie Rivulet	MR 13	-170	140	310	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	5120	50
Macquarie Rivulet	MR 18	-80	90	170	Distal delta deposit	*Notospisula trigonella*	Articulate	720	20
Macquarie Rivulet	MR 18	-180	90	270	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3590	60
Macquarie Rivulet	MR 19	-99	90	189	Fluvial sand	*Anadara trapezia*	Articulate	7990	130
Macquarie Rivulet	MR 26	-151	161	312	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	5880	40
Macquarie Rivulet	MR 32#	-626	-195	431	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4320	190
Macquarie Rivulet	MR 32#	-560	-195	365	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4230	190
Macquarie Rivulet	MR 33#	-250	-125	125	Distal delta deposit	*Notospisula trigonella*	Articulate	40	5
Macquarie Rivulet	MR 33#	-380	-125	255	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	320	10
Macquarie Rivulet	MR 33#	-554	-125	429	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3510	150
Macquarie Rivulet	MR 34#	-349	26	375	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	230	10
Macquarie Rivulet	MR 34#	-409	26	435	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	1410	70
Macquarie Rivulet	MR 34#	-464	26	490	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3730	160
Macquarie Rivulet	MR 36	-130	-85	45	Bay infill deposit	*Notospisula trigonella*	Articulate	460	20
Macquarie Rivulet	MR 36	-306	-85	221	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	510	30
Macquarie Rivulet	MR 36	-415	-85	330	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4600	30
Macquarie Rivulet	MR 36	-572	-85	487	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	5933	20
Macquarie Rivulet	MR 37#	-162	-25	137	Fluvial sand	*Anadara trapezia*	Articulate	1300	60
Macquarie Rivulet	MR 37#	-395	-25	370	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3890	170
Macquarie Rivulet	MR 37#	-515	-25	490	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	3850	170
Macquarie Rivulet	MR 37#	-623	-25	598	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4570	200
Macquarie Rivulet	MR 38#	-341	-175	166	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	270	10
Macquarie Rivulet	MR 38#	-409	-175	234	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	2710	120
Macquarie Rivulet	MR 38#	-603	-175	428	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3070	140

Location	Core	Sample depth (CM AHD)	Core Start (cm AHD)	Sample core depth (cm)	Facies	Specimen	Articulate/ disarticulate	Age	Error (±)
Macquarie Rivulet	MR 52#	-248	-75	173	Near shore muddy sand	*Notospisula trigonella*	Articulate	4610	200
Macquarie Rivulet	MR 55#	-95	-15	80	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	1880	80
Macquarie Rivulet	MR 55#	-165	-15	150	Near shore muddy sand	*Anadara trapezia*	Articulate	7520	350
Macquarie Rivulet	MR 56#	-160	-75	85	Low flow	*Notospisula trigonella*	Articulate	610	30
Macquarie Rivulet	MR 56#	-194	-75	119	Low flow	*Notospisula trigonella*	Articulate	1010	50
Macquarie Rivulet	MR 56#	-255	-75	180	Distal delta deposit	*Anadara trapezia*	Articulate	3170	140
Macquarie Rivulet	MR 56#	-455	-75	380	Near shore muddy sand	*Notospisula trigonella*	Articulate	5340	240
Macquarie Rivulet	MR 59	-78	-42	36	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	510	20
Macquarie Rivulet	MR 59	-127	-42	85	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	1780	80
Macquarie Rivulet	MR 59	-163	-42	121	Near shore muddy sand	*Anadara trapezia*	Articulate	6280	280
Macquarie Rivulet	MR 67	-125	-50	75	Distal delta deposit	*Anadara trapezia*	Articulate	5770	60
Macquarie Rivulet	MR 68	-199	-45	154	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	2020	240
Macquarie Rivulet	MR 68	-205	-45	160	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	7310	140
Macquarie Rivulet	MR 70	-274	-90	184	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4000	70
Macquarie Rivulet	MR 70	-298	-90	208	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	7370	110
Macquarie Rivulet	MR 71	-229	-125	104	Low flow	*Notospisula trigonella*	Articulate	4620	70
Macquarie Rivulet	MR 72	-297	-185	112	Low flow	*Notospisula trigonella*	Articulate	1840	40
Macquarie Rivulet	MR 72	-324	-185	139	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	5370	50

Table 4.6b: *Amino Acid Racemisation results from Notospisula trigonella and Anadara trapezia specimens from Mullet/Hooka Creek delta.*

Location	Core	Sample depth (CM AHD)	Core Start (cm AHD)	Sample core depth (cm)	Facies	Specimen	Articulate/ disarticulate	Age	Error (±)
Mullet/Hooka Creek	MC 1	-43	117	160	Fluvial sand	*Anadara trapezia*	Articulate	3150	20
Mullet/Hooka Creek	MC 1	-373	117	490	Fluvial sand	*Notospisula trigonella*	Articulate	3570	60
Mullet/Hooka Creek	MC 1	-403	117	520	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3130	80
Mullet/Hooka Creek	MC 2	-253	111	364	Distal delta deposit	*Notospisula trigonella*	Articulate	2520	110
Mullet/Hooka Creek	MC 2	-369	111	480	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	2400	30
Mullet/Hooka Creek	MC 3	-167	103	270	Fluvial sand	*Notospisula trigonella*	Articulate	3490	40
Mullet/Hooka Creek	MC 3	-267	103	370	Distal delta deposit	*Notospisula trigonella*	Articulate	3020	50

Location	Core	Sample depth (CM AHD)	Core Start (cm AHD)	Sample core depth (cm)	Facies	Specimen	Articulate/ disarticulate	Age	Error (±)
Mullet/Hooka Creek	MC 4	-320	155	475	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4230	80
Mullet/Hooka Creek	MC 4	-323	155	478	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3090	20
Mullet/Hooka Creek	MC 4	-391	155	546	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	5990	190
Mullet/Hooka Creek	MC 5	-215	120	335	Near shore muddy sand	*Anadara trapezia*	Articulate	7750	40
Mullet/Hooka Creek	MC 6	-224	171	395	Near shore muddy sand	*Anadara trapezia*	Articulate	6910	180
Mullet/Hooka Creek	MC 7	-132	66	198	Distal delta deposit	*Notospisula trigonella*	Articulate	690	10
Mullet/Hooka Creek	MC 7	-197	66	263	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3590	100
Mullet/Hooka Creek	MC 7	-469	66	535	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	5110	140
Mullet/Hooka Creek	MC 8	-108	129	237	Fluvial sand	*Anadara trapezia*	Articulate	5830	120
Mullet/Hooka Creek	MC 9	-380	105	485	Near shore muddy sand	*Anadara trapezia*	Articulate	6500	100
Mullet/Hooka Creek	MC 12	25	95	70	Fluvial sand	*Anadara trapezia*	Articulate	4260	80
Mullet/Hooka Creek	MC 12	5	95	90	Fluvial sand	*Anadara trapezia*	Articulate	4710	30
Mullet/Hooka Creek	MC 12	-100	95	195	Distal delta deposit	*Notospisula trigonella*	Articulate	4320	90
Mullet/Hooka Creek	MC 12	-165	95	260	Fluvial sand	*Anadara trapezia*	Articulate	5990	200
Mullet/Hooka Creek	MC 13	-151	89	240	Fluvial sand	*Anadara trapezia*	Articulate	7890	150
Mullet/Hooka Creek	MC 13	-176	89	265	Low flow	*Anadara trapezia*	Articulate	4180	30
Mullet/Hooka Creek	MC 14	69	109	40	Fluvial sand	*Anadara trapezia*	Articulate	6480	70
Mullet/Hooka Creek	MC 20	-178	-110	68	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	2100	250
Mullet/Hooka Creek	MC 20	-217	-110	107	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	6300	800
Mullet/Hooka Creek	MC 20	-269	-110	159	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	6200	850
Mullet/Hooka Creek	MC 20	-282	-110	172	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	7500	950
Mullet/Hooka Creek	MC 20	-327	-110	217	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	8200	105 0
Mullet/Hooka Creek	MC 22	-385	-155	255	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4180	30
Mullet/Hooka Creek	MC 22	-519	155	386	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6530	190
Mullet/Hooka Creek	MC 23	-112	-45	67	Fluvial sand	*Notospisula trigonella*	Articulate	590	30
Mullet/Hooka Creek	MC 23	-365	-45	320	Distal delta deposit	*Notospisula trigonella*	Disarticulate	1630	60
Mullet/Hooka Creek	MC 23	-525	-45	480	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	3560	60
Mullet/Hooka Creek	MC 25	-460	115	575	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	5540	40
Mullet/Hooka Creek	MC 26	-342	173	515	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	6590	60
Mullet/Hooka Creek	MC 27	-191	-10	181	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	6500	40
Mullet/Hooka Creek	MC 27	-217	-10	207	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6750	70
Mullet/Hooka Creek	MC 27	-278	-10	268	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	7200	110

Location	Core	Sample depth (CM AHD)	Core Start (cm AHD)	Sample core depth (cm)	Facies	Specimen	Articulate/ disarticulate	Age	Error (±)
Mullet/Hooka Creek	MC 29	-8	7	15	Bay infill deposit	*Notospisula trigonella*	Articulate	510	10
Mullet/Hooka Creek	MC 29	-146	7	153	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	2610	20
Mullet/Hooka Creek	MC 29	-223	7	230	Near shore muddy sand	*Anadara trapezia*	Articulate	7670	30
Mullet/Hooka Creek	MC 30	-271	0	271	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	7200	110
Mullet/Hooka Creek	MC 31	-49	0	49	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	300	20
Mullet/Hooka Creek	MC 31	-164	0	164	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4300	90
Mullet/Hooka Creek	MC 31	-257	0	257	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6590	60
Mullet/Hooka Creek	MC 32	-94	148	242	Fluvial sand	*Anadara trapezia*	Articulate	3360	10
Mullet/Hooka Creek	MC 32	-255	148	403	Near shore muddy sand	*Anadara trapezia*	Articulate	7370	200
Mullet/Hooka Creek	MC 36	-84	96	180	Fluvial sand	*Notospisula trigonella*	Articulate	5300	80
Mullet/Hooka Creek	MC 37	-238	-25	213	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6950	30
Mullet/Hooka Creek	MC 37	-259	-25	234	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6390	70
Mullet/Hooka Creek	MC 38	-241	45	286	Distal delta deposit	*Anadara trapezia*	Articulate	8170	70
Mullet/Hooka Creek	MC 39	-125	119	244	Distal delta deposit	*Notospisula trigonella*	Articulate	4990	50
Mullet/Hooka Creek	MC 39	-155	119	274	Distal delta deposit	*Anadara trapezia*	Articulate	7610	40
Mullet/Hooka Creek	MC 42	-139	111	250	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4970	150
Mullet/Hooka Creek	MC 45	-148	15	163	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	5210	190
Mullet/Hooka Creek	MC 45	-245	15	260	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	7750	40
Mullet/Hooka Creek	MC 48	-87	48	135	Fluvial sand	*Anadara trapezia*	Articulate	5900	40
Mullet/Hooka Creek	MC 49	-465	87	552	Prodelta/ lagoonal mud	*Notospisula trigonella*	Articulate	4400	80
Mullet/Hooka Creek	MC54	-236	8 4	320	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	5980	100
Mullet/Hooka Creek	MC 56	-279	87	366	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6070	50
Mullet/Hooka Creek	MC 63	-450	-95	355	Palaeochannel	*Anadara trapezia*	Articulate	8010	60
Mullet/Hooka Creek	MC 64	-224	-25	199	Fluvial sand	*Anadara trapezia*	Articulate	4300	90
Mullet/Hooka Creek	MC 64	-300	-25	275	Near shore muddy sand	*Notospisula trigonella*	Articulate	5210	60
Mullet/Hooka Creek	MC 65	-218	-20	198	Fluvial sand	*Notospisula trigonella*	Articulate	3580	60
Mullet/Hooka Creek	MC 65	-376	-20	356	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6320	120
Mullet/Hooka Creek	MC 66	-354	-40	314	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	8120	60
Mullet/Hooka Creek	MC 67	-216	-20	196	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	7540	30
Mullet/Hooka Creek	MC 68	-304	-15	289	Palaeochannel	*Notospisula trigonella*	Articulate	6540	90

4.8.2: Radiocarbon dating

Radiocarbon dating, both conventional and accelerated mass spectrometry (AMS), are isotopic methodologies measuring the extent of carbon 14 (^{14}C) to nitrogen 14 (^{14}N) decay. ^{14}C is continually formed in the upper atmosphere due to the interaction of cosmic rays with ^{14}N. Once formed, ^{14}C rapidly oxidises to form carbon dioxide ($^{14}CO_2$) and enters the carbon cycle and is subsequently absorbed by living organisms. Minute quantities of the absorbed $^{14}CO_2$ are then assimilated into the organism's shell (Arnold 1995; Beta Analytic 2011). On death ^{14}C assimilation ceases and thus, the residual ^{14}C content reduces due to the radioactive decay by beta (β) emissions to ^{14}N with a half life of 5,730 years.

The minimum age of samples suitable for radiocarbon dating is in the vicinity of 300 years BP. This is attributable to the combined impacts of the Suess/industrial and bomb effects. The Suess/industrial effect is associated with the onset of the industrial revolution in the 1890's where the burning of ^{14}C depleted fossil fuels increased CO_2, while not increasing ^{14}C levels within the atmosphere. As a result organisms which lived and, therefore, assimilated ^{14}C after this date tend to have a decreased ^{14}C signal. This decrease in the ^{14}C signal is evident up until the 1950's. Nuclear testing during the 1950's and 1960's artificially increased the amount of ^{14}C within the carbon cycle by approximately 100% above natural levels (Arnold 1995; Pilcher 1991, 2000; Higham 2010). The maximum age of detection is in the vicinity of 40,000 to 60,000 years BP (Arnold 1995; Trumbore 2000; Higham 2010). This upper limit is attributable to the fact that after 7-10 half lives the amount of remnant ^{14}C within samples is at or below detection levels which will not enable the determination of radiocarbon ages with acceptable confidence levels.

Ages derived from estuarine molluscs, such as those in this thesis, need to be corrected for the marine reservoir effect as it typically results in ages 400-500 years older than terrestrial material of an equivalent age (Stuiver and Becker 1993; Arnold 1995). This discrepancy is attributable to the dilution of CO_2 within marine/estuarine water and the

delay in exchange rates between atmospheric CO_2 and ocean bicarbonate. Due to varied environmental conditions, the age implications of the effect differ based on locality. With respect to this study the Marine Reservoir Correction Database (2011) suggests that the reservoir age proximal to the study site (Narooma) is 319 years.

Furthermore, resulting radiocarbon ages need to be converted to calendar/sidereal years. This conversion is achieved through the application of an empirical formula which compares the extent of ^{14}C activity to the International Radiocarbon Dating Standard, initially Oxalic Acid 1 but now Oxalic Acid II (Stuiver and Braziunas 1993; Higham 2010).

A total of six samples from the two study sites (two from Macquarie Rivulet and four from Mullet/Hooka Creek) were analysed by Beta Analytic Inc., Florida. Prior to undergoing analysis all samples were acid etched to remove residual organic material and the outer shell layer to minimise the inclusion of modern ^{14}C. MR26, MR68, MC37, MC48, MC63 and MC65 were analysed utilising conventional techniques. The AMS technique was applied to MC65* as this technique reduces the risk of modern ^{14}C contamination due to the highly laminated nature of oyster valves. The results from the radiocarbon analyses are presented in Table 4.7. The table also compares the ^{14}C derived ages to the AAR ages for five of the samples.

4.8.3: Lead 210 and Caesium 137 dating

Lead 210 (^{210}Pb), the third order decay product of uranium 238 (^{238}U), has a half life of 22.26 years (Oldfield and Appleby 1984) making it suitable for the determination of modern sedimentation rates in estuarine environments. Within sediments both unsupported and supported ^{210}Pb occurs. Unsupported ^{210}Pb is derived from the diffusion of radon 222 (^{222}Rn) through soil profiles into the atmosphere where it rapidly decays to ^{210}Pb. The resulting ^{210}Pb isotopes attach to particulate matter and settles out of the atmosphere as fallout or during rain events prior to incorporation in the sedimentary records. In contrast, supported ^{210}Pb isotopes are in equilibrium with ^{222}Rn, radium 226 (^{226}Ra) and ^{238}U (ANSTO 2009). As it is not possible to directly measure

unsupported ^{210}Pb, it is calculated by subtracting supported ^{210}Pb from total ^{210}Pb (ANSTO 2009). The resulting ^{210}Pb concentrations were modelled using the CRS (constant rate of ^{210}Pb supply) and/or the CIC (constant initial ^{210}Pb concentration) methods, which facilitated age determination.

Table 4.7: *Radiocarbon results from Macquarie Rivulet (MR) and Mullet/Hooka Creek (MC)* deltas. *Note* the MC *65* date was obtained utilising the AMS technique whereas all the* other *samples were dated using the conventional ^{14}C method. The table also illustrates the equivalent AAR dates obtained from the same specimen.*

Location	Core	Sample depth (cm AHD)	Core Start (cm AHD)	Sample core depth (cm)	Facies	Specimen	Articulate/ disarticulate	^{14}C age	AAR age
Macquarie Rivulet	MR 26	-149	161	310	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	7195± 215	
Macquarie Rivulet	MR 68	205	-45	160	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	7465± 215	
Mullet/Hooka Creek	MC 37	-238	-25	213	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	6845± 285	6920± 30
Mullet/Hooka Creek	MC 48	-87	48	135	Fluvial sand	*Anadara trapezia*	Articulate	5910± 250	5900± 40
Mullet/Hooka Creek	MC 63	-450	-95	355	Palaeochannel	*Anadara trapezia*	Articulate	6460± 200	8010± 60
Mullet/Hooka Creek	MC 65	-376	-20	356	Prodelta/ lagoonal mud	*Anadara trapezia*	Articulate	4700± 260	6320± 1230
Mullet/Hooka Creek	MC 65*	-400	-20	380	Near shore muddy sand	Oyster	Disarticulate	6760± 210	

Caesium 137 (^{137}Cs), an anthropogenic isotope, is attributable to atmospheric testing of nuclear bombs after 1954 (Appleby 2001; Walling *et al*. 2002). As a result ^{137}Cs can be used as an age verification tool for the ^{210}Pb dating technique. Specifically, sediments deposited prior to 1954 should not contain any ^{137}Cs. The ^{210}Pb results reported in Tables 4.8 and 4.9 have been verified using the ^{137}Cs methodology.

^{210}Pb dating was undertaken by the Australian Nuclear Science and Technology Organisation (ANSTO) at the Institute of Environmental research, Lucas Heights. Dried and crushed samples were packed into sealed petri dishes. Where sample sizes were not adequate Na_2CO_3 (an inert material) was added. After three weeks, enabling the samples to equalize, ^{137}Cs, ^{210}Pb and ^{226}Ra activities in samples were determined by

Compton suppression gamma spectrometry. ^{137}Cs activity was determined using the 662 keV peak after subtraction of the ^{214}Bi peak interference. ^{210}Pb activity was determined using the 46.5 keV peak. ^{226}Ra activity was estimated using ^{214}Pb and ^{214}Bi at 351.9 keV and 609.3 keV respectively. The geochronological results are reported for Mullet/Hooka Creek in Table 4.8 at a 95% confidence level.

4.9: Palaeoreceiving basin morphological model

Coleman and Wright (1975) noted the inherited morphology of receiving basins is one of the primary drivers for deltaic evolution. The palaeomorphology of the Pleistocene land surface near the present location of Mullet/Hooka Creek delta was established. The actual depth to the Pleistocene land surface, relative to AHD, was established based on the analysed core, drill hole and probe data (Tables 4.2, 4.3, Volume 2 Appendix 4). Where the Pleistocene land surface was not intersected it has been defined based on the analysis of proximal cores and long/cross sections. Initially, kreiging techniques, within an ArcGIS framework, were used to generate a continuous profile of the palaeoreceiving basin. Kriging is a geostatistical method of interpolation that assumes that a spatial relationship exists between points. A mathematical function is applied to the data points within a specific radius of each other to calculate the value of the predicted points (Booth 2000; Lloyd and Atkinson 2002. Booth (2000) noted that kriging is a two step process. Initially variograms and covariance functions are used to estimate the statistical/autocorrelation values. The second and final step is the actual prediction of the unknown values based on the outputs of the first stage. However, it was found the technique did not produce results which were repeatable even when the same interpolation criteria were use. The lack of repeatability diminished credibility and confidence in the outputs. Instead triangulated irregular network (TIN) models were used, within the ArcGIS framework, to generate the surfaces in a repeatable manner. A TIN model is used to represent surfaces in 3-D and is formed by a series of irregularly spaced nodes/points that have a known Z value (Booth 2000). These nodes are then connected to form a network of linked triangles that represent the surface. TIN's are generally used to visualise/model small areas in detail due to the costs associated with

the data collection required to produce the TIN. A significant benefit of TIN's is that they can be used to calculate volumes and surface areas (Booth 2000).

Table 4.8: *MC 20- ANSTO IDs, depth intervals, total, supported and unsupported ^{210}Pb, calculated CIC, CRS models sediment ages and CRS model mass accumulation rates. (CIC mass accumulation rate: 0.4 ± 0.1 g/cm^2/year r^2 = 0.7527)*

ANSTO ID	Depth (cm)	Total Pb-210 (mBq/g) or (Bq/kg)	Supported Pb-210 (mBq/g) or (Bq/kg)	Unsupported ^{210}Pb Corrected to reference date 24-Sep-09 (mBq/g) or (Bq/kg)	Calculated CIC Ages (years)	Calculated CRS Ages (years)	CRS model Mass Accumulation Rates g/cm^2/y	^{137}Cs at reference date 24-Sep-09 (mBq/g) or (Bq/kg)
L474	0 - 2	23.9 ± 3.8	14.8 ± 0.7	9.2 ± 3.9	3 ± 3	2 ± 4	0.4 ± 0.7	2.3 ± 0.4
L475	5 - 7	27.0 ± 4.0	14.2 ± 0.7	12.9 ± 4.0	15 ± 6	16 ± 8	0.4 ± 0.2	2.4 ± 0.4
L476	10 - 12	22.0 ± 4.9	15.0 ± 0.7	7.1 ± 4.9	28 ± 10	38 ± 11	0.3 ± 0.1	1.0 ± 0.4
L477	15 - 17	17.0 ± 4.8	14.5 ± 0.8	2.5 ± 4.8	40 ± 14	56 ± 12	0.3 ± 0.1	< 1.0
L478	20 - 22	17.9 ± 3.1	15.0 ± 0.6	2.9 ± 3.2	53 ± 18	77 ± 13	0.27 ± 0.05	3.0 ± 0.4

4.10: Chapter Summary

Sonic push coring, petrol powered vibracoring and solid auger drilling techniques were used to gather subsurface samples from 147 locations. Collected sonic push cores and petrol powered vibracores were split and logged at the University of Wollongong, whereas solid auger logging and sampling occurred in the field. Grain size, XRD, macrofossil and geochronological (AAR, ^{14}C, AMS and ^{210}Pb) techniques were used to establish the Holocene evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas. Triangulated irregular network (TIN) models within an ArcGIS framework were used to generate and visualise the morphology of the palaeoreceiving basin.

Chapter 5

Holocene Fluvio-deltaic Facies Architecture and Successions

5.1: Introduction

Fluvio-deltaic facies architecture and facies successions are influenced by the interaction of fluvial and estuarine processes to varying degrees. The interactions between these processes lead to the deposition of a diverse range of facies. This chapter establishes the facies architecture and facies successions in ten main and five minor deposits identified within the Macquarie Rivulet and Mullet/Hooka Creek delta cores. For each of the facies and stratigraphic units described, depositional environments have been inferred.

The complex interplay between allocyclic and autocyclic processes and anthropogenic impacts has produced a variety of distinct depositional environments which occur on temporal scales ranging from hours to years. For example, splay and flood deposits are formed rapidly whereas deposition of the prodelta/lagoonal mud facies occurs over several thousand years. Delineation of the facies characteristics and interpretation of the associated environments of deposition has enabled the evolutionary history of Macquarie Rivulet and Mullet/Hooka Creek deltas to be described (Chapters 6 and 7).

5.2: Facies and facies associations

Facies are sedimentary bodies with distinct lithological, structural and organic elements which differ from the underlying, overlying and laterally adjacent units (Walker 1992). The high resolution analysis of the 147 cores resulted in the identification of 17 sedimentary facies excluding the basal bedrock. Where facies similar in nature and depositional history were identified they have been grouped into one of ten facies associations. Furthermore, the study intersected two imported units within the Mullet/Hooka Creek study area. These units were imported to produce the levelled playing surfaces associated with Fred Finch Park. Facies described below have been delineated based on the sediment characteristics such as grain size (including internal

variability), degree of sorting, sand silt and clay percentages, mineralogy, organic constituents (plant debris) and post-depositional processes such as bioturbation.

5.3: Basal facies association (weathered bedrock and Pleistocene deposits)

The base of MC 34 and MC 51 intersected a highly weathered friable course- to very coarse-grained sandstone with a clay matrix (Volume 2, Appendix 4, 5). Based on stratigraphic position, the sandstone is inferred to be the lithic Permian Broughton Formation. The sandstone is yellow brown to greenish brown in colour with traces of red and yellow mottles throughout. The red and yellow mottles within the weathered rock represent oxidation of the iron-rich sediments.

Subaerial exposure of the northwestern margin of present day Lake Illawarra during the last glacial maximum led to the development of extensively oxidised sediments and, in some areas, produced a poorly developed soil. These sediments represent the Pleistocene floodplain, soil profile and channel-fill facies.

These Pleistocene facies were intersected in 58% of the analysed cores (Volume 2, Appendix 4). The facies is characterised by light blue grey clay with minor occurrences (5-10%) of medium- to coarse-grained sand (Figure 5.1). Other sedimentary characteristics include rare authigenic iron-rich concretions, large well rounded and weathered lithic inclusions, root traces, minor organic traces (e.g. coalified wood), desiccation cracks and sand in-filled burrows. The upper contact is typically sharp yet irregular in nature, suggesting a relatively abrupt transition between depositional environments. Similar weathered and oxidised clay-rich sequences, overlying the basement facies have been identified in deltas such as the Tuggerah Lakes and Lake Macquarie (Roy *et al.* 1980), Shoalhaven River (Umitsu *et al.* 2001), Wandandian Creek delta St Georges Basin (Hopley and Jones 2006), Erowal Bay St Georges Basin (Sloss *et al.* 2006a), Burrill Lake (Sloss *et al.* 2006b), Minnamurra (Panayotou *et al.* 2007) and Towradgi and Fairy lagoons (Hollins *et al.* 2011).

Results from laser particle size analysis of representative samples indicate that the Pleistocene sediment is typically very poorly sorted, strongly positive (fine) skewed, very fine-grained sandy silt (Table 4.4). Sand grains from the coarser fraction are typically subangular to subrounded indicating limited transportation and a common source area for the sediment. Quartz is the dominant mineral constituent at an average of 71.2% with kaolinite (9.0%), illite (8.0 wt%), albite (6.5 wt%), mixed layer illite-smectite (2.7 wt%), aragonite (1.9 wt%) and labradorite (1.8 wt%; Table 4.5). The high clay content within the facies is attributable to extensive weathering of the Pleistocene land surface while exposed during the latest low stand. The sedimentological characteristics outlined above are consistent with descriptions of Pleistocene sediment from the region by authors such as Bradshaw (1987), Sloss (2005), Hopley and Jones (2006) and Jones *et al.* (2006).

In 5% of the analysed cores (7 cores; Volume 2, Appendix 4), the Pleistocene facies is overlain by up to 50 cm of friable orange brown poorly sorted fine- to medium-grained sand in a moderately compact light blue grey sandy clay interpreted to represent a relict soil. Facies characteristics include common root traces (Figure 5.2), coalified wood fragments and authigenic concretions up to 50 mm in diameter. Typically soil horizons are weakly developed if evident at all. Upper contacts are sharp yet irregular in nature, whereas the basal contact typically grades into the Pleistocene land surface facies.

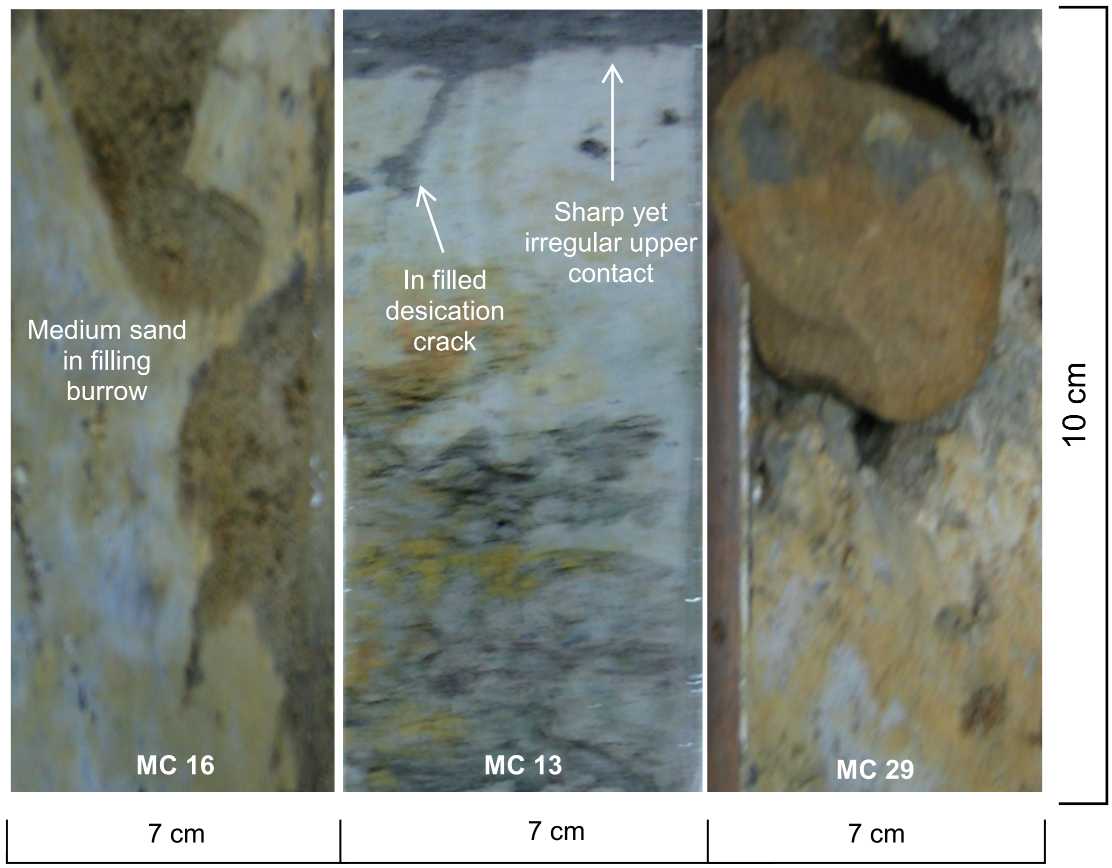


Figure 5.1: *The Pleistocene sedimentary facies is characterised by compact light blue grey clay with minor occurrences (5-10%) of medium- to coarse-grained sand (often infilling burrows, photo on the left) and extensive mottling. Note the irregular yet sharp upper contact and infilled crack between the Pleistocene facies and overlying facies in the photo in the centre. Photo on the right shows a rare well rounded small cobble.*

Cores MC 70 and 71 intersected a layer of compact cohesive very muddy fine- to medium-grained sand with rare authigenic iron-rich concretions and lithic fragments directly overlying the Pleistocene land surface (Volume 2, Appendix 4). This facies is interpreted to represent Pleistocene channel channel-fill deposits based on the stratigraphical relationship of this facies with adjacent facies and the observed sedimentological characteristics. The sediment is olive yellow brown in colour with common orange and red mottles. A visual, in field, assessment of the facies indicated the sand fraction was very poorly sorted and contained subrounded quartz grains.

Facies mineralogy is consistent with the XRD results obtained for the Pleistocene land surface.

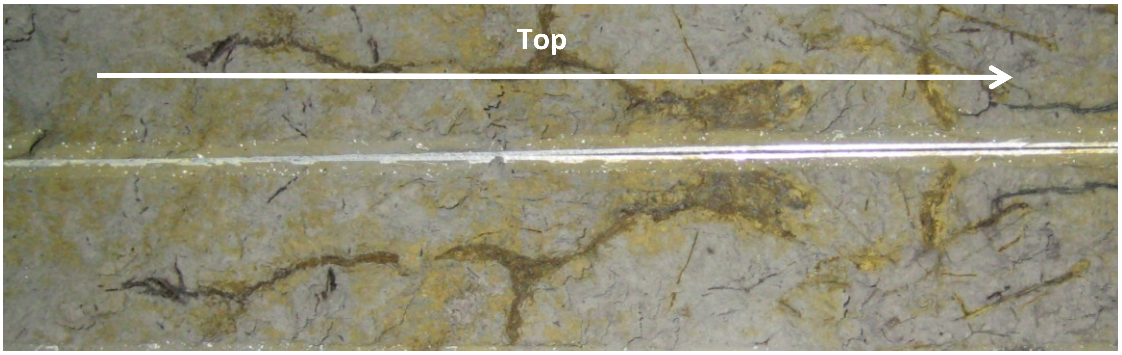


Figure 5.2: *Photo illustrates the light blue grey compact clay-rich Pleistocene palaeosol facies identified in MC 14 between 225-250 cm. Note the common root traces, the large root trace is 15 cm long.*

5.4: Near shore muddy sand facies

The basal bedrock and Pleistocene facies are overlain, in places, by a discontinuous greenish black muddy sand to sandy mud deposit intersected in 23% of the analysed cores (32 cores, Volume 2, Appendix 4). Where intersected the facies in the Mullet/Hooka Creek study area is typically draped over palaeohighs; however this association is less pronounced in the Macquarie Rivulet cores where the facies is more widespread.

Sediments within this facies are typically dewatered and relatively compact. However, in several of the cores the facies was thixotropic in nature. The remanent high water content suggests the facies, in places, is confined by capping layers preventing dewatering. The facies is composed predominantly of fine- to medium-grained, poorly sorted subrounded muddy sand with common subangular to subrounded lithic fragments and rare small woody debris (Table 4.4; Figure 5.3). The facies typically contained examples from three estuarine bivalve and two gastropod species. The identified species include abundant abraded articulated and disarticulated *Anadara*

trapezia, minor *Notospisula trigonella* and *Batillaria australis*, rare *Nassarius burchardi* and very rare disarticulate oyster shells of various sizes. The robust structure of the articulate species suggests energy levels within the depositional environment were relatively high.

Quartz is the dominant mineral within the facies at 74.0 wt% (Table 4.5). Minerals identified within the facies include albite (14.3 wt%), kaolinite (3.2 wt%), mixed layer illite-smectite (2.6 wt%), illite (1.9 wt%), and aragonite (1. 7 wt%; Table 4.5).

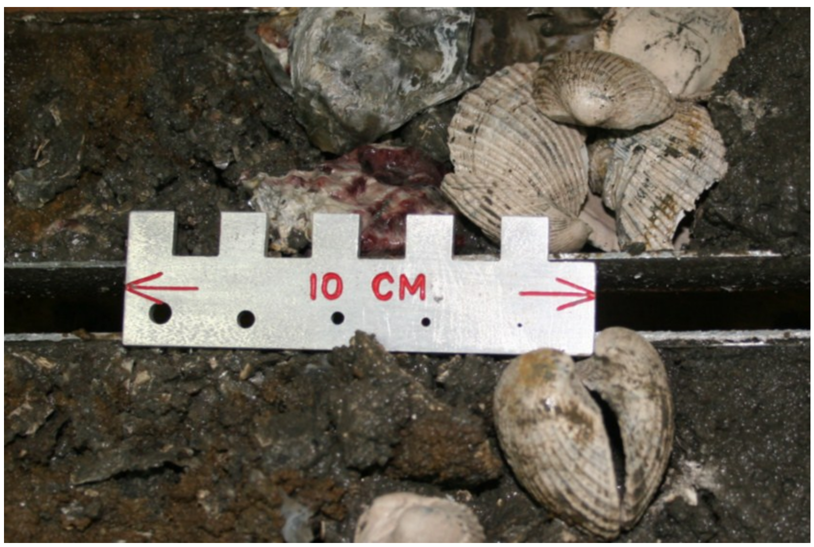


Figure 5.3: *Near shore muddy sand facies. Matrix is poorly sorted fine- to medium-grained sand with high carbonate content. Articulated and disarticulated Anadara trapezia and disarticulate* oyster shell *(MC 6, 386-400 cm).*

Previous research (e.g. Sloss *et al.* 2004, 2005 and 2006a) had suggested the Macquarie Rivulet and Mullet/Hooka Creek deltas are underlain by a marine sand sheet deposited during the latest transgressive event. The sand sheet has been described by Sloss *et al.* (2004, 2005 and 2006a) as containing medium-grained quartz sand with increased mud and terrestrial content towards the western margin of the lake with a faunal assemblage consistent with an estuarine environment. The results of this study generally support the previous findings however, this study suggests the terrestrial influence is greater than previously indicated. The sedimentary characteristics, subrounded lithic clasts, and

high organic content suggests sediments within the facies are predominantly terrestrial in origin and transported by the palaeo-waterways prior to deposition in a open estuarine environment (Stage 1a Figure 3.7). It is interpreted the near shore muddy sand facies represents the interaction between the rising sea level and fluvial processes forming the palaeo-near shore environment along the western boundary of the estuary. This interpretation is further supported as sediments with similar characteristics can be currently found along the western margin of Lake Illawarra.

5.5: Transgressive bay-fill/back-swamp facies

The transgressive bay-fill/back-swamp facies was identified in 9% of the Mullet/Hooka Creek cores analysed (13 cores; Volume 2, Appendix 4). Notably, the facies was not intersected in the Macquarie Rivulet cores.

The facies forms a thin discontinuous layer which, where present, directly overlies the Pleistocene facies. Facies colour is highly variable ranging from dark brown greys to dark purple greys. The facies is typically massive, highly plastic, very poorly sorted, strongly positive (fine) skewed, compact mud with very fine- to fine-grained sand (Table 4.4, Figure 5.4). The facies is organic-rich with common root traces, sea grass fragments and organic/woody lenses within the matrix. Although sharing similar characteristics to the Pleistocene palaeosols this facies is devoid of mottles suggesting no long term subaerial exposure has occurred during its depositional history.

The fine-grained nature of the facies (predominantly mud) and the presence of sea grass indicate facies deposition occurred in a relatively shallow low energy back-water environment, such as a sub-embayment or back-swamp. This back-water environment would have been created due to the protection provided by Hooka Point (Figure 4.3). The lack of any significant headlands and/or rocky outcrops within the Macquarie Rivulet study area is the probable reason for its absence in the 74 cores analysed from the delta.

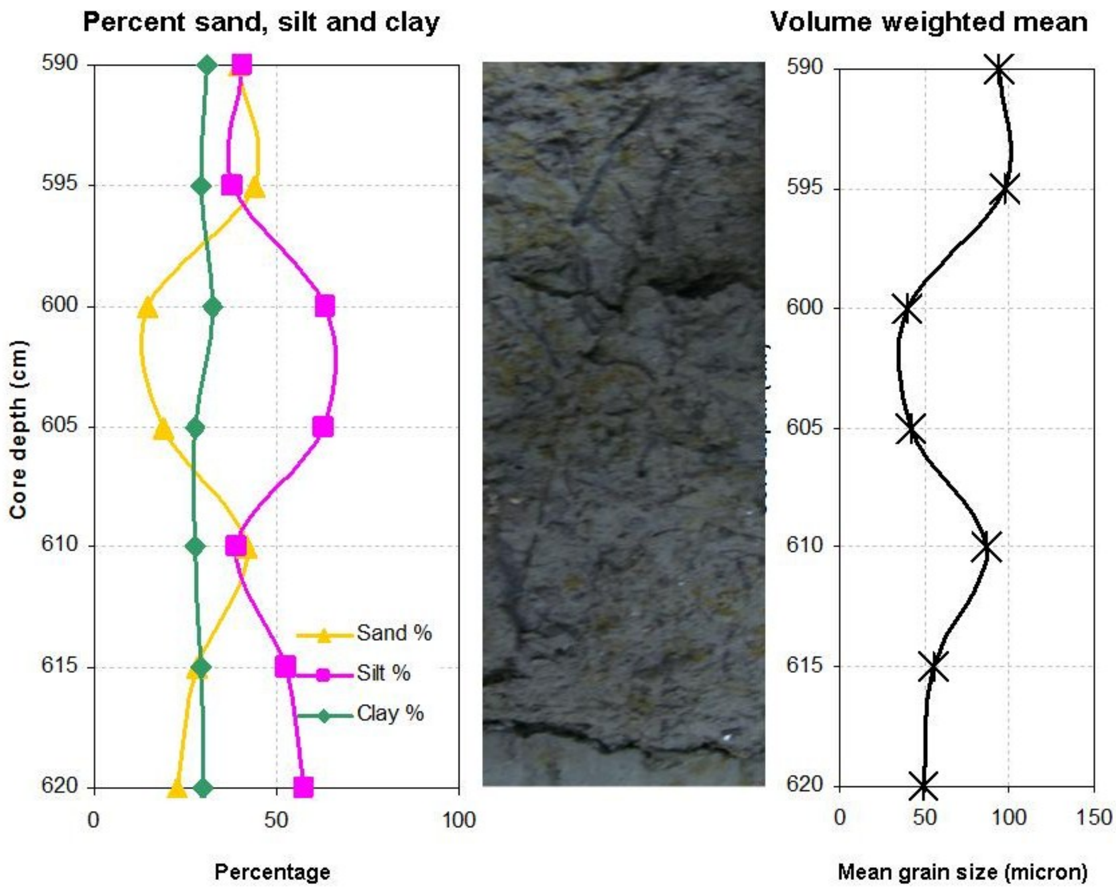


Figure 5.4: *Transgressive bay-fill/back-swamp facies (MC 49, 590-620 cm). Facies is characterised by common root traces, sea grass and organic matter. The variable grain size is due to fluvial-derived sand within the matrix. Samples analysed taken at 5 cm intervals.*

5.6: Regressive delta (Palaeodelta) facies

The basal Pleistocene and near shore muddy sand facies are overlain, in places, by a compact organic-rich, fining upwards facies (Figure 5.5). This facies was intersected in 17% of the cores analysed (25 cores, Volume 2, Appendix 4) of the cores analysed. The majority of the facies intersections occurred within the Mullet/Hooka Creek study area. This facies has been interpreted to represent a regressive delta/distributary channel which was submerged as water level within the receiving basin increased.

Basal sediments range from subrounded relatively clean very coarse-grained sand to clean fine- to medium-grained sand. Muddy fine-grained sand to very muddy very fine-grained sand is characteristic of the upper sediments. Overall the facies is poorly to very poorly sorted with positive (fine) to negative (coarse) skewness (Table 4.4). The varied mean grain size and skewness results reflect the fining upwards nature of the facies as it grades into the overlying prodelta/lagoonal mud facies.

The sedimentological characteristic of the facies intersected in MC 38 (Figure 5.6, Volume 2, Appendix 4, 5) differs slightly from the characteristics described above. In this core, the basal portion of the facies is characterised by a fining upwards succession of very compact alternating very fine- to fine-grained sand and mud laminae. The majority of the laminae in the basal sandy section (-729 to –732 cm AHD) are 2 to 3 mm thick. Above the basal succession, mud lamina thickness and frequency of occurrence increase upwards as the facies grades into the overlying prodelta/lagoonal mud facies. The upper section of the facies was intersected between -724 m and -729 cm AHD. Coleman and Gagliano (1965) noted the occurrence of parallel laminae, such as these, is typically attributable to changes in flow velocity. Furthermore, the fine-grained nature of the sediments indicates deposition possibly occurred in a low energy environment, such as in an abandoned channel or shallow back-water embayment, with decreasing fluvial/terrestrial input. The decrease in fluvial/terrestrial sediments reflects increasing water levels within the receiving basin associated with the late Pleistocene/early Holocene transgression.

Sediment grains within the facies are predominantly subangular to subrounded quartz grains (85.9 wt%; Table 4.5). The high quartz content, relative to the fluvial sand facies (72.6 wt%; Table 4.5), may reflect high energy levels within the marine influenced receiving basin reworked that facies stripping the finer sediments. The basal portions of the facies contain rare subrounded lithic fragments up to 30 mm in size. The mineralogy and extent of rounding of the lithic fragments indicate a source area proximal to the present day location of the delta. Organic components within the facies are

predominantly small twigs, coalified wood/charcoal fragments and sea grass fragments. Basal contacts are typically sharp whereas the upper contact is gradational.

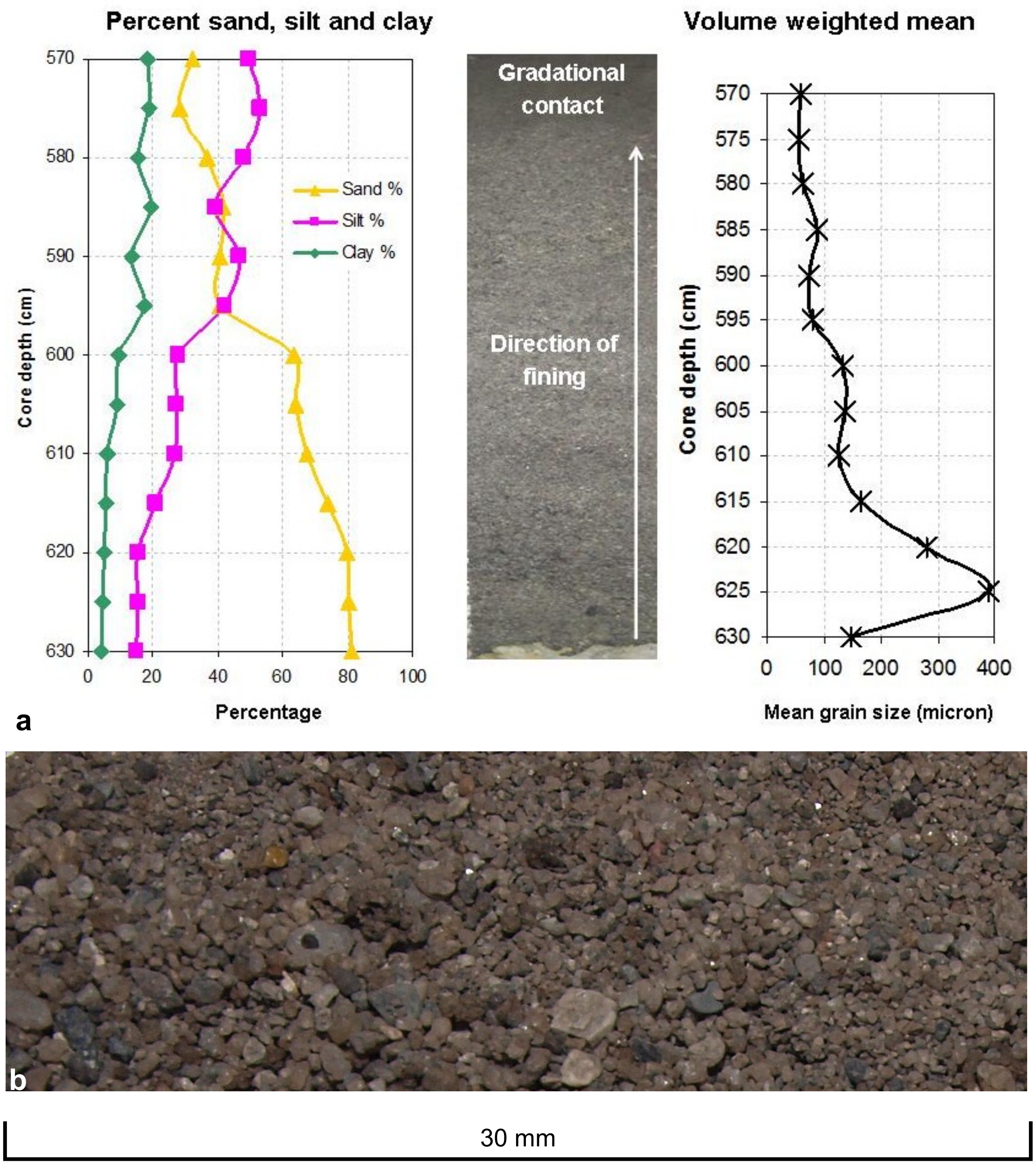


Figure 5.5: *A: Fining upwards regressive delta facies (MC 12, 570-630 cm) with corresponding grain size and percentage sand silt clay graphs. Samples analysed taken at 5 cm intervals. B: close up image of the sediment at 620-623 cm.*

Figure 5.6: *Compact fining upwards alternating sand and mud laminae overlying an organic-rich palaeosol in core MC 38 (-724 to -732 cm AHD). The frequency and thickness of mud laminae increase upwards prior to grading into the overlying prodelta/lagoonal mud. Deposit is interpreted to represent the transitional phase of the regressive delta deposit, with deposition occurring in an area of reduced flow, such as in an abandoned channel or shallow back-water embayment.*

5.7: Palaeochannel/lobe and channel/lobe abandonment facies association

The palaeochannel/lobe facies was intersected in cores MC 27, 28 31, 34, 37, 63, and 67 from the Mullet/Hooka Creek study site (Volume 2, Appendix 4, 5). Within the Macquarie Rivulet study area the facies was intersected in MR 21, 22 (Volume2, Appendix 5). The reduced number of intersections may suggest that Macquarie Rivulet's channel has been more stable and avulsed to a lesser extent within the study area. Conversely the limited number of intersections may simply represent the spatial distribution of cores simply did not intersect the facies due the channel being highly dynamic. However, the channel stability within the initial phases of the deltas evolution is supported by the underlying Pleistocene topography (Chapter 6) and historical maps of the delta (Chapter 8).

The stratigraphic position of the facies varied from core to core. For example, the facies in MC 34 directly overlies the basal bedrock whereas in MC 63 (Figure 5.7) both the upper and lower contacts are adjacent to the prodelta/lagoonal mud facies. The observed variability is attributable to a combination of the erosive capacity of the channels, sea level and the autocyclic processes of channel avulsion combined with channels operating within different time frames.

Typically, the facies grain size coarsens upwards. In the thicker successions, such as in MC 34, minor internal sedimentary packages of varied thicknesses, similar to those of the fluvial sand facies (section 5.10) were observed (Figure 5.7). These thinner coarser units have been interpreted to represent flood deposits. Facies sediments range from very poorly sorted muddy fine-grained sand through to poorly sorted relatively clean coarse-grained sand containing subrounded lithic clasts (Table 4.4, Figure 5.7). The coarser grained cleaner deposits are interpreted to represent in-channel or proximal deposits, whereas the muddy finer grained deposits are more distal. Facies sedimentology and the observed depth to which the modern fluvial sediments are found suggest water depths would have been in the vicinity of 2 to 2.5 m at the time of deposition.

Basal contacts are typically sharp with gradational upper contacts. This is particularly pronounced when the upper and lower facies contacts are in the prodelta/lagoonal mud facies. Furthermore, cores MC 31 and 63 intersected a fining upwards succession directly overlying the palaeochannel/lobe facies (Figure 5.7). Basal sediments of the overlying facies are typically poorly sorted muddy sand fining upwards to a very poorly sorted fine-grained sandy mud (Table 4.4). This facies is interpreted to represent channel/lobe abandonment, attributable to increased water levels within the basin and/or channel avulsion.

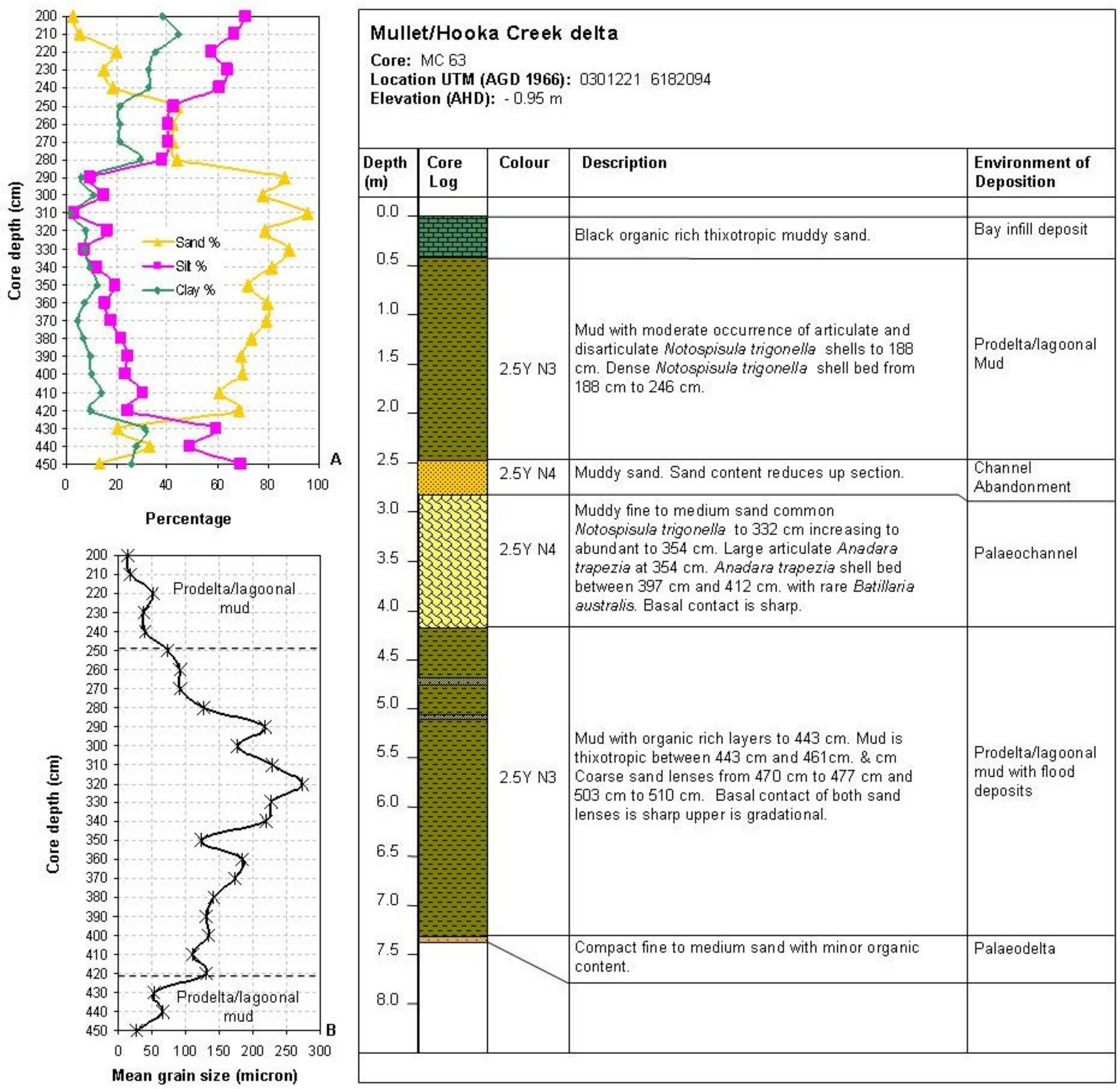


Figure 5.7: *MC 63 core log shown with sand, silt and clay percentages (A) and mean grain size (B) graphs for the palaeochannel/lobe facies and overlying channel/lobe abandonment succession between 240-420 cm. Note the increased mean grain size between 300-320 cm and overlying fining upwards sequence. This sequence is interpreted to be a period of higher flow, such as more common flood events. Samples analysed taken at 10 cm intervals.*

The mineralogical composition of the palaeochannel/lobe facies is similar to the distal delta (section 5.9) and fluvial sand (section 5.10) facies. These similarities suggest the sediment within the facies is sourced from the same area. Within the facies quartz is the

most abundant mineral at 67.9 wt% with albite (11.2 wt%), mixed layer illite-smectite (6.4 wt%), kaolinite (5.7 wt%), illite (3.5 wt%), aragonite (3.4 wt%), pyrite (1.4 wt%) and labradorite (1.4 wt%; Table 4.5).

5.8: Prodelta/lagoonal mud facies

The prodelta/lagoonal mud facies forms a semi-continuous, layer underlying both the Macquarie Rivulet and Mullet/Hooka Creek study sites. This facies was intersected in 102 of the 147 cores (69.5%; Volume 2, Appendix 4). Typically, within the modern lake Illawarra setting the prodelta/lagoonal mud facies is found in water depths of 2 m or greater, where flocculation can occur in calmer water. However, there are examples in the modern environment, such Koona Bay adjacent to the Macquarie Rivulet delta, where muds are accumulating. The presence of muds within Koona Bay is attributable to the Macquarie Rivulet delta lobes reducing the impact of wind waves enabling a calm environment in which sedimentation can occur. This variability in the facies depositional depth is inferred to have occurred in the past based on the stratigraphic sequences and facies depths relative to current sea level and the sea level curve proposed by Sloss *et al.* (2007) preserved in the analysed cores.

The facies is dark greenish black to olive black in colour, very poorly to poorly sorted with a positive (fine) to near symmetrical skewness and a mean grain size equivalent to silt (Table 4.4, Figure 5.8). Although the mean grain size is silt, the facies is bimodal as the matrix contains minor quantities of very fine-grained sand in some sections. The presence of very fine-grained sand within the facies differs from the equivalent facies in the Wandandian Creek delta, St Georges Basin as described by Hopley (2004) and Hopley and Jones (2006). The facies is typically cohesive in nature; however several thixotropic sections were identified. Organic constituents include sea grass fragments, rare small woody debris, charcoal fragments and remnants of leaves. It is not uncommon for the facies to contain thinly parallel laminated organic-rich layers. These organic-rich layers are likely to reflect settling of suspended organic matter transported during flood events. Significantly, the facies lacks ripple cross-beds as observed by

Nichol *et al.* (1997) in the central basin mud from the Hawkesbury River estuary. The lack of ripples or similar sedimentary structures within the facies is likely to reflect the reduced influence of tidal currents within Lake Illawarra when compared to the Hawkesbury River estuary. The reduced tidal influence is attributable to the presence of the emerging/emerged barrier to the east of the study area limiting the influence of marine processes.

Quartz is the primary mineralogical constituent at an average of 54.4 wt% (Table 4.5). The facies also contains albite (27.3 wt%), calcite (19.8 wt%), kaolinite (9.2 wt%), orthoclase (8.4 wt%), mixed layer illite-smectite (7.0 wt%), illite (3.2 wt%), labradorite (2.6 wt%) and aragonite (2.3 wt%; Table 4.5). The high average carbonate content within the samples analysed is attributable to the small shell fragments within the facies.

In areas where the facies is proximal to the water table, such as MC 41 (Volume 2, Appendix 4), the sediment shows signs of acidification. The sediment in these localities contains common pale yellow jarosite traces, formed by a series of oxidation reactions from pyrite (Figure 5.9a, Grattan-Bellew and Eden 1975). Furthermore, the facies, in these localities, is characterised by a lack of carbonate material, such as shells. However, shells were originally present in this facies as several shell moulds were found (Figure 5.9b). The gypsum crystal in MC 41 (Figure 5.9c) provides further evidence for the acid generation potential of the facies. The formation of gypsum crystals in these environments would have been due to the dissolved carbonate reacting with the saline and acidic ground water. The likely reaction equation is

$CaCO_3 + H_2SO_4 + H_2O \longrightarrow CaSO_4.2H_20 + CO_2$ (Grattan-Bellew and Eden 1975).

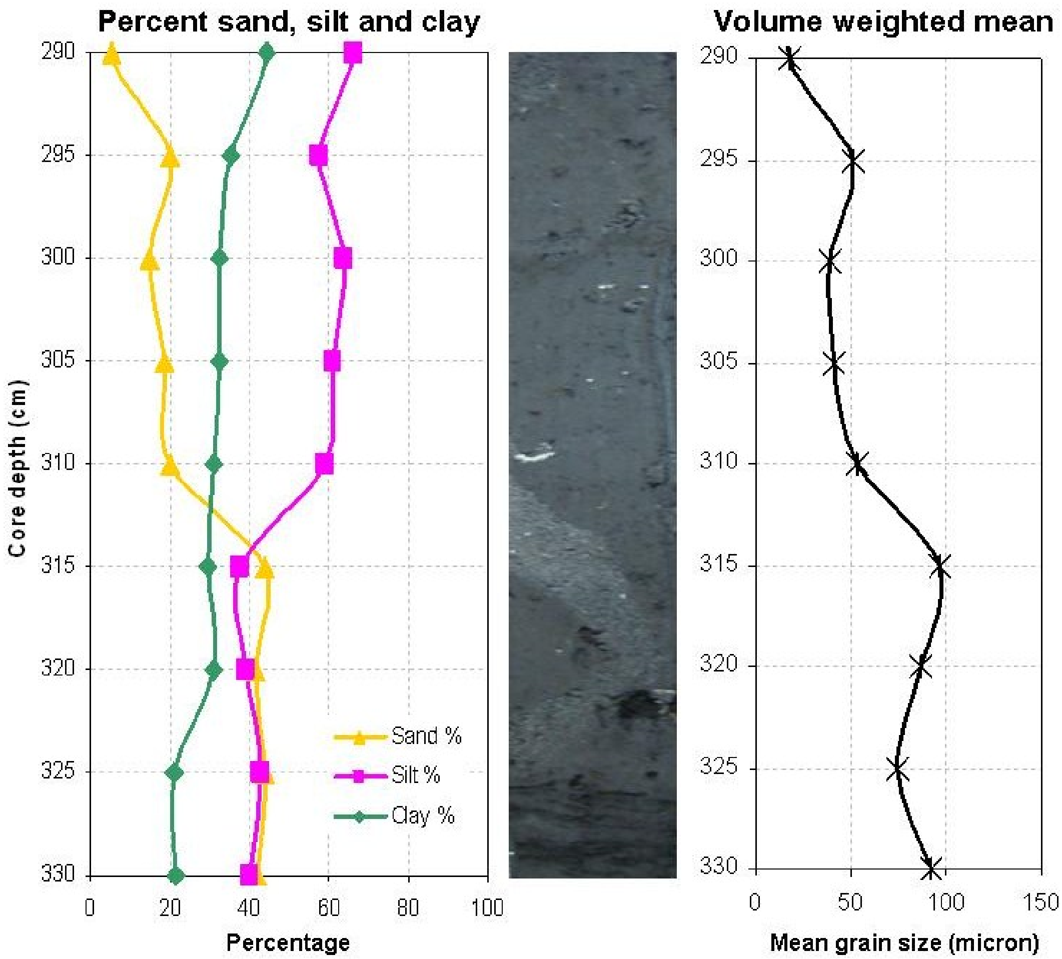


Figure 5.8: *Typical appearance of sediments within the prodelta/lagoonal mud facies (sub-section of MC 13, 290-330 cm) with corresponding grain size and percentage of sand, silt and clay graphs. Note burrow infilled with sand. Samples analysed taken at 5 cm intervals.*

The facies contains common densely packed shell beds of various thicknesses and vertical distributions. Shell beds are dominated by articulated and disarticulated examples of the estuarine mollusc *Notospisula trigonella* in a matrix of shell hash and mud (Figure 5.10). Thin walled *Tellina deltoidalis* (Figure 5.11), moderate *Notospisula trigonella* and rare *Anadara trapezia* (Figure 5.11) fragments are the primary constituents of the shell hash. *Notospisula trigonella* valve widths range in size from 15 mm to 30 mm, with the majority having valve widths of 20 mm.

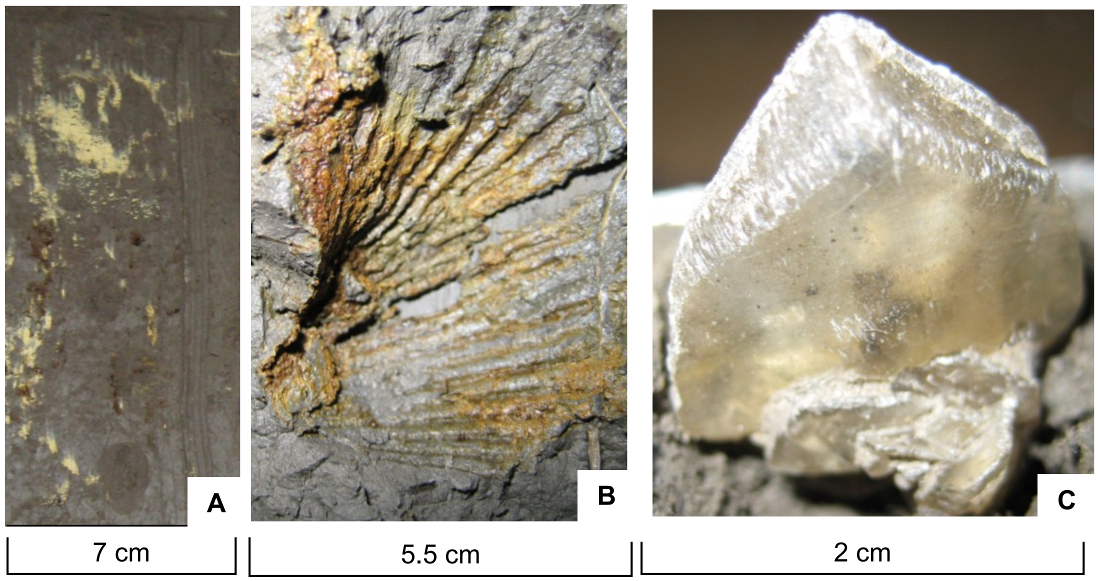


Figure 5.9: *Photos A (jarosite traces; MC 42), B (shell mould; MC 40) and C (gypsum crystal; MC 41) provide evidence of the high acid generation potential of the prodelta/lagoonal mud facies where it occurs close to the current water table.*

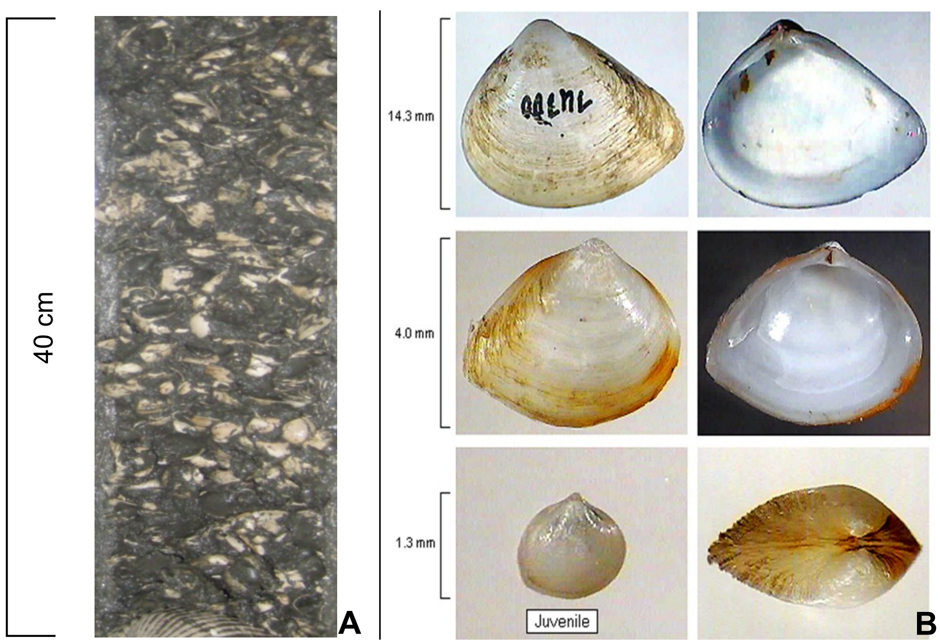


Figure 5.10: *Photo A illustrates a typical example of a densely packed* Notospisula trigonella *shell bed, note the presence of articulate* Anadara trapezia *at the base of the image (MC63, 265-305 cm). Images of adult (top), adolescent (middle) and juvenile bottom)* Notospisula trigonella *along with typical valve widths (from Ponder et al. 1998).*

5.9: Distal delta facies

In 50% (73 cores) of the analysed cores the distal delta facies was observed (Volume 2, Appendix 4). This facies represents the transition from the deeper water, low energy central basin deposits associated with the prodelta/lagoonal mud to the higher energy fluvial influenced zone. The facies consists of very poorly to poorly sorted, strongly fine to fine skewed sandy silt that coarsens upwards (Table 4.4). The coarsening upwards nature of the facies is attributable to delta progradation (Figure 5.12).

Within several cores (e.g. MC 25 and MC 26; Volume 2, Appendix 5) the facies contained coarser units with sharp basal and gradational upper contacts. The facies also contains rare thin organic-rich and muddy lenses of varied thicknesses and distributions throughout the facies. The presence of the coarser units, associated with high flow periods, and the organic-rich/muddy units, associated with low flow periods, highlight the variable nature of flow regimes and climatic conditions within the catchments throughout the Holocene.

Visual delineation of the boundary between the distal delta and underlying prodelta/lagoonal mud facies is difficult due to the gradational nature of the contact. However, texturally the boundary can be delineated with ease as it is characterised by a significant increase in the quantity of very fine-grained sand within the matrix. Laser particle size analysis was the most accurate way to delineate the boundary between the facies. This study has defined the boundary as the point where the volume weighted mean transitions from silt to very fine-grained sand while the percentage silt exceeds the percentage of sand (Figure 5.13). Mineralogical composition of the facies is comparable to the underlying facies with quartz being the major constituent at 66.6 wt% (Table 4.5).

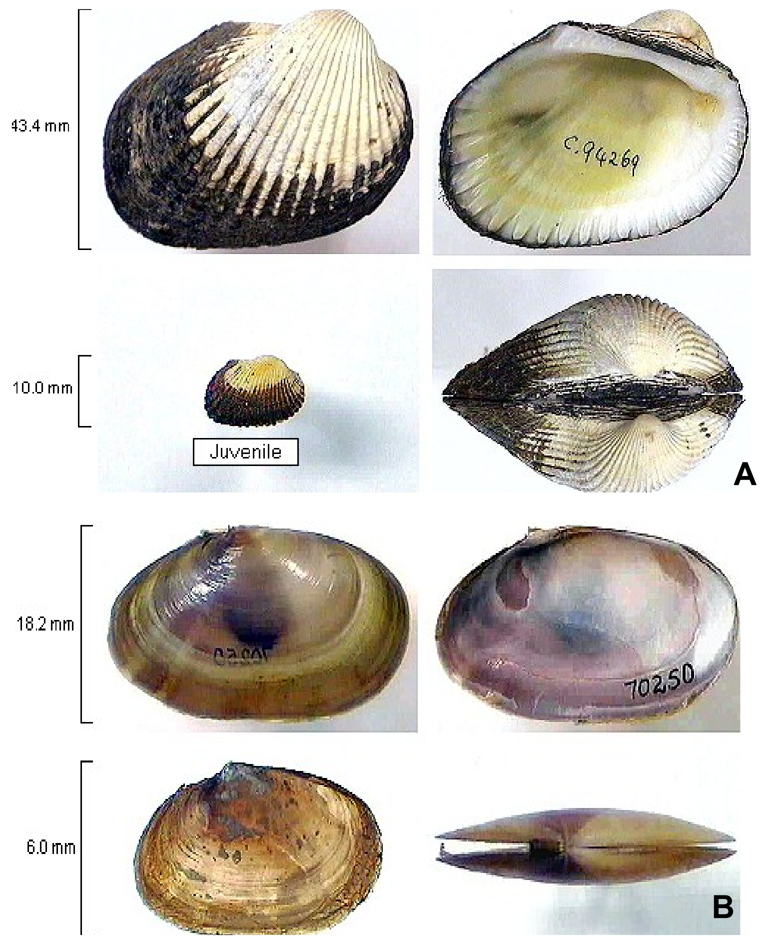


Figure 5.11: *Photos illustrates articulated and disarticulated specimens of* Anadara trapezia *(A) and* Tellina deltoidalis *(B) (from Ponder et al. 1998).*

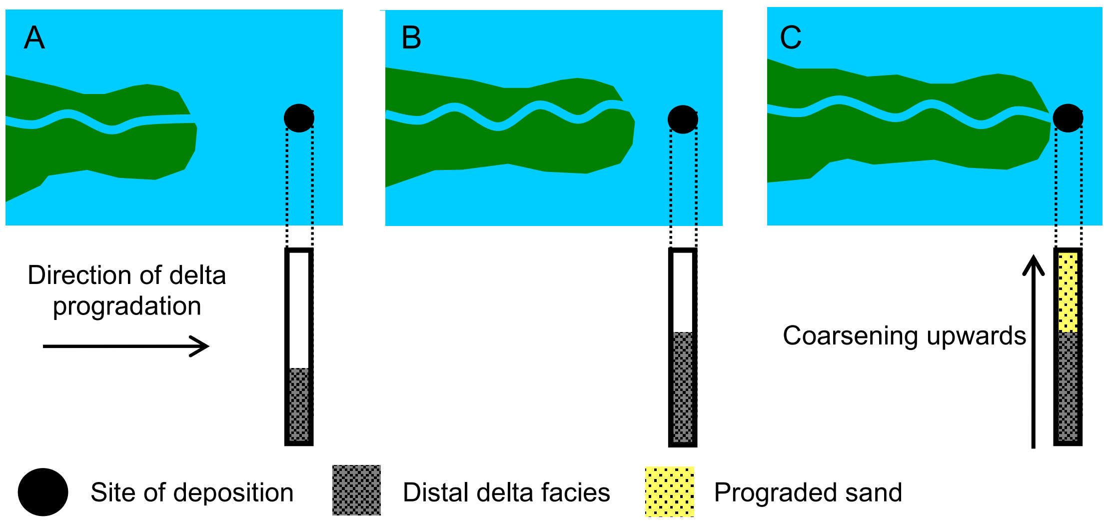


Figure 5.12: *The relationship between the site of deposition, the channel mouth and the type of sediment deposited is illustrated. The distal delta facies is deposited when the channel mouth is more distal (A) and coarsens upwards as the channel mouth becomes more proximal (B), whereas prograded sand is deposited when the channel mouth is at the site of deposition (C).*

5.10: Fluvial sands facies

The organic-rich fluvial sand facies forms the uppermost facies deposited entirely in a subaqueous environment as a result of active delta progradation. The facies forms a discontinuous layer in relatively shallow water, typically above -1.5 m AHD in the modern environment. The facies was intersected in 74% of the cores analysed (109 cores; Volume 2, Appendix 4).

The facies is characterised by sharp high energy erosional contacts (low frequency of occurrence) and higher frequency low energy gradational contacts. Sediments associated with sharp contacts are typically poorly sorted, fine skewed, medium to coarse-grained sands (Table 4.4, Figure 5.14). Where the contact is gradational the contact is defined as the point in the core where sand content, by percentage of total sample, exceeds the silt content. Furthermore, the percentage of sand above the defined contact must, as a minimum, remain stable or increases upwards.

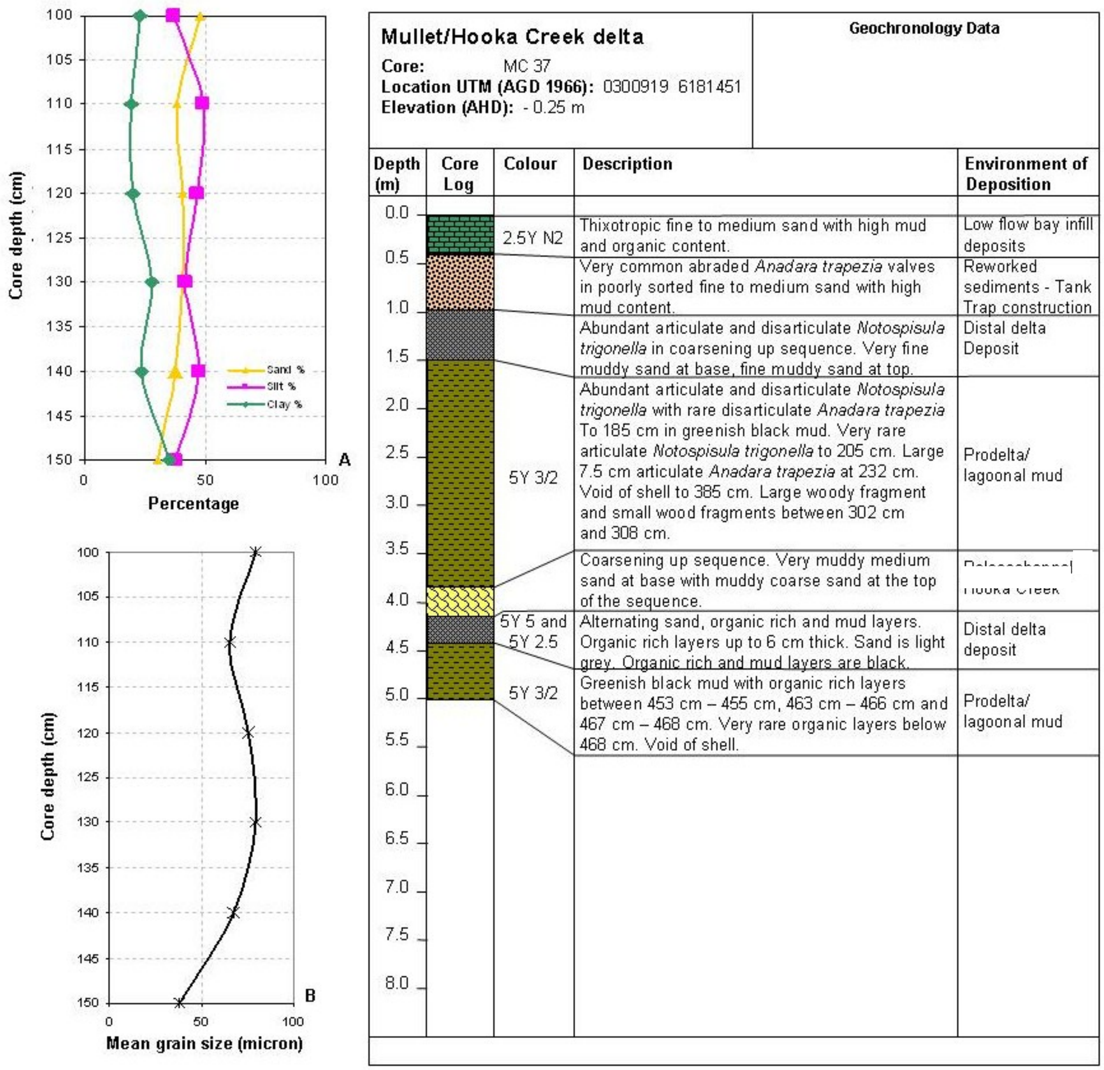


Figure 5.13: *MC 37 core log shown with sand, silt and clay percentages (A) and mean grain size (B) graphs for the distal delta facies, between 100-150 cm. Note the percentage sand exceeds the percentage silt between 100-105 cm marking the upper boundary of the facies in the core. Samples analysed taken at 10 cm intervals.*

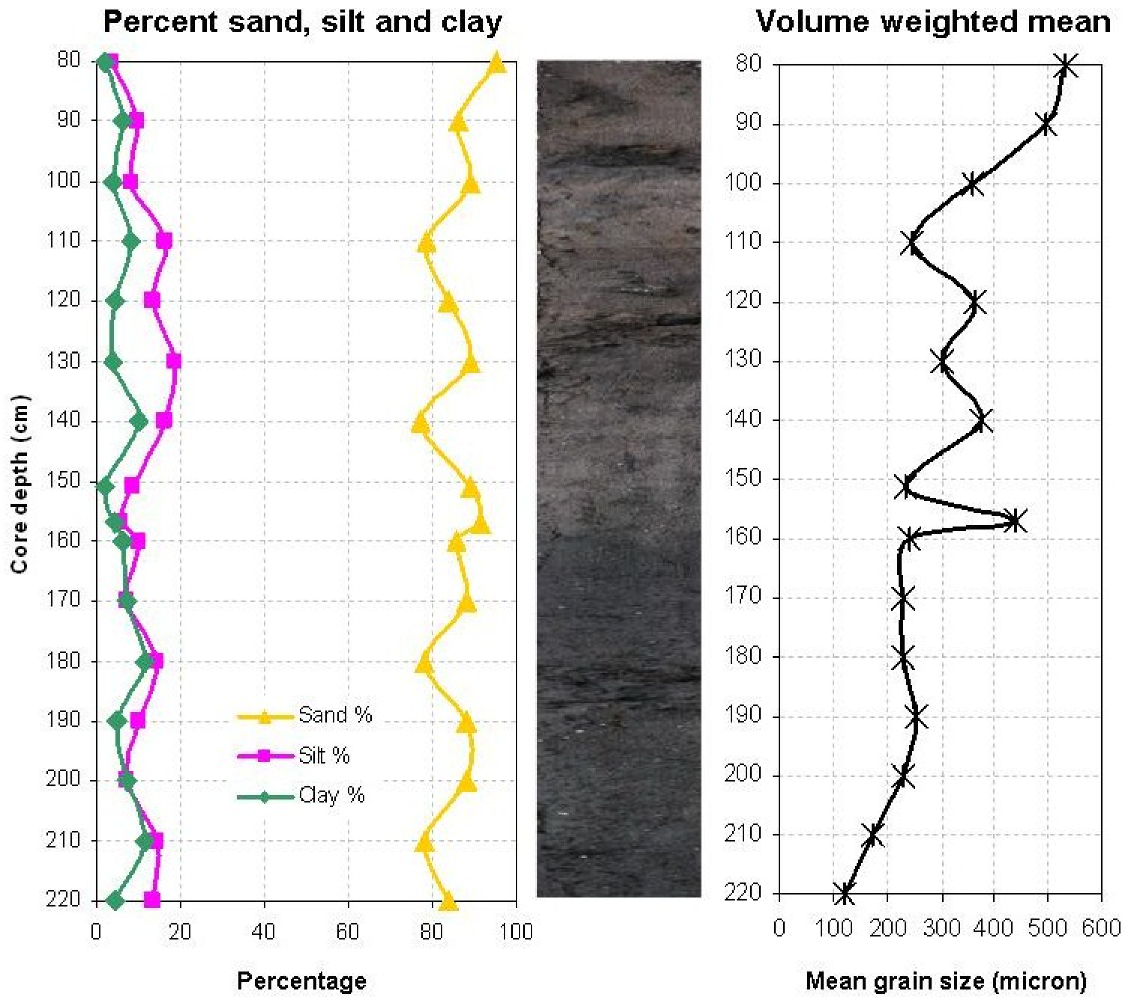


Figure 5.14: *Photo of fluvial facies (MR 19, 80-220 cm) with sand, silt and clay percentages and grain size analysis graphs. Note the sharp increase in grain size at 157 cm core depth and subsequent fining upwards trend to 151 cm. This is characteristic of a flood deposit. Samples analysed taken at 10 cm intervals.*

Irrespective of the basal contact, the facies typically coarsens upwards (Figure 5.14). Maximum observed grain size was very coarse sand with rare subrounded granules and pebbles of mixed lithologies. This coarsening upwards trend is attributable to delta progradation and proximity of the channel mouth (Figure 5.12). The overall degree of sorting also increases up section to moderate from the poorly sorted basal sediments. The facies also contains common organic fragments and rare organic-rich laminae such as those observed in MC 38.

Although the overall facies coarsens upwards, sedimentary packages of varied thicknesses were identified in several of the cores analysed. These packages have been interpreted to represent flood deposits, due to the fining upwards nature of the sequences, the sharp basal and gradational upper contacts. Basal grain size is highly variable, however all of the identified packages fined upwards (Figure 5.14). The variability in the basal grain size observed is attributed to the proximity of the channel mouth and the magnitude of the flood event.

Modern fluvial sands deposited in Koong Burry Bay (Figure 4.12) contain higher mud contents than those at the mouth of Mullet Creek. It is probable the observed variance is attributable to the higher velocity waters in the tank trap entering the very shallow bay. The shallow nature of the bay results in the rapid expansion and diffusion of the outflowing water, forming a localised turbulent homopycnal flow. These interactions reduce the outflowing waters capability to transport sediment resulting in rapid deposition of the bedload, saltating and suspended sediment.

Facies mineralogy is consistent with the other identified facies, due to the confined nature of the catchments limiting the sediment source area (Table 4.5). However, the average weighted quartz content of 72.6 wt% is lower than the averaged result for the regressive delta facies at 85.9 wt% (Table 4.5). The lower quartz content in the fluvial facies is likely to represent the removal of the finer material as the transgressive event reworked the regressive delta deposit. Colour is highly variable ranging from dark grey black, to lighter greys and olive yellows in the subaqueous sediments. Sediments, now elevated above the current water table are typically oxidised to various extents. Colour of the oxidised sediments ranges from light yellows, associated with oxidation of sulfur-rich minerals such as pyrite, through to bright reds and oranges, associated with the oxidation of iron-rich mineral constituents.

This facies contains rare examples of *Anadara trapezia* yet is void of other bivalves such as *Notospisula trigonella*. The lack of *Notospisula trigonella* is due to increased energy levels and sedimentation rates proximal to the distributary channel mouths. The most prevalent macrofossils present in reducing frequency of occurrence are *Batillaria australis, Nassarius burchardi and Polinces (Conuber) sordidus* (Figure 5.15). Many of the gastropods identified showed evidence of predation (bore holes in shells) and post-mortem reworking.

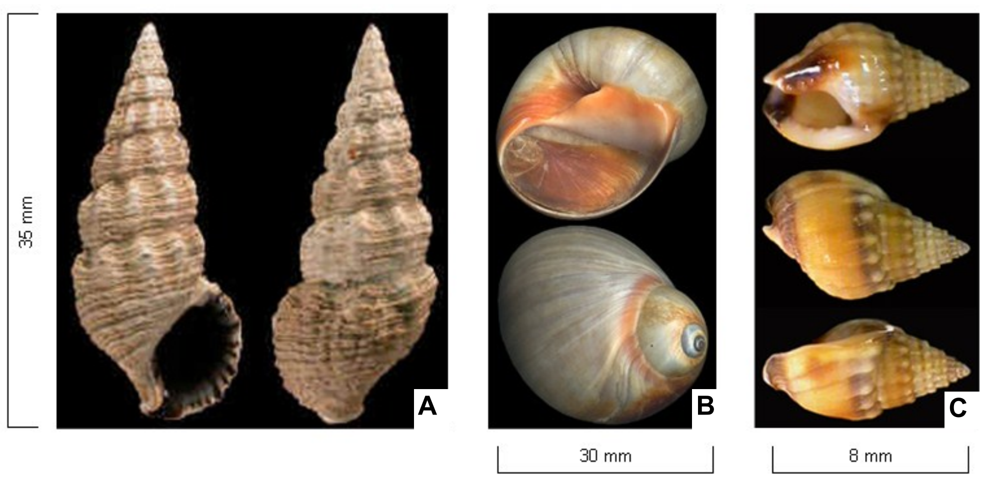


Figure 5.15: *Images of gastropods* Batillaria australis *(A),* Polinces (Conuber) sordidus *(B) and* Nassarius burchardi *(C) (from Beechey 2010).*

5.11: Floodplain levee and splay facies association

The floodplain levee and splay facies association was observed in 56% of cores analysed (87 cores; Volume 2, Appendix 4). The facies thickness and sedimentary composition is highly variable; however, overall the facies fines upwards.

The basal component of the facies association contains relatively clean poorly sorted fine to medium-grained sands (Table 4.4) interspersed with brownish black silty sand layers (Figure 5.16). The alternating nature of the lower facies, observed in some cores, is due to decreasing water depths as the facies transitions from the underlying subaqueous environment to a subaerial depositional environment. Due to continued

vertical accretion, the thickness and frequency of the sandy layers decreases rapidly once subaerial exposure occurs.

After subaerial exposure the facies is characterised by organic-rich black/brown very poorly sorted silty sand or sandy silt (Figure 5.16, Table 4.4). The ratio of sand to silt in the upper portion is highly variable throughout the cores analysed. This compositional variability is likely to reflect the channels proximity to the depositional site, i.e. the silty sands are likely to be more proximal to the channel than the sandy silt. The upper portion of the facies is also characterised by well developed modern root traces.

Within the floodplain/levee facies several sandy subunits of various thicknesses and vertical positions with respect to 0 m AHD were observed. These units have been interpreted to be splay deposits and are characterized by sharp basal and gradational upper contacts. Provision of a sedimentological description of the unit, where intersected, is problematic as the sediments are highly variable. This observed variability is attributable to the proximity of the channel from which the splay originated, as the grain size decreases rapidly away from the source channel as the energy dissipates across the floodplain.

5.12: Cut-off bay infill facies

The cut-off bay infill facies was identified in both the Macquarie Rivulet (8% or 6 cores; Volume 2, Appendix 4) and Mullet/Hooka Creek (19% or 13 cores; Volume 2, Appendix 4) cores. The facies, when intersected, forms a thin continuous layer as a shallow water distal deposit in shallow cut-off embayments.

Sediments within the facies are dark olive to greenish black in colour very poorly to poorly sorted, strongly fine to fine skewed, fine-grained sandy silt to silty fine-grained sand (Figure 5.17, Table 4.4). The observed variability, particularly mean grain size, is

due to the proximity of the delta's distributary channel mouth to the point of deposition and the velocity of the out flowing water. Although, facies sedimentology is similar to the distal delta facies, there are several distinguishing features of the bay infill facies including:

1. mean grain size fines upwards or remains stable up profile;
2. thixotropic;
3. contains significant quantities of organic material such as sea grass; and
4. the facies contact with the underlying unit can be visually distinguished.

Mineralogy of the cut-off bay infill facies is similar to the underlying facies. Quartz was the dominant mineral identified, with an average weight percentage of 69.0 wt%. Other minerals identified included illite (9.0 wt%), kaolinite (8.9 wt%), mixed layer illite-smectite (5.2 wt%), albite (3.1 wt%), labradorite (2.1 wt%) and aragonite (2.0 wt%; Table 4.5).

5.13: Minor deposits and imported fill

Although not defined as significant facies/facies associations with respect to the Holocene evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas, three additional facies and two imported fill units were identified. The facies and fill discussed in this section are low flow deposits, flood deposits, reworked muddy sands, back-swamp deposits and imported fill/coal wash. Due to the nature of the facies (i.e. high organic contents and the difficulty in extracting representative samples) it was not possible to obtain grain size data using laser particle analysis. Thus the sedimentary description outlined below is based on visual assessments of the units within the split cores.

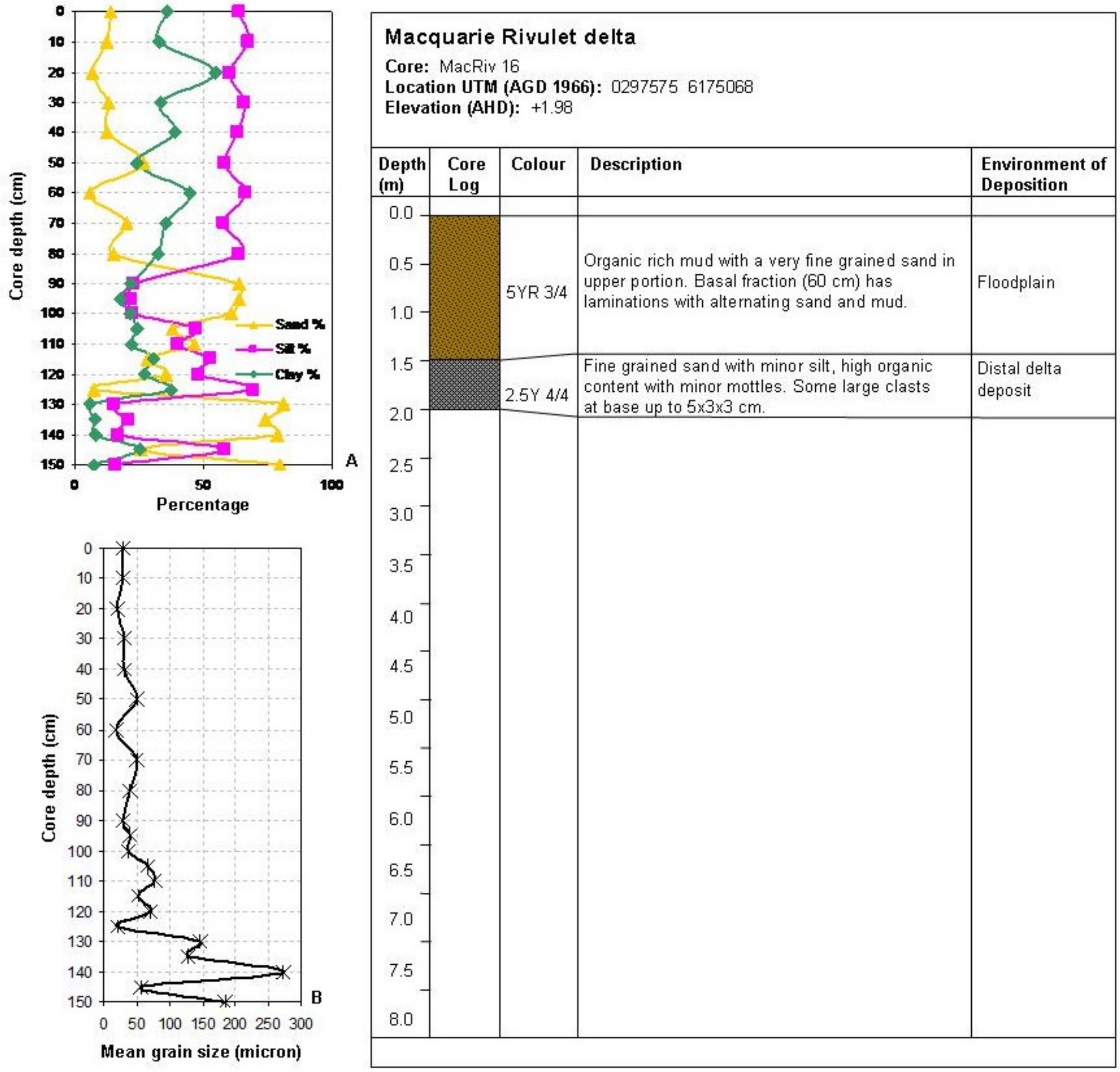


Figure 5.16: *MR 16 core log shown with sand, silt and clay percentages (A) and mean grain size (B) graphs for the floodplain/levee facies, between 0-150 cm. Note the variability in the basal 60 cm of the mean grain size and sand, silt and clay graphs. This variability is due to the alternating sand and silty sand layers marking the transition from the subaqueous to subaerial depositional environments. Samples analysed taken at 10 cm intervals.*

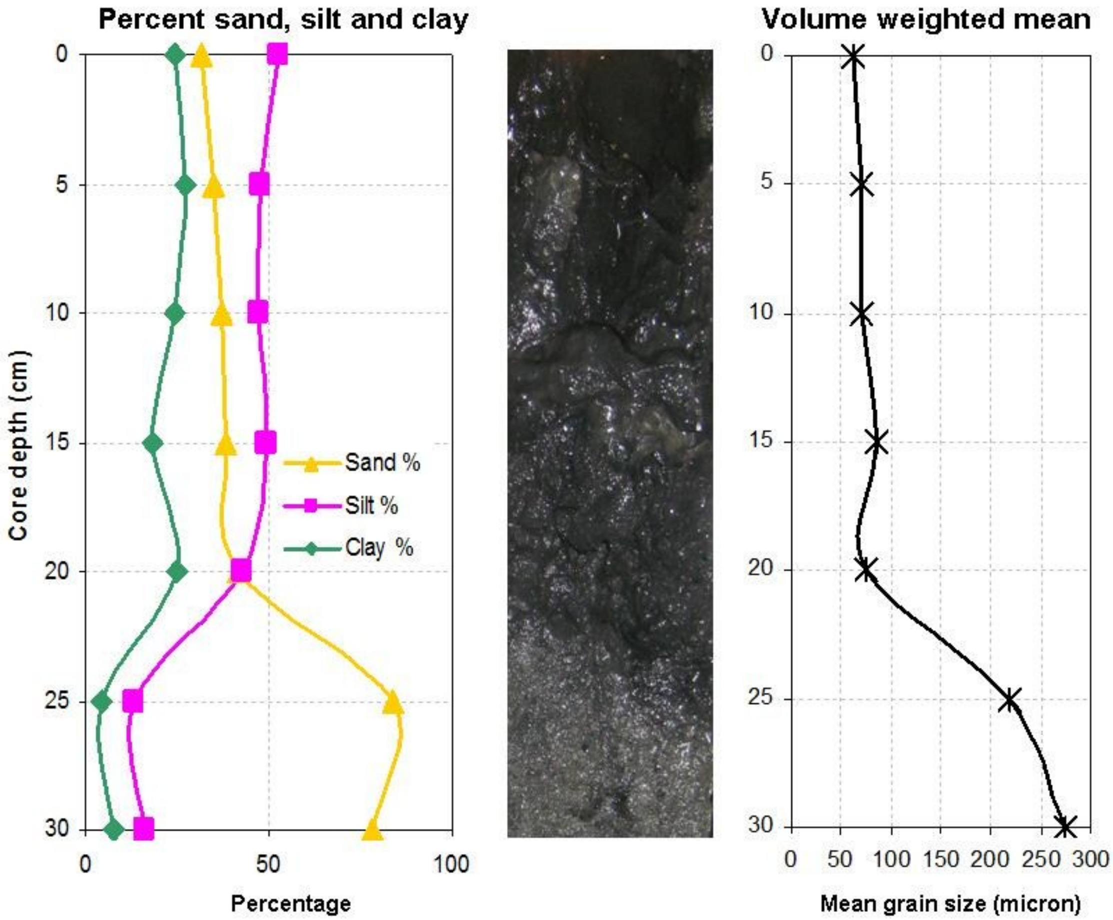


Figure 5.17: *Extract of core log (MC 65, 0-30 cm) with sand, silt and clay percentages and grain size analysis graphs. Note the distinct visual and sedimentological distinction between the dark coloured bay infill facies and underlying fluvial sand. Samples analysed taken at 5 cm intervals.*

5.13.1: Low flow deposits

Low flow deposits were identified in a total of 29 cores, 19 from the Macquarie Rivulet and ten from Mullet/Hooka Creek study sites (Volume 2, Appendix 4, 5). This facies is typically associated with the fluvial sand facies; however the facies, to a lesser extent, occurred in the distal delta deposits.

The facies is characterised by a significant increase in organic matter, which is often in distinct layers, and mud content. The basal contact is typically sharp with a gradational

upper contact. Furthermore, grain size within the unit is noticeable finer than the surrounding sediments. The overall sedimentological composition of the low flow deposit ranges from organic muddy fine-grained sand to fine-grained sandy mud. However, several of the deposits identified were composed of muddy medium- to coarse-grained sand. These coarser deposits are typically more proximal to channels which are likely to have been reactivated during high flow periods, such as flood events.

5.13.2: Flood deposit facies

Cores MC 33-36, 59, 60, 63, 66 and 68 intersected a sedimentary unit of variable thickness and elevation relative to 0 m AHD. These deposits have been interpreted to represent flood deposits (Figure 4.3, Volume 2, Appendix 4, 5). Deposits typically occur within the fine-grained prodelta/lagoonal mud; however the unit was also associated with the fluvial facies (MC 34, 59 and 60).

The flood deposit unit is characterised by a sharp basal contact, significant increase in grain size above the contact followed by a fining upwards profile. Flood deposits within the prodelta/lagoonal mud facies are characterised by organic-rich muddy fine-grained sand to muddy fine- to medium-grained sand. Based on grain size characteristics it is interpreted that the coarser units are more proximal to the distributary channel than the finer units. However, when the stratigraphic position and deposit thickness of the coarser units (e.g. MC 66) is taken into consideration it is also possible that the coarser units represent larger sustained flood events. Identified flood deposits associated with the fluvial sand facies are much coarser than those associated with the prodelta/lagoonal mud facies. For example, the two lower flood deposits identified in MC 34 contained coarse-grained sand with common sub- to well-rounded quartz granules. The increased grain size and stratigraphic position indicates that these units were deposited in-channel or proximal to the distributary channel mouth.

5.13.3: Back-swamp deposits

Delta progradation, levee development and channel avulsion can result in the formation of back-swamps, which are either permanently or intermittently inundated. Cores MR 5, 12, 22-23, 36 (Figure 4.2) and MC 35 (Figure 4.3) intersected, at shallow depths (relative to AHD), a facies which has been interpreted to represent a deposition within a back-swamp (Volume 2, Appendix 4, 5).

Where intersected the facies is characterised by dark brownish black to greenish black organic-rich silt-sized sediments with minor amounts of very fine-grained sand. Decomposition of the organic matter within the facies has resulted in the formation of biogenic gas with a very strong and distinctive hydrogen sulphide smell. In the case of MR 36, a subaqueous core, core extraction facilitated degassing of the deposit. This degassing resulted in the continued release of gas from the core hole for several minutes. The nature of the sediment and the highly gaseous nature of back-swamp deposits is consistent with Hopley (2004) and Hopley and Jones (2006) descriptions of the Wandandian Creek delta, St Georges Basin back-swamp deposits.

5.13.4: Reworked muddy sands

Excavation of the tank trap in the early 1940's resulted in the formation of the reworked muddy sand unit. Although only intersected in MC 37 between -65 cm and -125 cm AHD (Volume 2, Appendix 4, 5), it is probable the unit is laterally extensive and would be intersected if additional cores were collected near the tank trap and mouth of Hooka Creek. The unit contains abundant abraded disarticulated *Anadara trapezia* valves and valve fragments in a very poorly sorted muddy fine- to medium-grained sand. Based on the stratigraphic position of the unit and its sedimentary composition it is probable the unit would have formed part of the upper distal delta or fluvial sand facies before disturbance.

5:13.5: Imported top soil and coal wash

Cores MC 53 and 54 intersected a layer of imported topsoil and coal wash that overlies the fluvial sand (MC 53) and the prodelta/lagoonal mud (MC 54) facies (Volume 2, Appendix 4, 5). This material has been imported to level the northern side of Fred Finch Park (Figure 4.3) which is currently used as an open space recreation area. Although, not significant with respect to delta evolution, coal wash emplacements can generate ammonia (Ecoengineers 2012). The mobilisation of ammonia and introduction into waterways can have adverse impacts on water quality.

5.14: Chapter summary

High resolution analysis of 147 cores from the Macquarie Rivulet (73) and Mullet/Hooka Creek (74) deltas resulted in the identification of a 17 facies with several combined to facies associations. The identified facies/facies associations and minor deposits include:

- basal facies association (weathered bedrock, Pleistocene sediments, channel fill sands and palaeosol);
- near shore muddy sand facies;
- transgressive bay fill/back swamp;
- regressive delta (palaeodelta) facies;
- palaeochannel/lobe and channel/lobe abandonment facies association;
- prodelta/lagoonal mud facies;
- distal delta facies;
- fluvial sands;
- floodplain levee and splay facies association;
- cut-off bay infill facies;
- low flow deposits;
- flood deposit faces;
- back-swamp deposits;
- reworked muddy sands; and
- imported coal wash and top soil.

The results indicate the near shore muddy sand deposit, previously described and interpreted as marine in origin, is primarily estuarine in origin and composed of terrestrial sediments in the delta study areas. This reclassification of the facies origin is due to the subrounded lithic clasts and sediments, poor sorting, high organic content, presence of fauna associated with estuarine environments and lack of marine fauna. The research has identified two facies which have previously been undescribed in Lake Illawarra or other estuaries along the South Coast of New South Wales. The transgressive bay-fill facies represents deposition of sediments within a sheltered environment as sea level flooded the palaeoland surface. Identification and description of the regressive delta facies within the study areas is the more significant of the two newly described facies. These data provides additional information about how these deltas responded to the Holocene transgression. Specifically, the palaeodeltas were unable to keep up with the rate of sea level rise resulting in them becoming drowned.

Chapter 6
Holocene Evolution of Macquarie Rivulet delta

6.1: Introduction

Macquarie Rivulet delta, a fluvial dominated delta, is actively prograding into the southwestern quadrant of Lake Illawarra. The Holocene stratigraphic and morphological evolution of the delta with respect to autocyclic and allocyclic processes is discussed in this chapter. The evolutionary discussion presented in this chapter is based on the analysis and interpretation of 74 cores (Volume 2, Appendix 5) and six cross/long-sections (Figure 6.1). GIS models representing the receiving basin morphology and the spatial distribution of various key facies will be presented and discussed. The application of AAR, ^{210}Pb, AMS and ^{14}C dating techniques were utilised to establish the delta's geochronology.

6.2: Evolution of Macquarie Rivulet delta

The Holocene evolution of Macquarie Rivulet has been influenced by a range of autocyclic, allocyclic and anthropogenic factors. The following sections will address the evolution of the delta based on the geochronological and sedimentological information derived from the detailed coring program.

6.2.1: The late Pleistocene receiving basin and basal regressive delta units

River channels during the late Pleistocene sea level low adjusted their hydraulic gradients by incising into the antecedent land surface forming topographic lows, such as those identified in Lake Illawarra by Roy and Peat (1974, 1975) and Sloss *et al.* 2005. These topographic lows have subsequently been partially infilled during the Holocene. The Macquarie Rivulet study area appears to have been dissected by a major channel south of the current channel (Figure 6.2). This channel is also evident in Macquarie Rivulet delta section E-F. Topographically, the minimum depth to the channel at the

northeastern end approaches, and may exceed, -10 m AHD in cores MR 28 and 32 (Volume 2, Appendix 5). Figure 6.2 and Macquarie Rivulet section C-D (Figure 6.1) suggests the channel tapered out towards the southwest. The apparent tapering off of the channel observed is more likely a reflection of the increased spatial distribution of the cores (MR 46-49, 54-55) in the southwestern quadrant of the study area. The increased spatial distribution is attributable to limited access as much of the western margin of the study area is covered by a housing development.

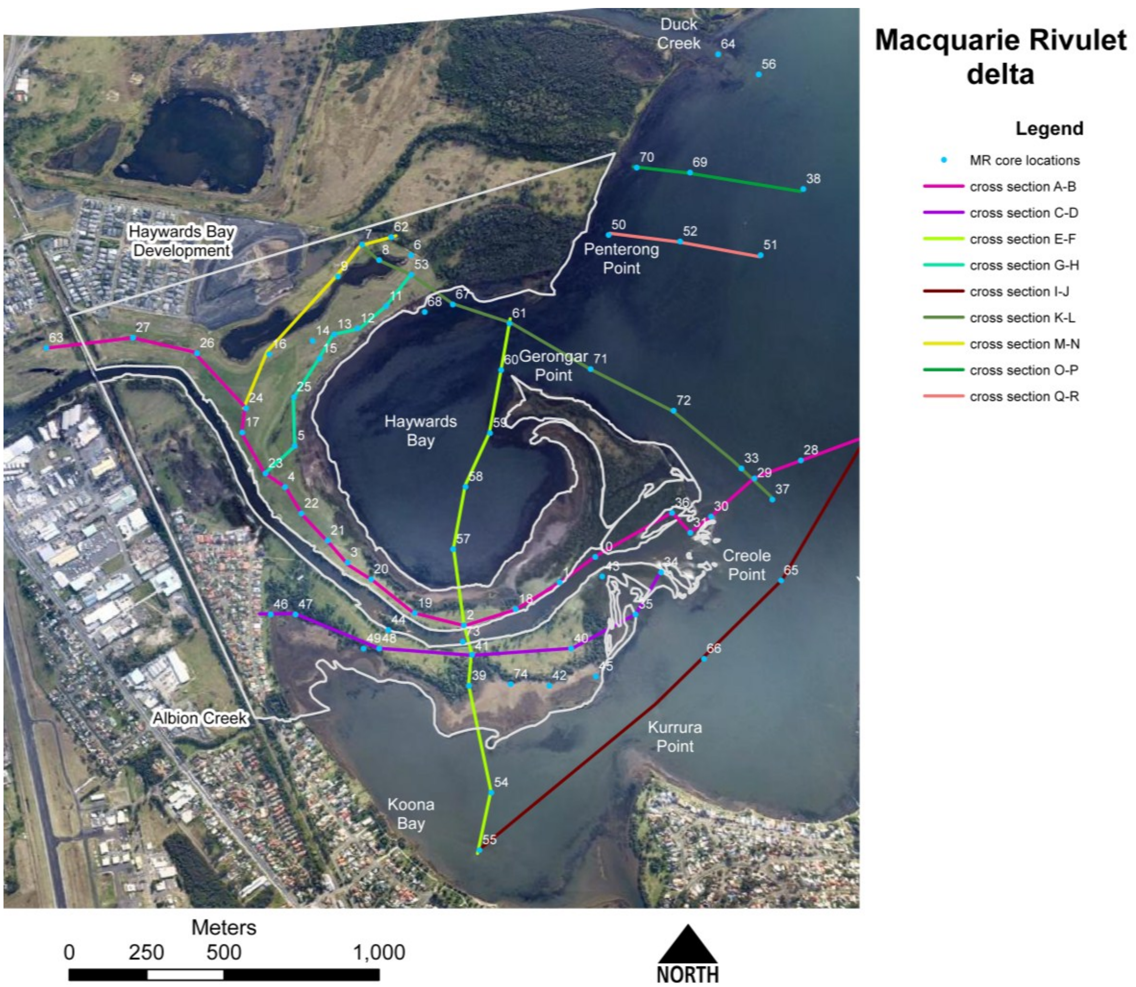


Figure 6.1: *Long/cross section location map and corresponding sections A-B to Q-R below. Note the multiple vertical exaggerations (VE) utilised in the production of the sections was necessary to illustrate the variety of facies, some of which are quite thin, in each section.*

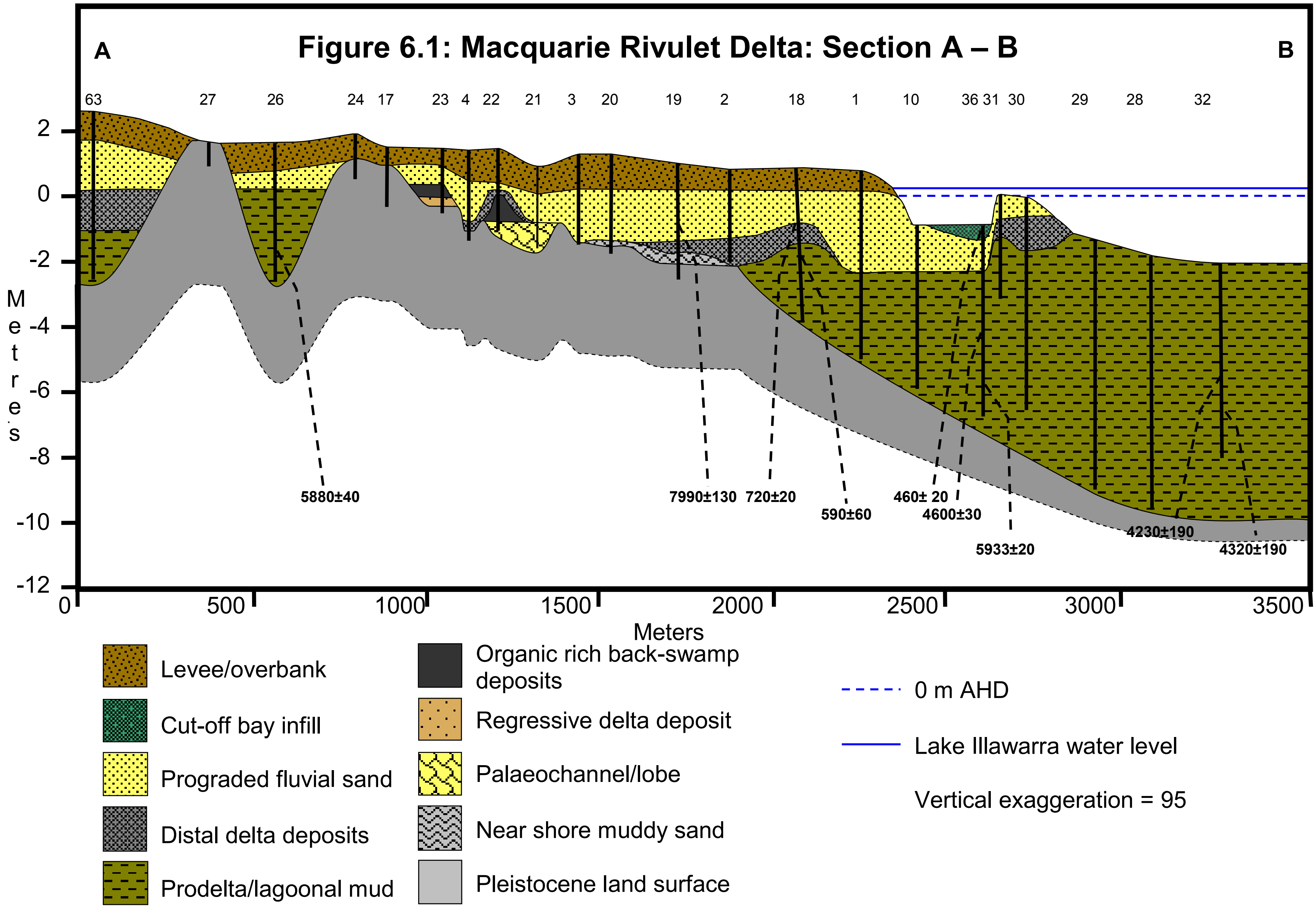


Figure 6.1: Macquarie Rivulet Delta: Section A – B

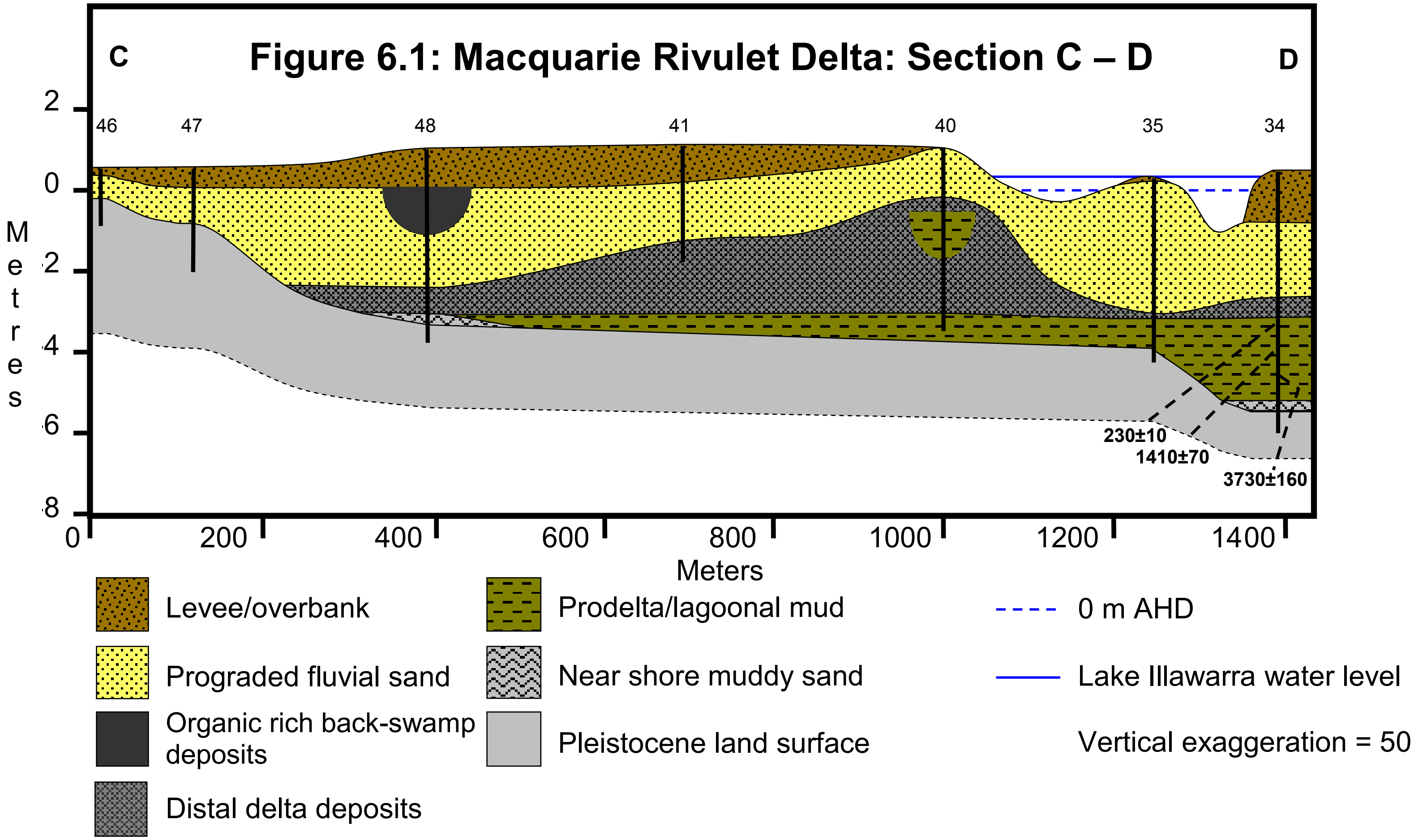


Figure 6.1: Macquarie Rivulet Delta: Section C – D

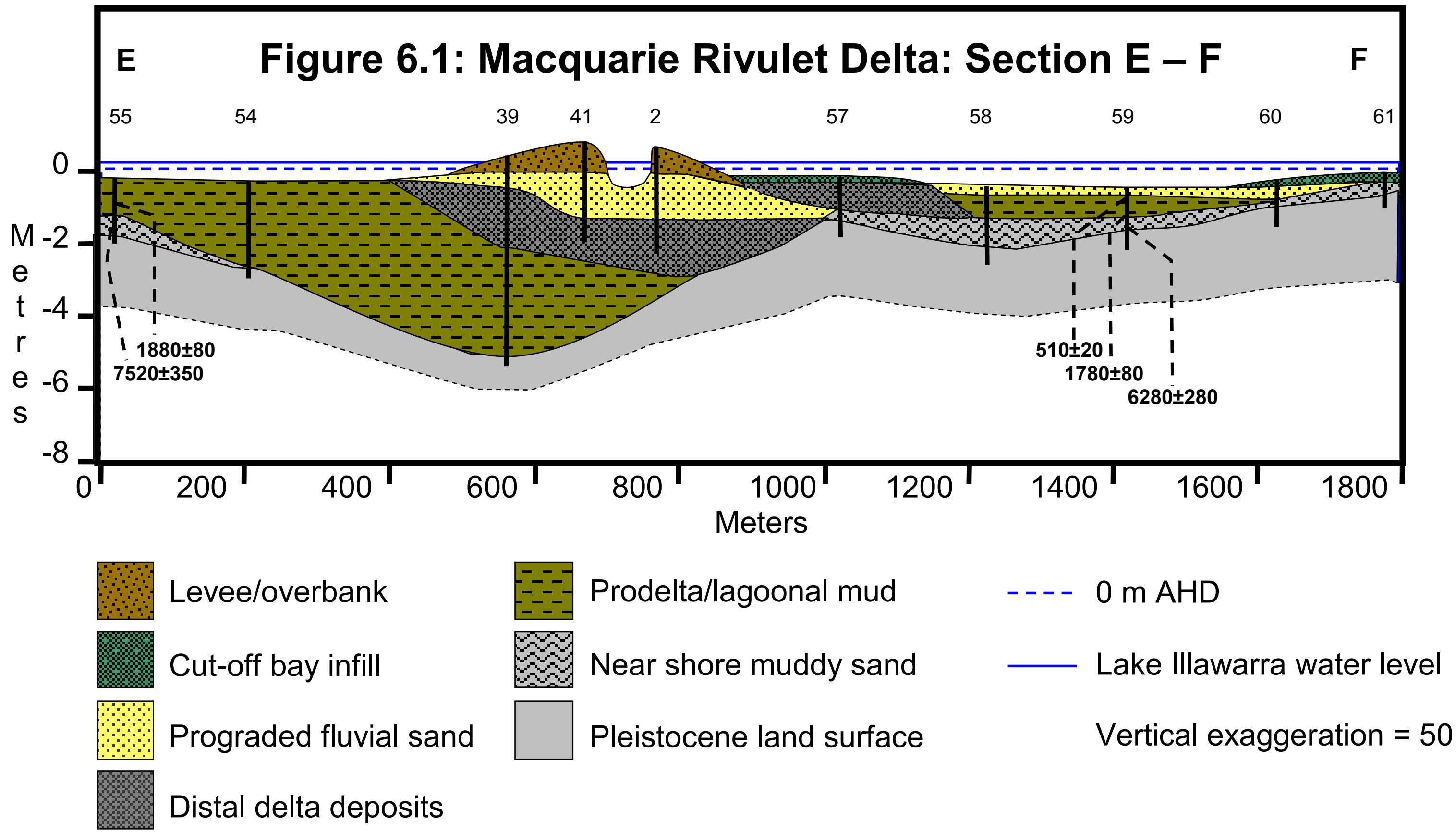


Figure 6.1: Macquarie Rivulet Delta: Section E – F

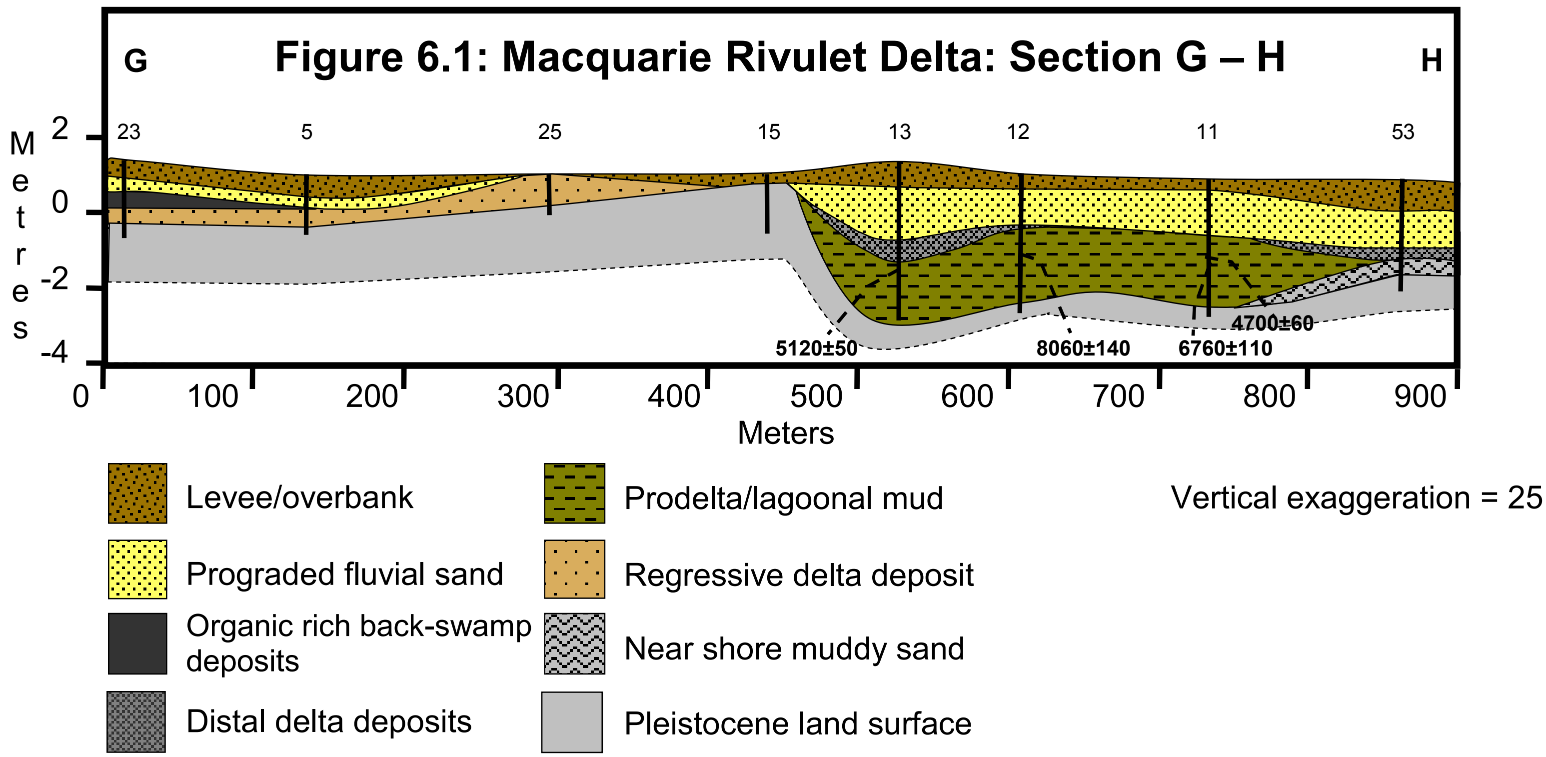


Figure 6.1: Macquarie Rivulet Delta: Section G – H

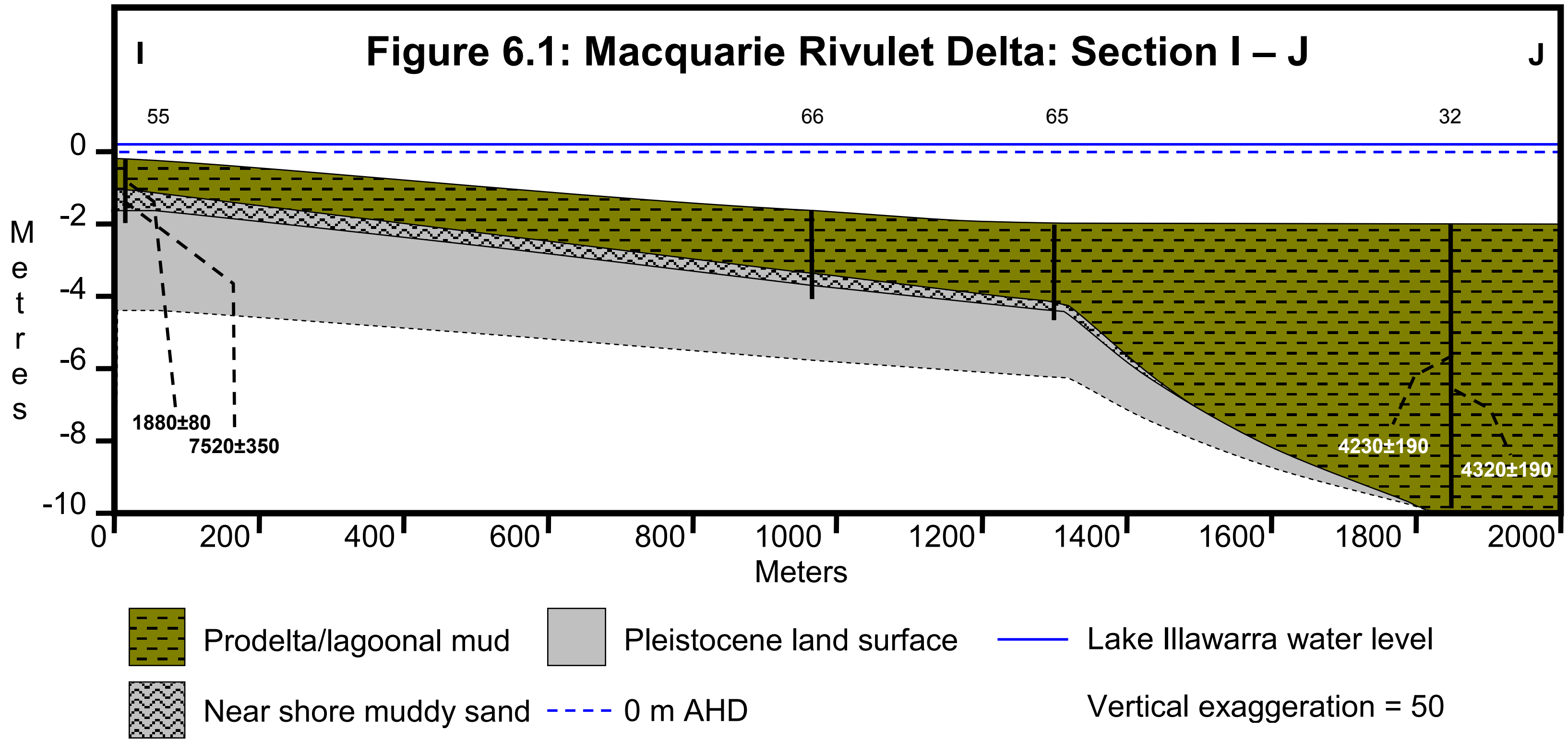


Figure 6.1: Macquarie Rivulet Delta: Section I – J

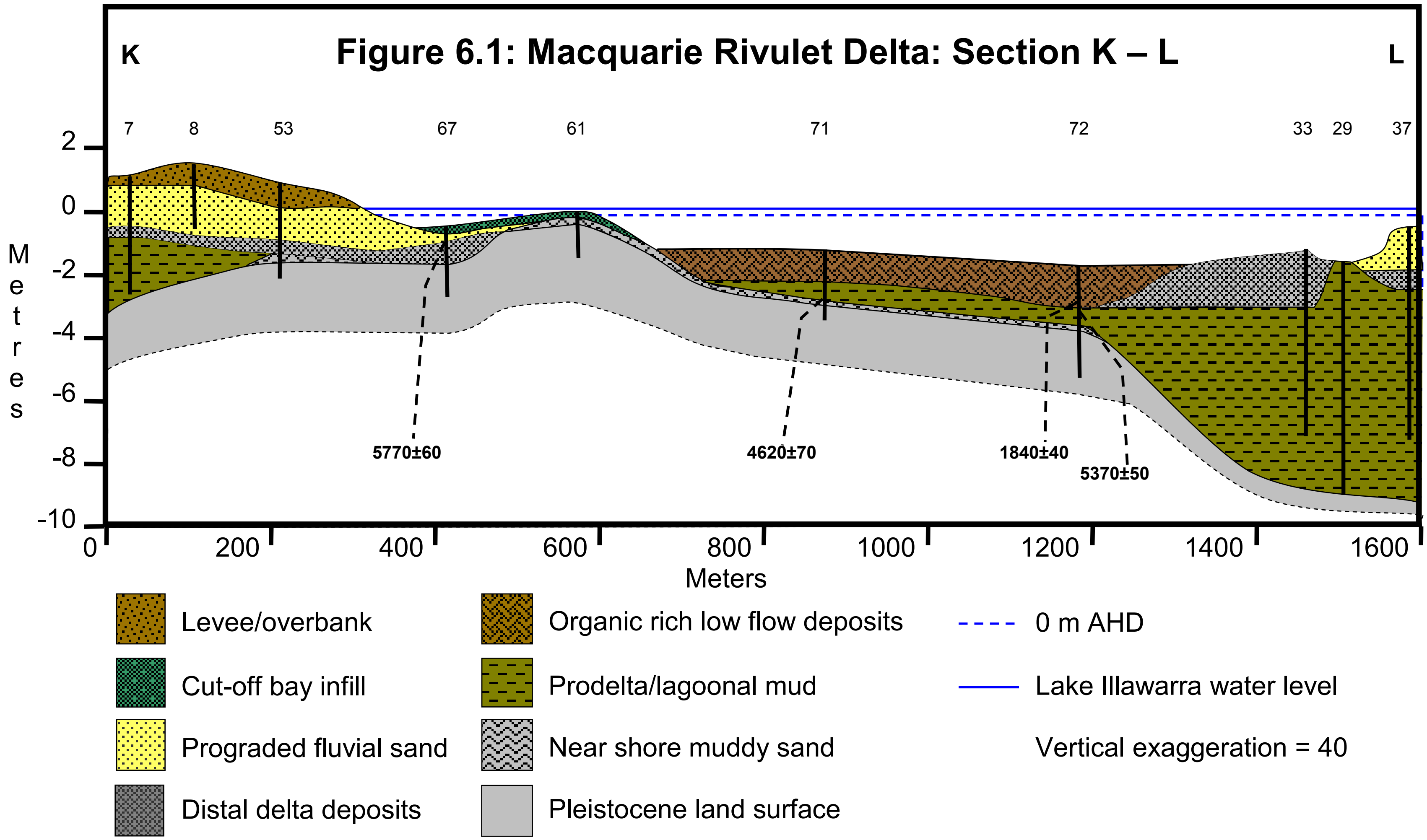


Figure 6.1: Macquarie Rivulet Delta: Section K – L

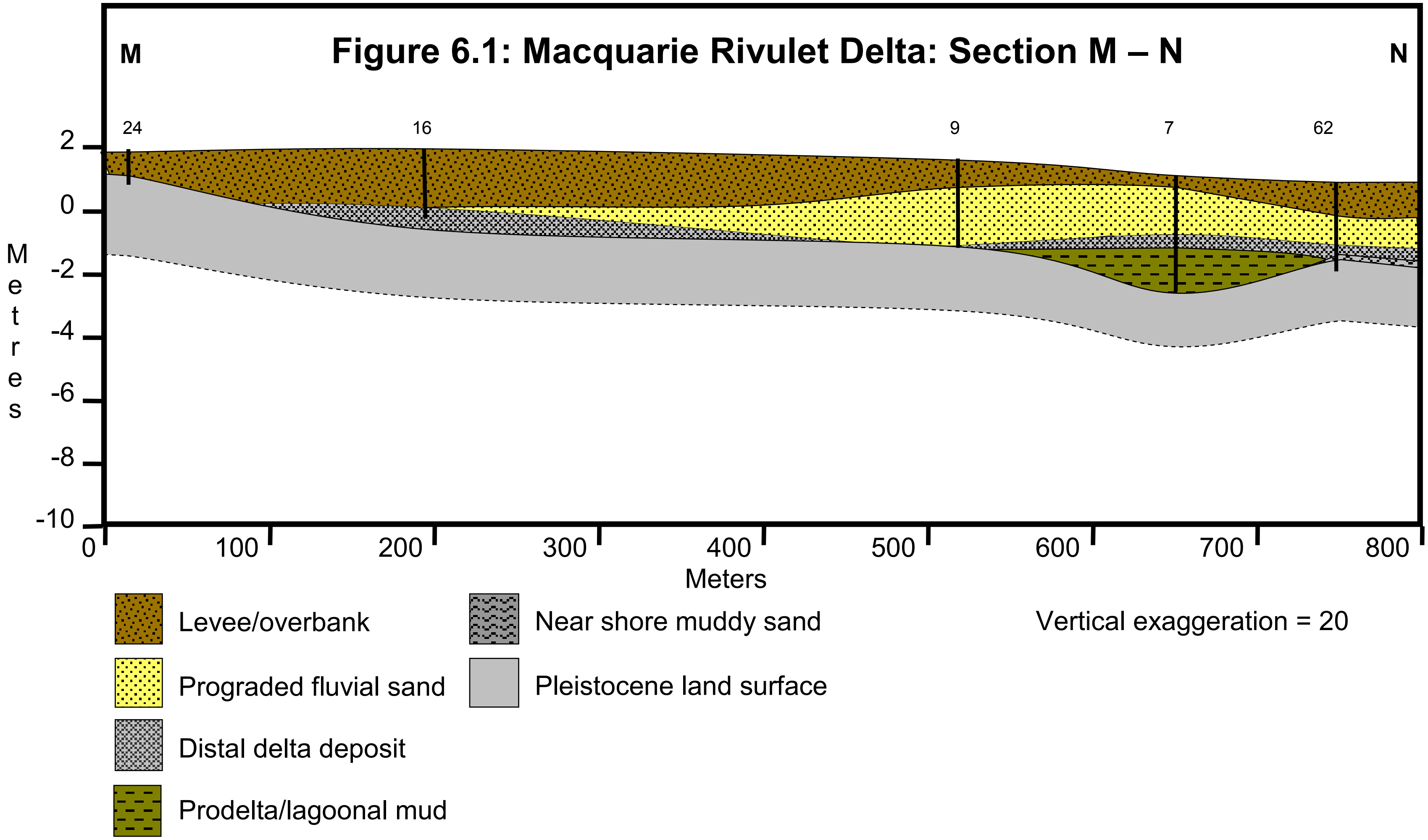


Figure 6.1: Macquarie Rivulet Delta: Section M – N

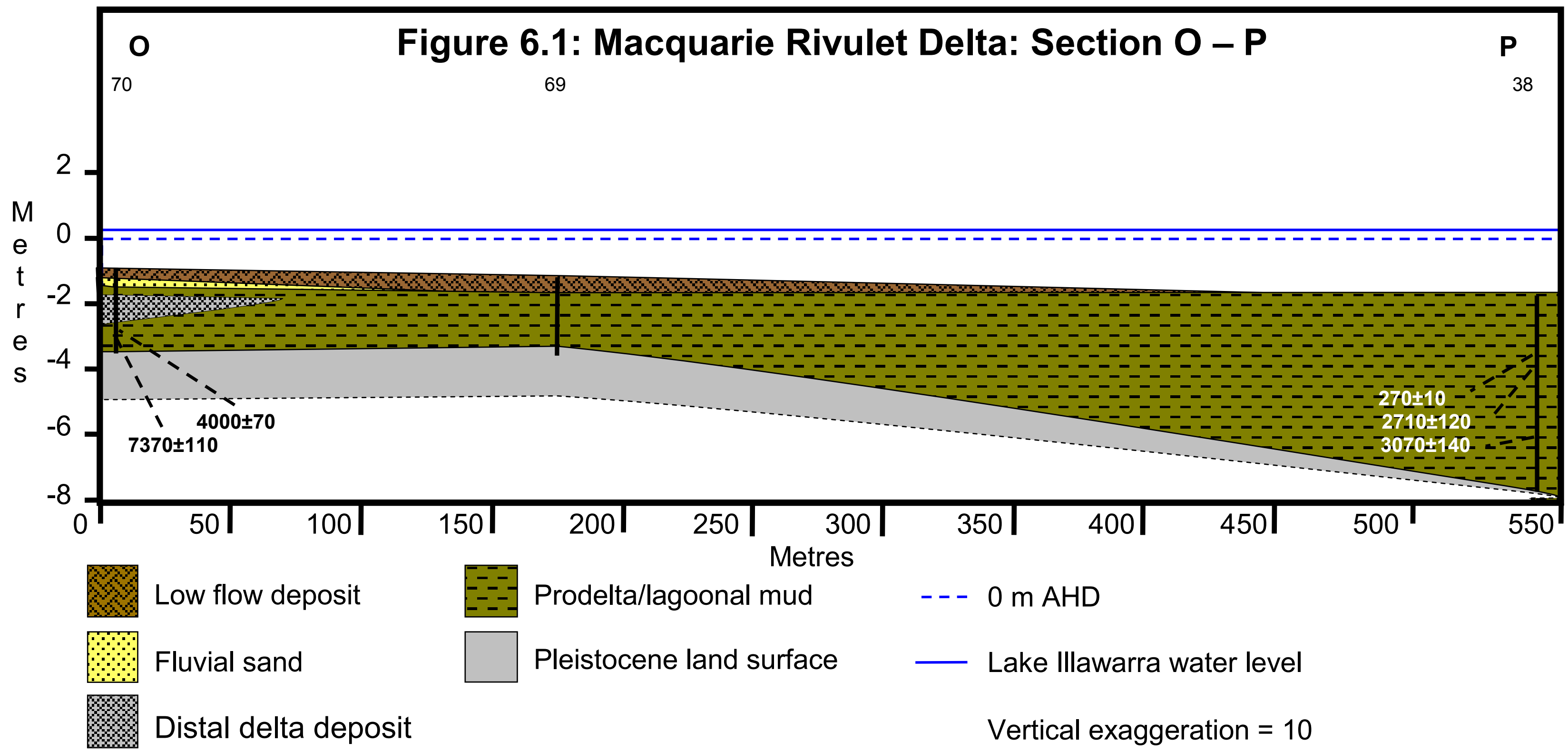


Figure 6.1: Macquarie Rivulet Delta: Section O – P

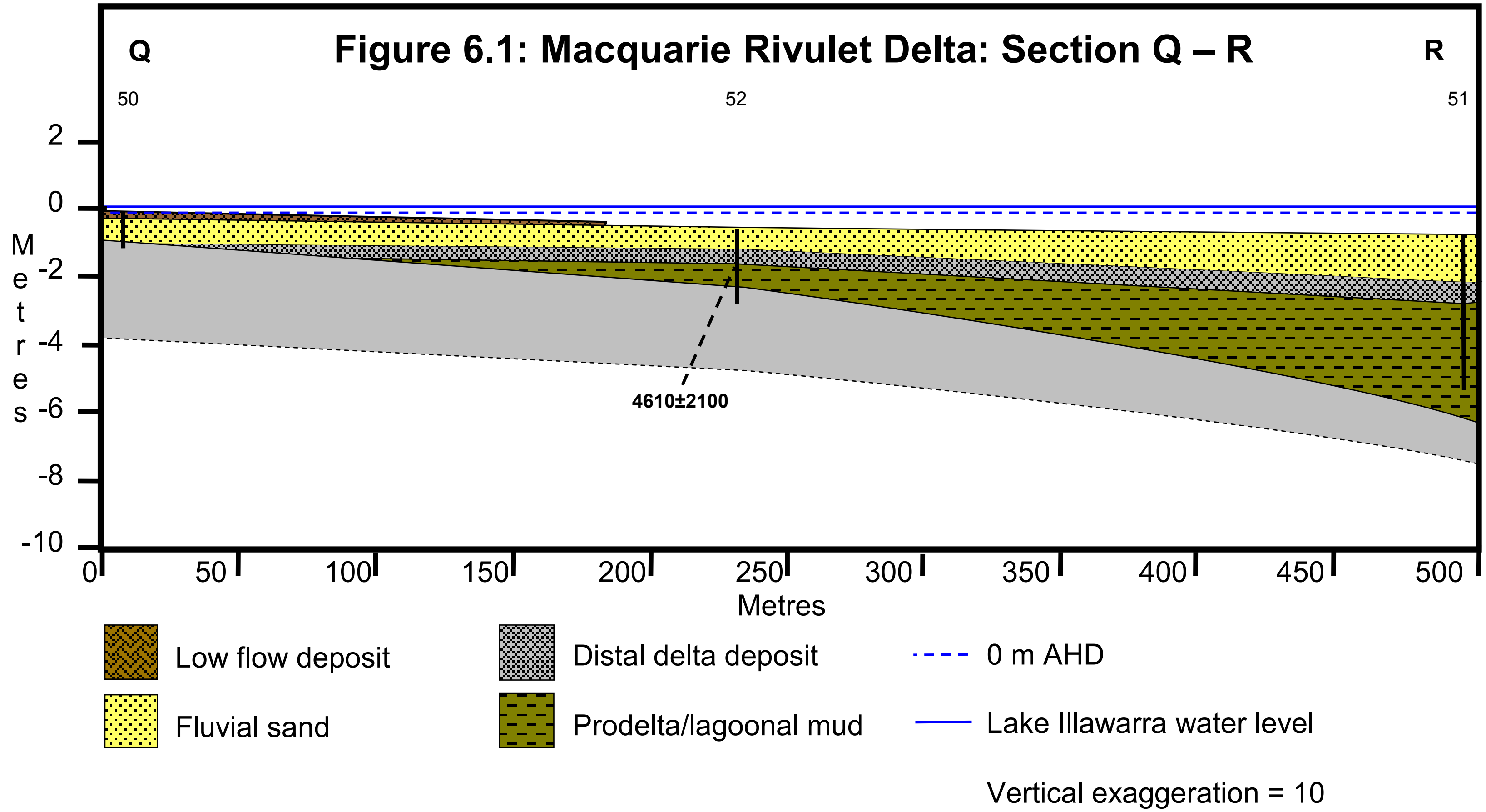


Figure 6.1: Macquarie Rivulet Delta: Section Q – R

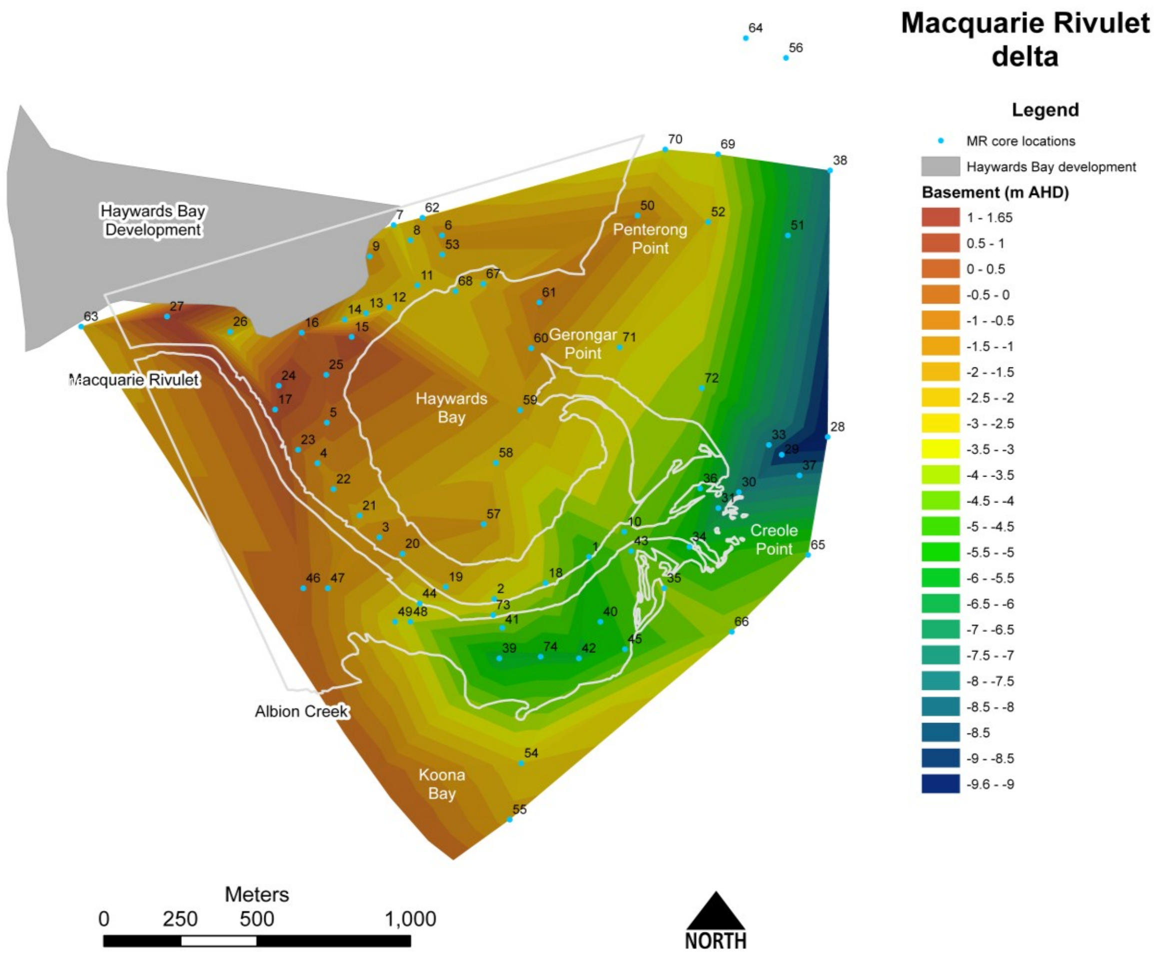


Figure 6.2: *TIN model of the minimum depth to the Macquarie Rivulet palaeoreceiving basin morphology derived from the analysis of 74 subsurface vibracore/drill holes. The grey shaded area is the location of the Haywards Bay residential development. Note, care must be taken when assessing the western margin of the model due to limited input data.*

Sloss *et al.* (2005) suggested two main Pleistocene palaeochannels occurred within the Macquarie Rivulet study area, one flowing through Koona Bay and the other through Haywards Bay (Figure 6.3). The increased spatial resolution of this study has refined the position of the main channel, indicating its location is similar to the location of the current channel (Figure 6.3). The results from this study are inconclusive as to the existence of the channel illustrated flowing through Haywards Bay. Specifically, cross/long section G-H (Figure 1) indicates that a channel occurred in this area during

the Pleistocene. However, cross/long section E-F (Figure 1) which runs north-south across Haywards Bay does not indicate the occurrence of a channel.

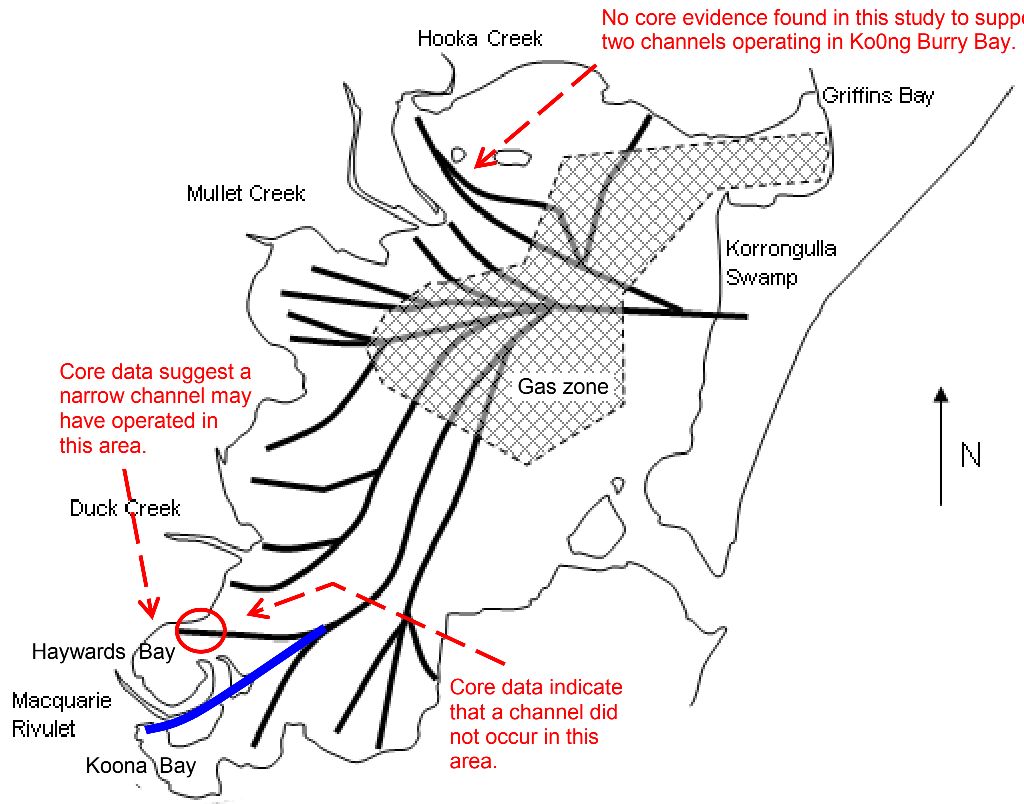


Figure 6.3: *Location map of Pleistocene palaeochannels proposed by Sloss et al. 2005 based on seismic data. The blue line indicates the location of the main palaeochannel based on the results from this study.*

The near shore muddy sand facies (Chapter 5, section 5.4) was intersected in 21 of the 74 cores from the Macquarie Rivulet study site (Volume 2, Appendix 5). Where intersected the facies directly overlies the antecedent Pleistocene land surface. Analysis of the facies distribution shows it has a predominant north-northeast orientation, similar to the current shoreline orientation (Figure 6.4).

Where the basement occurs at depth (e.g. MR 34 and 45) so to does the upper surface of this facies. This relationship represents the transition from the relatively shallow near shore depositional environment to a deeper water environment attributable to the late

Pleistocene/Early Holocene marine transgression. It would be anticipated that during this early evolutionary phase the lack of a fully developed Holocene barrier (Between Stage 1a, 2a; Figure 3.7) is likely to have increased the influence of marine related processes, such as wave and tidal reworking. However, Sloss (2005) have noted the presence of a remanent Pleistocene barrier, at shallow depths, underlying the current barrier confining Lake Illawarra. The presence of this barrier would have acted to reduce the energy levels within the palaeoreceiving basin and may be the reason for the lack of sedimentary structures such as those described by Nichol *et al.* (1997) for the Hawkesbury River estuary and Coleman and Gagliano (1965) for the Mississippi delta. Similar, remnant barrier's have been intersected or inferred in the Minnimurra River estuary (Boyle 2004, Panayotou *et al.,* 2007) and in the western portion of St Georges Basin proximal to the Wandandian Creek delta (Hopley and Jones 2006).

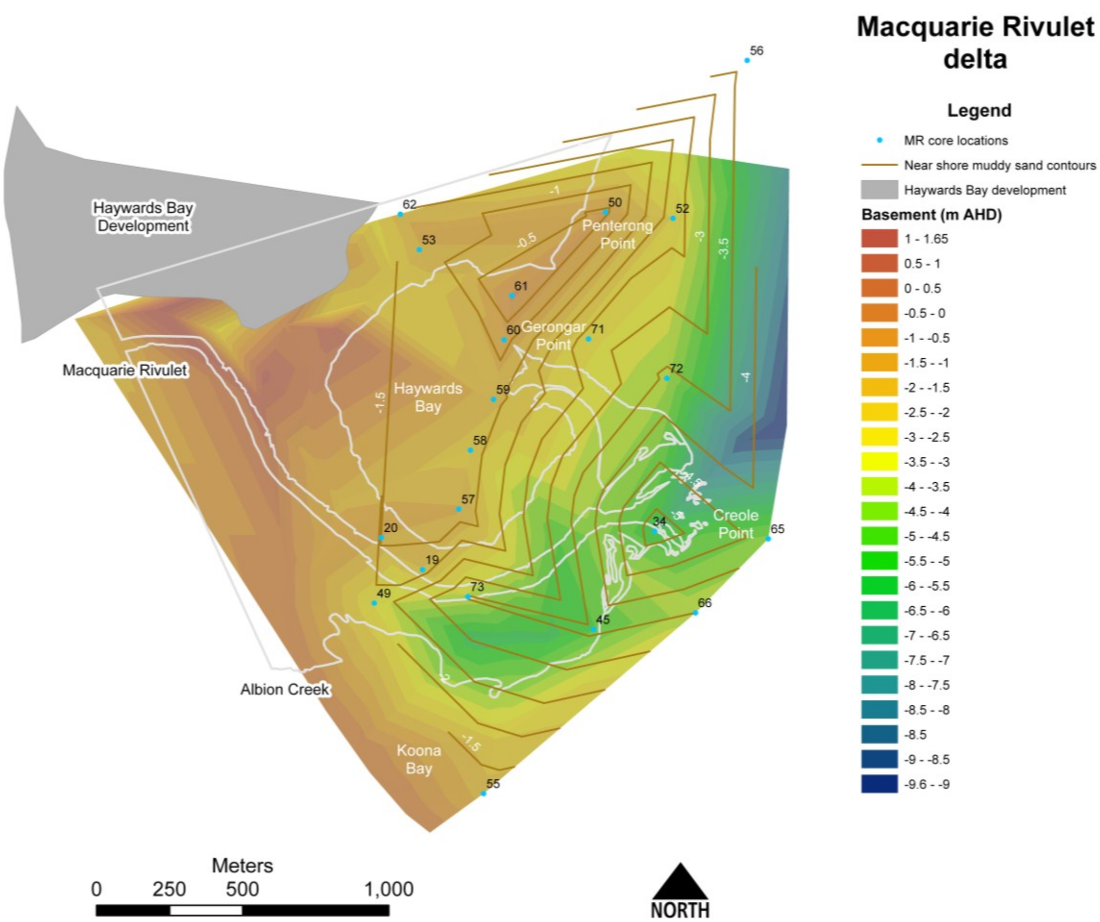


Figure 6.4: *Map illustrating the spatial distribution of the near shore muddy sand facies and its relationship to the basement TIN model illustrated in Figure 6.2.*

The near shore muddy sand facies thickness is highly variable ranging from 0.1 m (MR 20) to 1.1 m (MR 73). The absence of the facies to the west of core MR 20 indicates the facies thins out in a westerly direction. The thicker facies intersections (>0.75 m) are typically associated with basement lows as evident in Macquarie Rivulet long/cross section E-F (Figure 6.1). The increased facies thickness in these lows is likely to represent an extended depositional period proximal to the core site. However, the thickness of the facies in MR 34, located within the Pleistocene palaeochannel, is 0.2 m (Volume 2, Appendix 5). This reduced thickness is likely to represent the facies being drowned during the early stages of the transgressive event as the overlying prodelta/lagoonal mud would not have the erosive capacity to thin the underlying facies.

Ages, as determined by amino acid racemisation and ^{14}C dating techniques, ranged from 4,610±200 years BP (MR 52) to 7,520±350 years BP (MR 55; Table 4.6b and 4.7; Figure 6.1; Volume 2, Appendix 5). The observed maximum age obtained is similar to the maximum facies age obtained from the Mullet/Hooka Creek study site (Chapter 7). Despite the similarity between the maximum derived age, the minimum age is approximately 600 years younger than the minimum facies age obtained for the Mullet/Hooka Creek study site (Chapter 7).

The age/depth of the four dated samples, from the study area, plotted onto the sea level curve published by Sloss *et al.* (2007) suggests that the water level during the depositional period ranged from 3 m to 6 m depth at the time of deposition (Figure 6.5). However, these derived water depths are more consistent with the depositional depths typically associated with the prodelta/lagoonal mud facies. This may indicate the near shore muddy facies extended into deeper water during the early Holocene evolution of Lake Illawarra's evolution.

Inundation of the study area attributable to the late Pleistocene/early Holocene transgression resulted in the palaeo-Macquarie Rivulet delta regressing as evidenced by

the presence of the regressive delta facies in cores MR 5, 23 and 25 (Figure 6.6, Volume 2, Appendix 5). Within the Macquarie Rivulet study area the facies appears to have a reduced spatial distribution when compared to the 27 facies intersections within the Mullet/Hooka Creek study area (Chapter 7). The reduced number of intersections within the study area is likely to reflect the increased depth of the Pleistocene palaeochannel within this study area. As discussed in chapter 5, the regressive delta facies is characterised by a fining upwards sequence attributable to the depositional environment transitioning from a shallow water environment to a deeper water environment more suited to the deposition of finer sediment.

Where intersected, the regressive delta facies directly overlies the Pleistocene high proximal to the western shoreline of Haywards Bay (Figure 6.1; Section G-H). Facies thicknesses range from 0.3 m (MR 5) to 0.8 m (MR 25; Volume 2, Appendix 5). The basal elevation, relative to AHD, is within ± 0.2 m of 0 m AHD which is significantly higher than the basal elevations observed within the Mullet/Hooka Creek study area (Chapter 7). The increased elevation of the facies, within the Macquarie Rivulet study area, suggests deposition would have occurred when sea level had/or was close to the maximum elevation during the Holocene. However, the lack of specimens suitable for geochronological analysis within and above the facies, prevents the establishment of a depositional timeframe.

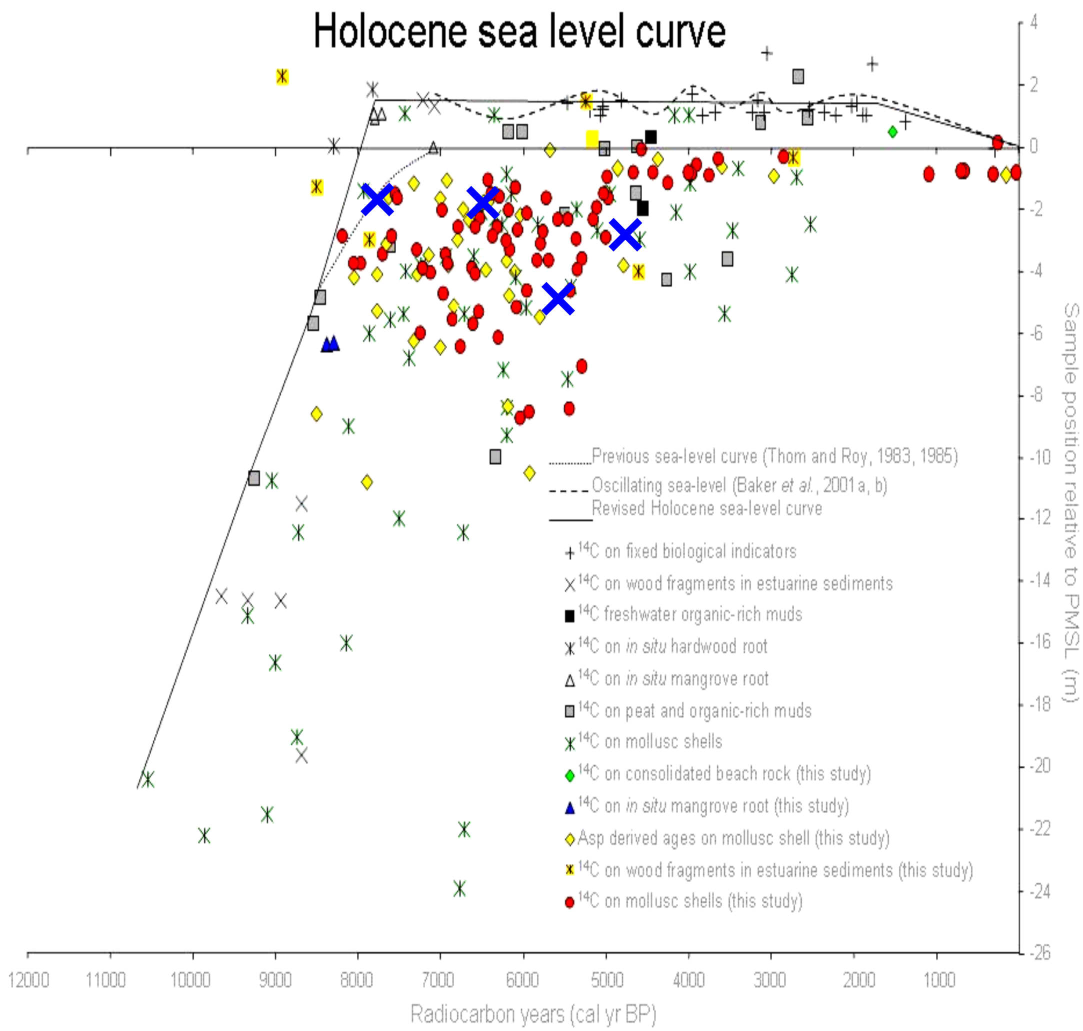


Figure 6.5: *Dated samples from the near shore muddy sand facies overlayed on the sea level curve published by Sloss (2005). The blue crosses mark the intersection point between the age and sample depth. From left to right cores are: MR 55, 59, 56, 52.*

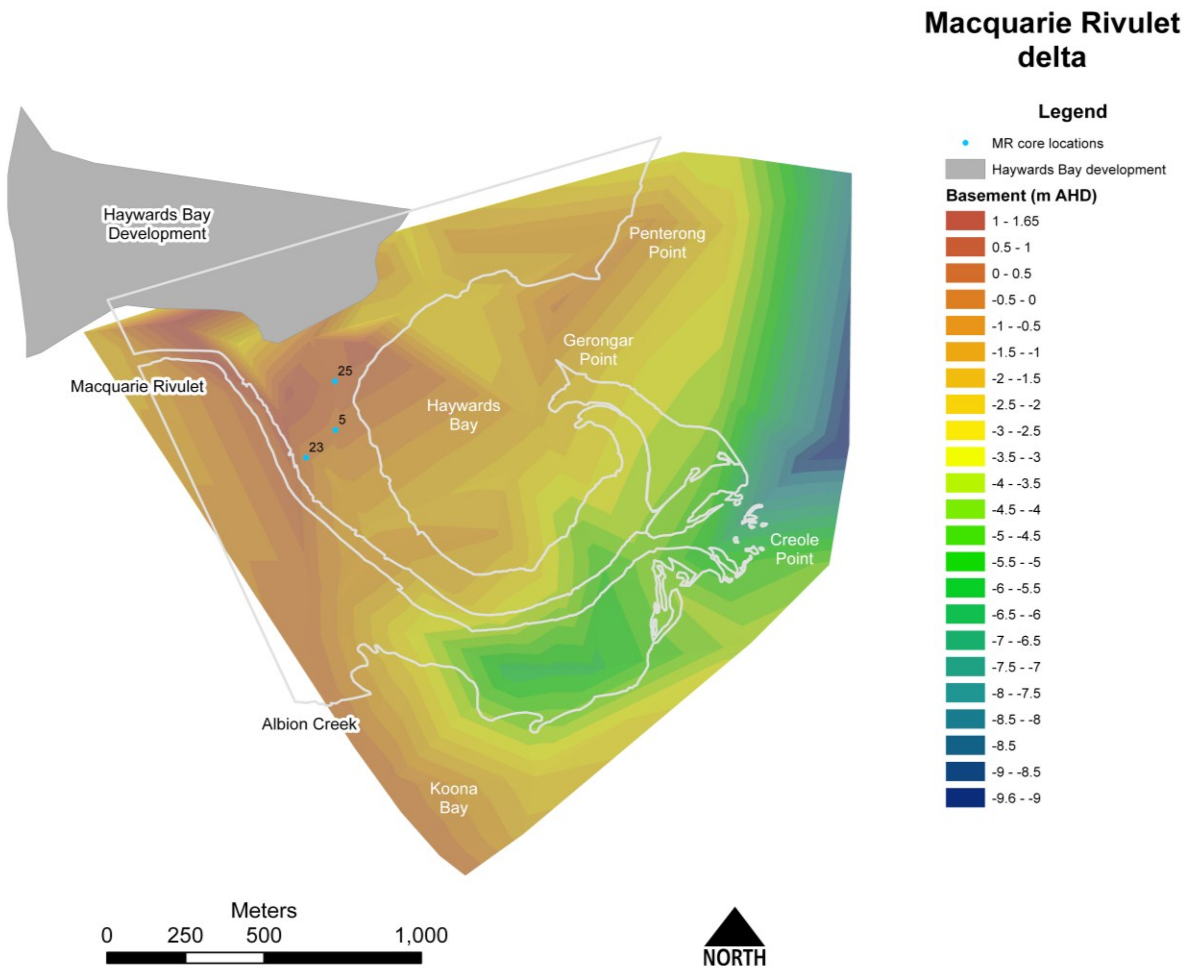


Figure 6.6: *Map illustrating the spatial distribution of the regressive delta facies and its relationship to the basement TIN model illustrated in Figure 6.2. The lack of core intersections inhibited the generation of the upper facies surface contour map.*

Macquarie Rivulet long/cross-section G-H (Figure 6.1) suggests this facies distribution is not strongly related to the main palaeochannel evident in Figure 6.6. This finding is contrary to what was found within the Mullet/Hooka Creek study area where a strong relationship between the facies and palaeochannel occurred (Chapter 7). Instead, the section indicates that the facies may be related to a smaller channel located to the north-northeast of MR 25. However, the facies absence within this channel, and the lack of an overlying erosive facies in cores MR 11, 12, 13 and 53 (Volume 2, Appendix 5), does not support this notion. To clarify the facies stratigraphic/morphological

relationship with the apparent palaeochannel additional core data to the west and south-southwest of MR 23 would be required.

6.2.2: Infilling the palaeoreceiving basin

The prodelta/lagoonal mud facies, intersected in 44 cores, was found to overlie either the antecedent Pleistocene sediments or the near shore muddy sand facies (Volume 2, Appendix 5). Presence of the facies in these cores suggests conditions within the receiving basin must have been calm to enable the flocculation of the fine-grained sediments as described in section 5.8. Significantly, the calm environment could only have developed once the Lake Illawarra barrier was close to or fully subaerially exposed restricting the influence of marine processes (Stage 2a; Figure 3.7).

Facies thickness ranges from 0.25 m (MR 35) to 8 m (MR 32; Volume 2, Appendix 5) with an average thickness of 2.33 m. The thicker facies intersections in cores MR 28, 29 and 32 are strongly associated with the deeper portions of the Pleistocene palaeochannel (Figure 6.7). Furthermore, the palaeochannels intersected in MR 26 and 63 enabled deposition of this facies farther inland with respective thicknesses of 2.35 m and 1.1 m (Figure 6.1; Volume 2, Appendix 5). Beyond the confines of the palaeochannels the facies typically thins in a westerly direction due to reduced water depths in the area (Figure 6.1, Section A-B and K-L).

A total of 26 *Notospisula trigonella* and seven *Anadara trapezia* molluscs from 16 cores were extracted and analysed using AAR and/or ^{14}C techniques. Sample depths ranged from – 0.78 m to - 5.25 m AHD with derived ages ranging from 230±10 to 8060±140 years BP (Table 4.6a and 4.7). The derived age range suggests the *ca.* 5 ka age assigned to Stage 2a of estuarine evolution model proposed by Sloss *et al.* (2005, 2006a; Figure 3.7) may need to be revised to *ca.* 6.5-7 ka. Of the samples analysed MR 37 was the only core to contain an age inversion (Table 6.1).

Long term sedimentation rates extrapolated from the established facies geochronological data (Tables 4.6a and 4.7) range from 0.2 mm/year (MR 68) to 16.3 mm/year (MR 34), with an average rate of 1.76 mm/year. The long term sedimentation rates established in this study are consistent with previously established rates published by Sloss *et al.* (2004, 2004a, 2006a and 2011). Ten of the 16 cores analysed contained multiple samples enabling the establishment of the sedimentation rate for the core sections dated. Excluding the anomalous rates of -30 mm/year (MR 37) to 7.33 mm/year (MR 32) the sedimentation rates range from 0.03 mm/year (MR 68) to 3.35 mm/year (MR 37) with an average rate of 0.69 mm/year (Table 6.1). The significant variance between the minimum and maximum rate is attributable to the proximity of MR 37 to the mouth of the delta front where as MR 68 is located proximal to the shore line in Haywards Bay.

6.2.3: Fluvial progradation

Within the Macquarie Rivulet study area the palaeochannel/lobe facies was intersected in cores MR 21 and 22 (Figure 6.1, section A-B; Volume 2, Appendix 5). The reduced number of intersections suggests there were minimal channel avulsions during the delta's early evolution. The lack of avulsions suggests the delta's morphology was more consistent with a single channel wave dominated delta prior to the transitioning to the current multi channel birdsfoot delta morphology. The sedimentary evidence for the initial delta morphology is further supported by Figure 6.8, a map extract showing the delta from 1834 (Mitchell 1856).

Table 6.1: *Comparison of the ages and associated sedimentation rates derived from cores where multiple ages were determined from the prodelta/lagoonal mud facies. Ages associated with core codes marked with # were determined by Sloss et al. (2005).*

Core	**Sample core depth (cm)**	**Age**	**Error**	**Comparative sedimentation rate (mm/yr)**	**Sedimentation rate range for dated section of core (mm/yr)**
MR 11	230	4700	60		
MR 11	246	6760	110	0.08	0.08
MR 32#	365	4230	190		
MR 32#	431	4320	190	7.33	
MR 33#	255	320	10		
MR 33#	429	3510	150	0.55	0.55
MR 34#	375	230	10		
MR 34#	435	1410	70	0.51	
MR 34#	490	3730	160	0.24	0.33
MR 36	221	510	30		
MR 36	311	2371	20	0.48	
MR 36	330	4600	30	0.09	
MR 36	487	5933	20	1.18	0.49
MR 37#	370	3890	170		
MR 37#	490	3850	170	-30.00	Inversion
MR 37#	598	4570	200	0.15	3.35
MR 38#	166	270	10		
MR 38#	234	2710	120	0.28	
MR 38#	428	3070	140	5.39	0.94
MR 59#	36	510	20		
MR 59#	85	1780	80	0.39	0.39
MR 68	154	2020	240		
MR 68	172	7465	215	0.03	0.03
MR 70	184	4000	70		
MR 70	208	7370	110	0.07	0.07
Average sedimentation rate (mm/yr)					**0.69**

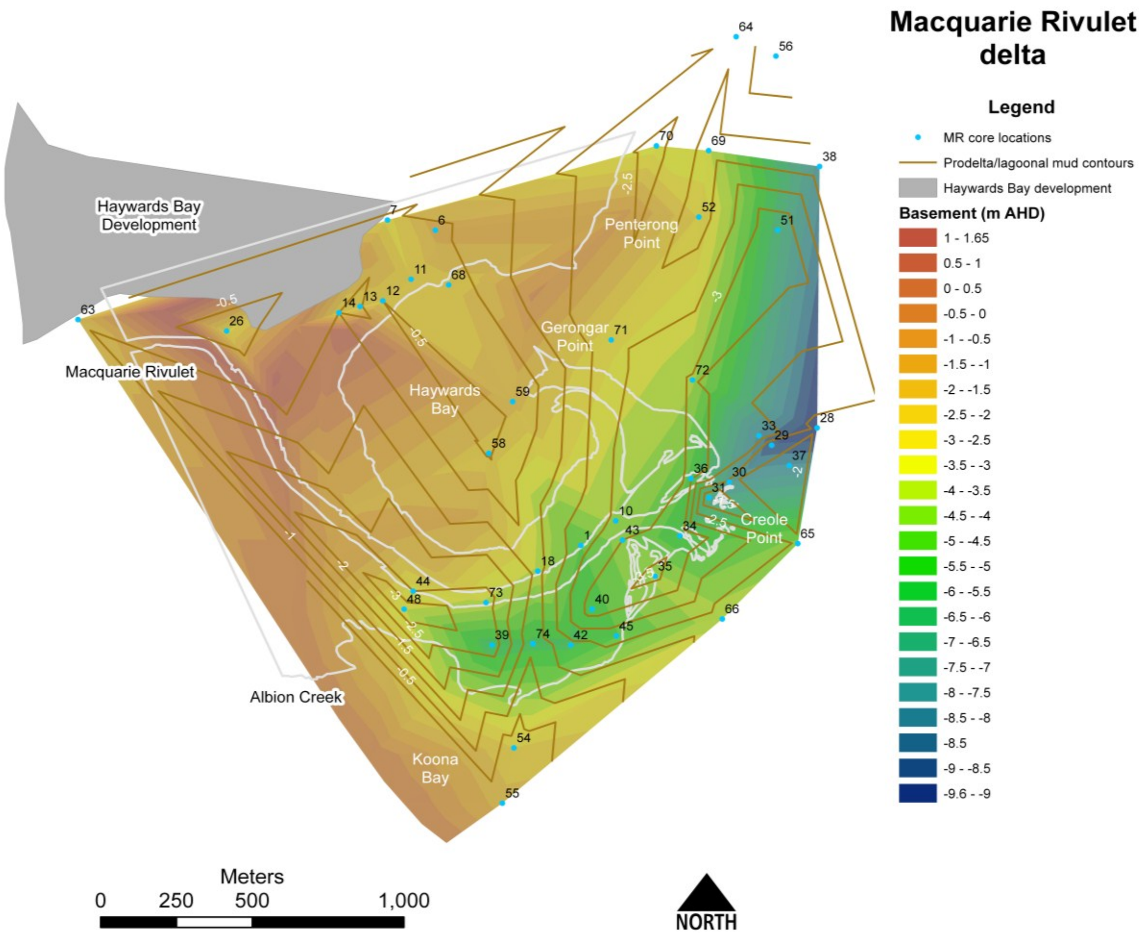


Figure 6.7: *Map illustrating the spatial distribution of the prodelta/lagoonal mud facies and relationship to the basement TIN model illustrated in Figure 6.2.*

Stabilisation and subsequent fall of the Holocene sea level enabled the delta to prograde into the Lake Illawarra receiving basin depositing the distal delta facies (Stage 1b; Figure 3.7). Within the study area the facies was intersected in 37 of the 74 cores with the majority (24) proximal to the Macquarie Rivulet distributary channel (Figure 6.9; Volume 2, Appendix 4 and 5). The remaining intersections are associated with two Holocene palaeochannels north of Penterong Point and Duck Creek (Figure 2.5). Typically, the distal delta facies overlies the prodelta/lagoonal mud, however it was also found to overlie the near shore muddy sand and the Pleistocene substrate (Figure 6.1, Sections A-B to G-H, K-L; Volume 2, Appendix 5). Overall the upper surface of the facies

dips in an easterly direction. This easterly dip is attributable to delta progradation in response to falling sea level. Facies thickness is highly variable ranging from 0.1 m (MR 12, 22) to 2.75 m (MR 40, Volume 2, Appendix 5) with an average thickness of 0.8 m.

The fluvial sand facies was intersected in 54 of the 74 cores (Volume 2, Appendix 5). Spatially the facies displays a strong correlation with the underlying basement as evidenced by the clustering of cores proximal to the palaeochannels evident in Figure 6.3 and the current channel (Figure 6.10). Typically, the facies directly overlies the distal delta facies, as is, evident in the Macquarie Rivulet sections A-B to G-H and K-L to Q-R (Figure 6.1). However, in 16 cores the facies is in direct contact with the regressive delta facies (MR 5), the Pleistocene basement (MR 3, 46, 47), the near shore muddy sand (MR 20, 49, 50) and the prodelta/lagoonal mud facies in cores MR 6, 10, 11, 14, 36, 58, 59, 60, 68 (Volume 2, Appendix 5). Although no longer present it is feasible to suggest the distal delta facies in these 16 cores may have initially been present prior to reworking/erosion by the prograding fluvial sands.

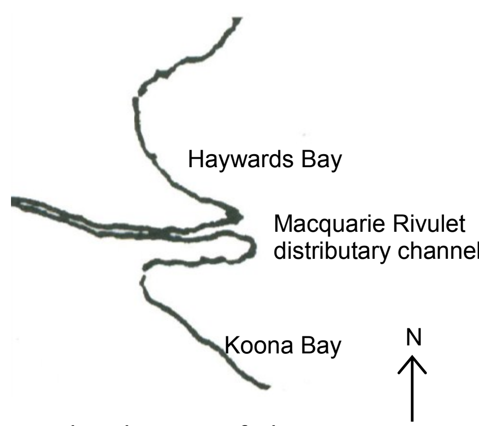


Figure 6.8: *Extract from an 1834 sketch map of the Macquarie Rivulet area (scanned copy from Mitchell 1856).*

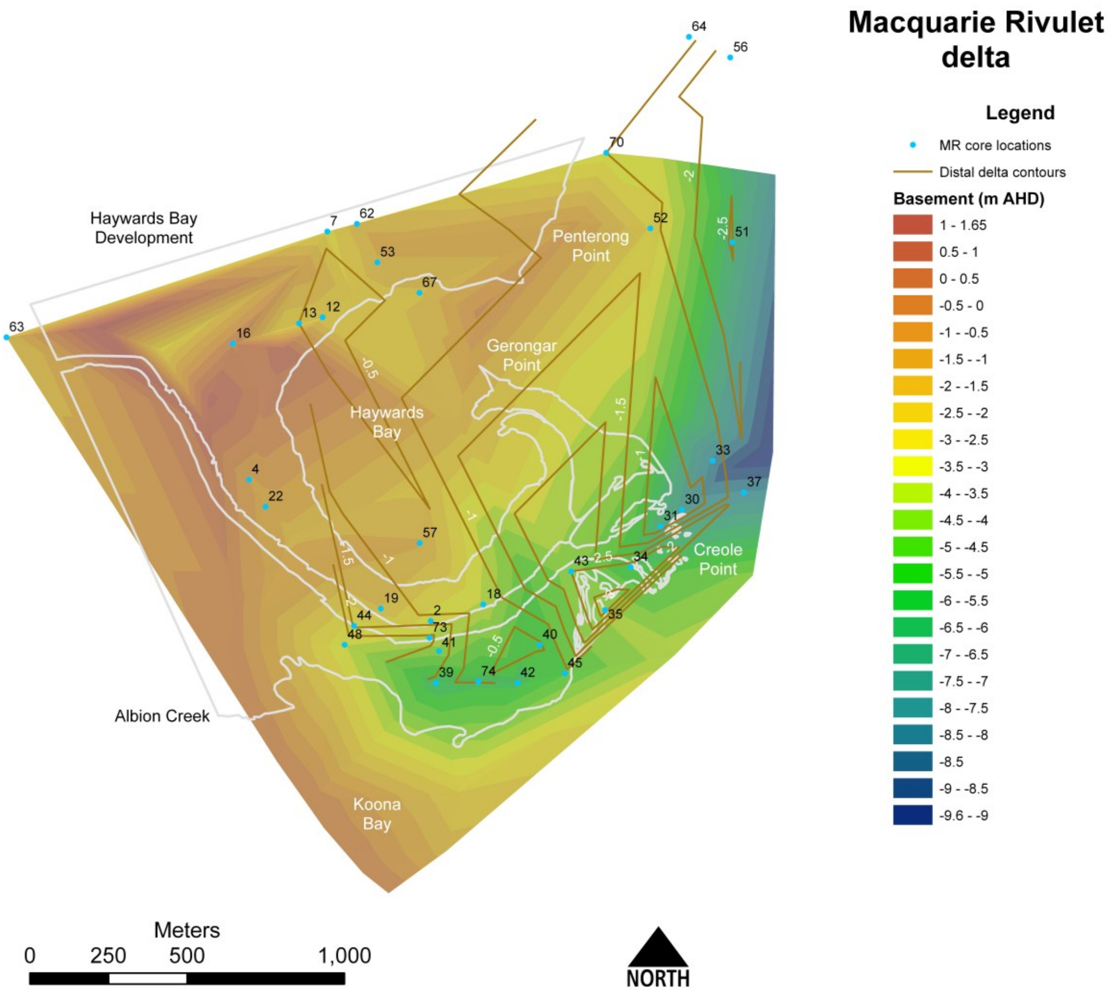


Figure 6.9: *Map illustrating the spatial distribution of the distal delta facies and its relationship to the basement TIN model illustrated in Figure 6.2.*

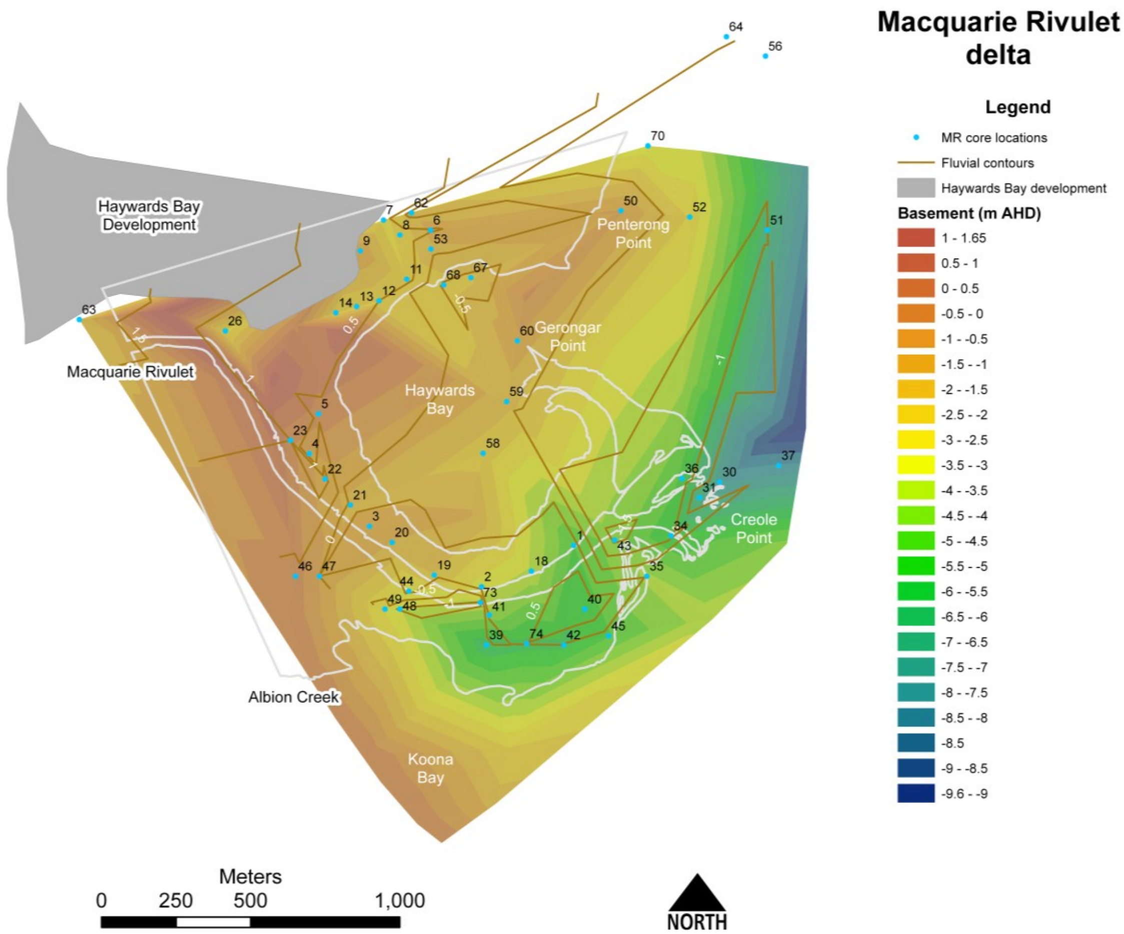


Figure 6.10: *Map illustrating the spatial distribution of the fluvial sand facies and its relationship to the basement TIN model illustrated in Figure 6.2.*

The distal delta and fluvial sand facies contained seven macrofossils suitable for geochronological analysis utilising AAR and ^{14}C techniques (Table 4.6a and 4.7). The lack of material within the distal delta and fluvial sand facies suitable for dating is attributable to increasing energy levels within this depositional environment, reducing diversity and reworking specimens post mortem. Specimens from the distal delta facies yielded ages ranging from 40±5 years BP (MR 33) to 5770±60 years BP (MR 67, Table 4.6a). The derived ages for the fluvial sand facies ranged from 1300±60 years BP (MR 37) to 7990±130 years BP (MR 19, Table 4.6a). However, the age derived in MR 19 is likely to be erroneous due to its stratigraphic position relative to AHD (Figure 6.1). Despite this erroneous age, the other derived ages indicate that delta progradation into the study

area may have commenced *ca.* 6 ka approximately 2 ka earlier than reported by Sloss *et al.* (2005, 2006a). Sedimentation rates extrapolated from the derived ages from the distal delta and fluvial sand facies ranged from 0.08 mm/year (MR 52) to 31.25 mm/year (MR 33) with ranges from 0.08 mm/year (MR 52) to 1.1 mm/year (MR 37) for the fluvial sand facies.

The upper rate established from the two facies are consistent with those published by Chenhall *et al.* (1995) and Sloss *et al.* (2005, 2006a, 2011). The apparent increase in sedimentation rate in MR 33 is likely to reflect changes within the catchment over the past 40 years, such as urbanisation. The presence of a weir, upstream of the study area, may be limiting the true amount of coarser sediment transported downstream and thus deposited at the delta's mouth. The increased sedimentation rates can also be inferred by the increased subaerial footprint of the delta in Figure 8.2 and published by Hopley *et al.* (2007). The variable sedimentation rates calculated for the study area are attributable primarily to core locations relative to the main distributary channel. For example, the reduced rate extrapolated for MR 52 is attributable to its proximity to a relatively inactive distributary channel proximal to Penterong Point, whereas MR 33 is located in line with the current main distributary channel outlet (Figure 6.1).

Low flow deposits contained within the fluvial sand facies were found within 14 cores from the Macquarie Rivulet study area (Volume 2, Appendix 5). These deposits are characterised by a reduction in average grain size relative to the underlying and overlying fluvial sands, due to increased mud contents. The upper and lower contacts are typically sharp. Thickness of the low flow deposits ranges from 0.1 m (MR 14) up to 0.5 m (MR 35; Volume 2, Appendix 5). The thinner deposits may represent periods of reduced rainfall within the catchment due to climatic systems such as the Southern Oscillation (El Niño and La Niña cycle). In contrast the thicker deposits may represent temporary channel abandonment. To test the usefulness of the deposits as proxy indicators the establishment of accurate minimum and maximum age ranges would be

required, which was not possible in this study due to a lack of material suitable for dating.

6.2.4: Floodplain and levee development

A combination of vertical accretion and lateral migration of Macquarie Rivulet's distributary channels has resulted in the deposition of floodplain/levee and splay facies over 160 ha (Figure 6.1). Measured facies thickness is highly variable ranging from 0.1 m to 2 m (MR 43; Volume 2, Appendix 5) with the thickest deposits generally located proximal to the channel. The true thickness of the facies may have been greater in some locations as former land owners and the site developer (Winton Property Group) suggested portions of the floodplain had been sand mined. However, no evidence for the mining of the sand was found.

Two levee morphologies occur along the length of Macquarie Rivulet within the study area. Levees in the western portion of the study area are characterised by A-type levees (Figure 6.11). These levees have a crest situated higher than the floodplain and then taper steeply towards the floodplain. Towards the active distributary mouth the levees are less pronounced as the crest is at a similar elevation to the floodplain (Figure 6.11: B-type levee). In these areas the floodplain exhibits a gentle slope from crest to adjacent floodplain. This subdued morphology is more consistent with the morphology observed within the Mullet/Hooka Creek study area (Chapter 7).

The sandy unconsolidated nature of the levees makes them prone to failure by rotational bank collapse particularly on the convex side of bends. For example, during the March 2010 flood event sections of the floodplain, just upstream of the study area failed when high velocity water flowing through a chute channel impacted the opposite bank resulting in rotational slumping (Figure 6.12). Failure along the channel margin during these events is also exacerbated when trees lining the bank fail, as the waterlogged sediment can no longer adequately support the tree when blown by strong winds, which often occur simultaneously with the flood event. The combination of these

factors has contributed to bank instability and subsequent widening of Macquarie Rivulet. Continued bank instability has the potential to increase downstream sedimentation rates and impact on the deltas morphology and the water quality in Lake Illawarra. Furthermore, these factors could be further enhanced by continued anthropogenic modification of the catchment altering peak flood discharge and by predicted climate change impacts such as increased storminess and sea level rise.

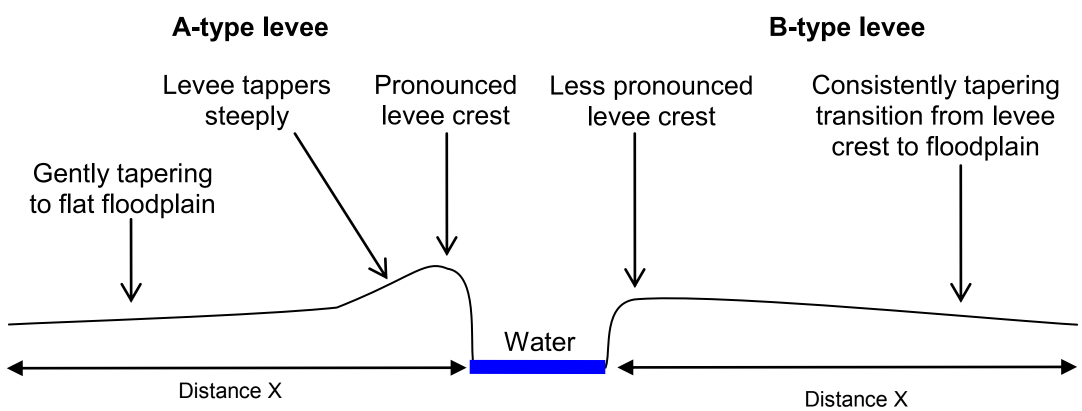


Figure 6.11: *Typical levee morphologies observed within the Macquarie Rivulet study area. The A-type has a steep slope extending from the crest to the floodplain. The B-type levee has less distinct crests then has a gentle continuous slope from crest to floodplain.*

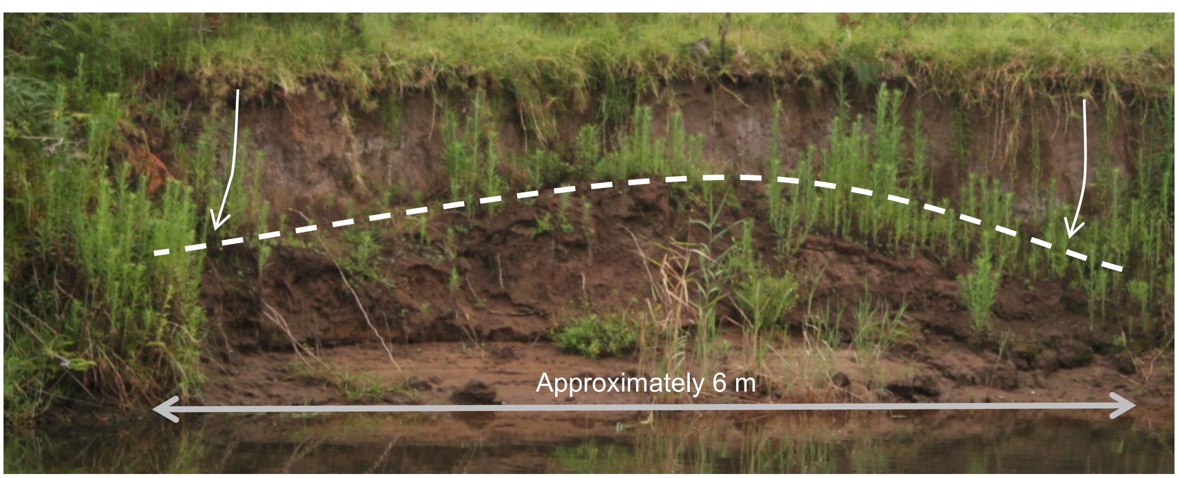


Figure 6.12: *Rotational bank slump which occurred during the 21st March 2010 flood event. Arrows represent slump direction. Dashed line represents top of slump material.*

Assigning a depositional commencement date for the floodplain/levee facies was not possible due to the lack of material suitable for dating using ^{14}C or ARR techniques. The use of thermo-luminescence (TL) and/or optically stimulated luminescence (OSL) dating techniques was not attempted as there were concerns over their ability to establish an age due to limited sediment bleaching time. However, as the facies was deposited in shallow water to subaerial environments, it is probable the facies was deposited after 2 ka when sea level within the receiving basin fell. This interpretation is based on the sea level curve published by Sloss *et al.* (2007).

MR 34 and MR 42 intersected thin (10 cm and 30 cm, respectively) splay deposits within the levee/overbank facies. These deposits are characterised by sharp basal and gradational upper contacts, were most probably deposited during flood events. Despite the lack of datable material within the two deposits it is possible to infer, the splay intersected in MR 34 was deposited some time after 1981 due to subaerial exposure of the levee in which it is located occurring between 1981 and 1984 (Figure 8.7a).

6.3: Chapter summary

Nine cross/long sections based on 74 cores and 49 dates have been used to establish the Holocene evolution of Macquarie Rivulet delta. The research has shown the current morphology of the delta is influenced by the inherited morphology of the receiving basin. This relationship is particularly evident with the close alignment of the current main distributary channel with the Pleistocene palaeochannel apparent in the three dimensional reconstruction of the receiving basin. These observations are consistent with the findings published by Coleman and Wright (1975) and Coleman (1976). However, the research has suggested the number of palaeochannels within the study area is less than the number previously published by Sloss *et al.* (2005).

The Late Pleistocene/early Holocene transgression flooded the study area resulting in the deposition of the near shore muddy sands *ca.* 7.5 ka. Continued flooding of the receiving basin resulted in the deposition of the prodelta/lagoonal mud facies across

much of the study area. Deposition of fluvial sediments in the western portion of the study area is likely to have commenced *ca.* 6 ka. Morphologically, the delta appears to have transitioned from a cuspate shape, typically associated with wave dominated deltas to a birdsfoot delta associated with fluvial dominance. The research has suggested the change in morphology is attributable to increased sedimentation rates post-European settlement and subsequent land clearing increased the dominance of the fluvial processes.

Determining the depositional time frames of the intersected facies was problematic. The key issues encountered included a lack of material suitable for dating, wide depositional time frames and age inversions within cores. These issues are directly attributable to the dynamic nature of deltas with multiple deposition environments occurring simultaneously and the varied energy levels within the system.

Chapter 7

Holocene Evolution of Mullet/Hooka Creek Delta

7.1: Introduction

The Mullet/Hooka Creek delta is actively prograding into the northwestern region of Lake Illawarra. This chapter outlines the Holocene stratigraphic and subsequent morphological evolution of the delta with respect to autocyclic and allocyclic processes. The chapter discusses the emplacement and evolution of the antecedent Pleistocene land surface and associated deposits through to the present sedimentary deposits. The delta's evolution has been established based on the interpretation of 73 detailed sedimentary logs, resultant cross-sections (Figure 7.1) and surface models generated within a GIS framework. AAR, ^{210}Pb, AMS and ^{14}C dating techniques were utilised to establish the delta's geochronology.

7.2: Evolution of Mullet/Hooka Creek delta

The following section outlines the morphological and sedimentological evolution of Mullet/Hooka Creek delta in response to controlling factors such as receiving basin morphology, sedimentation rates and sea level. The discussion has been divided into four subsections based on sea level and deltaic processes.

7.2.1: The late Pleistocene receiving basin and basal regressive delta units

The Mullet/Hooka Creek study area is dissected by a single predominantly northwest to the southeast trending low interpreted to represent the Pleistocene Mullet Creek palaeochannel (Figure 7.2). The observed directional change in the central section of the study area is likely due to the northeast to northwest trending bedrock highs (Hooka Point, Hooka Island and connecting saddle) along the eastern bank (Figure 7.2) and the opposite palaeohigh visible in Mullet/Hooka Creek delta section A–B (Figure 7.1) and Figure 7.2.

Long/cross section location map: Mullet/Hooka Creek

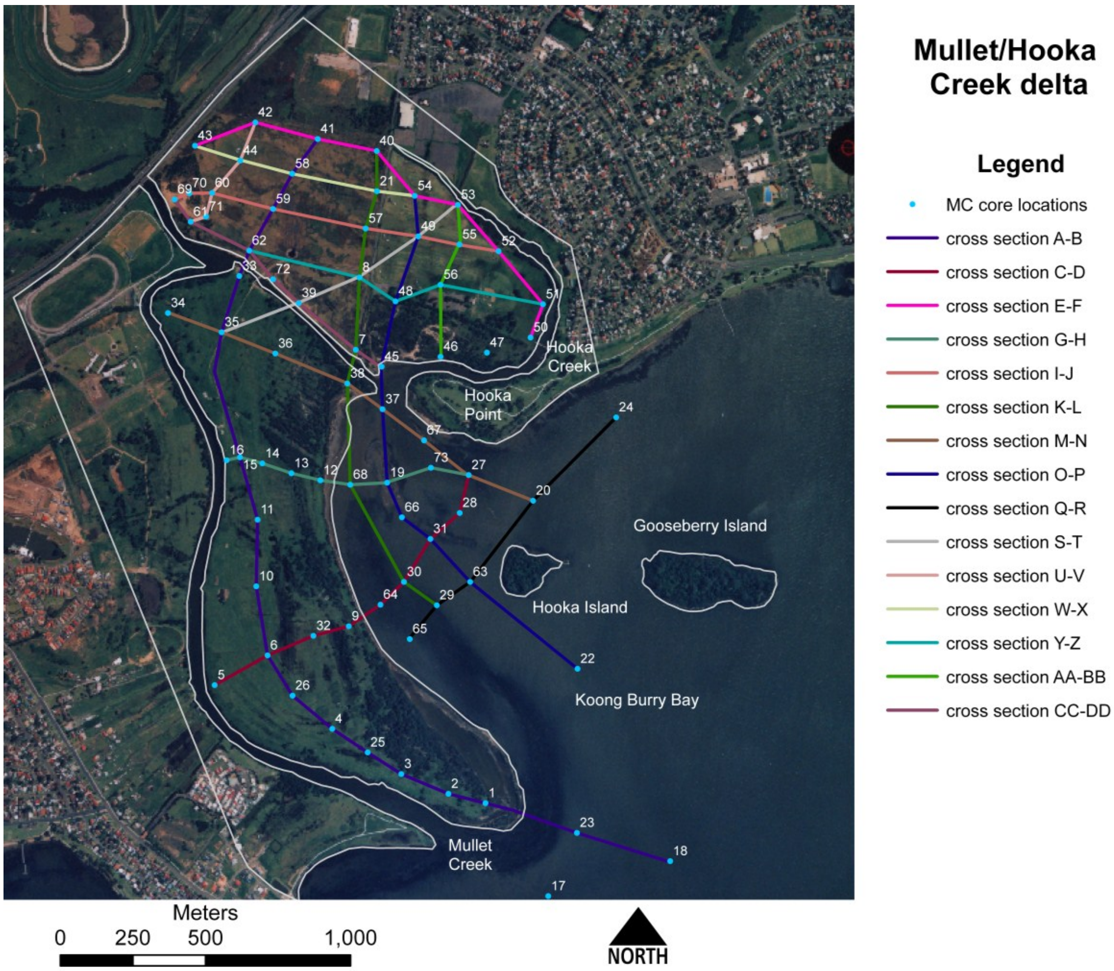


Figure 7.1: *Long/cross section location map and corresponding sections A-B to CC-DD below. Note the multiple vertical exaggerations (VE) utilised in the production of the sections was necessary to illustrate the variety of facies, some of which are quite thin, in each section.*

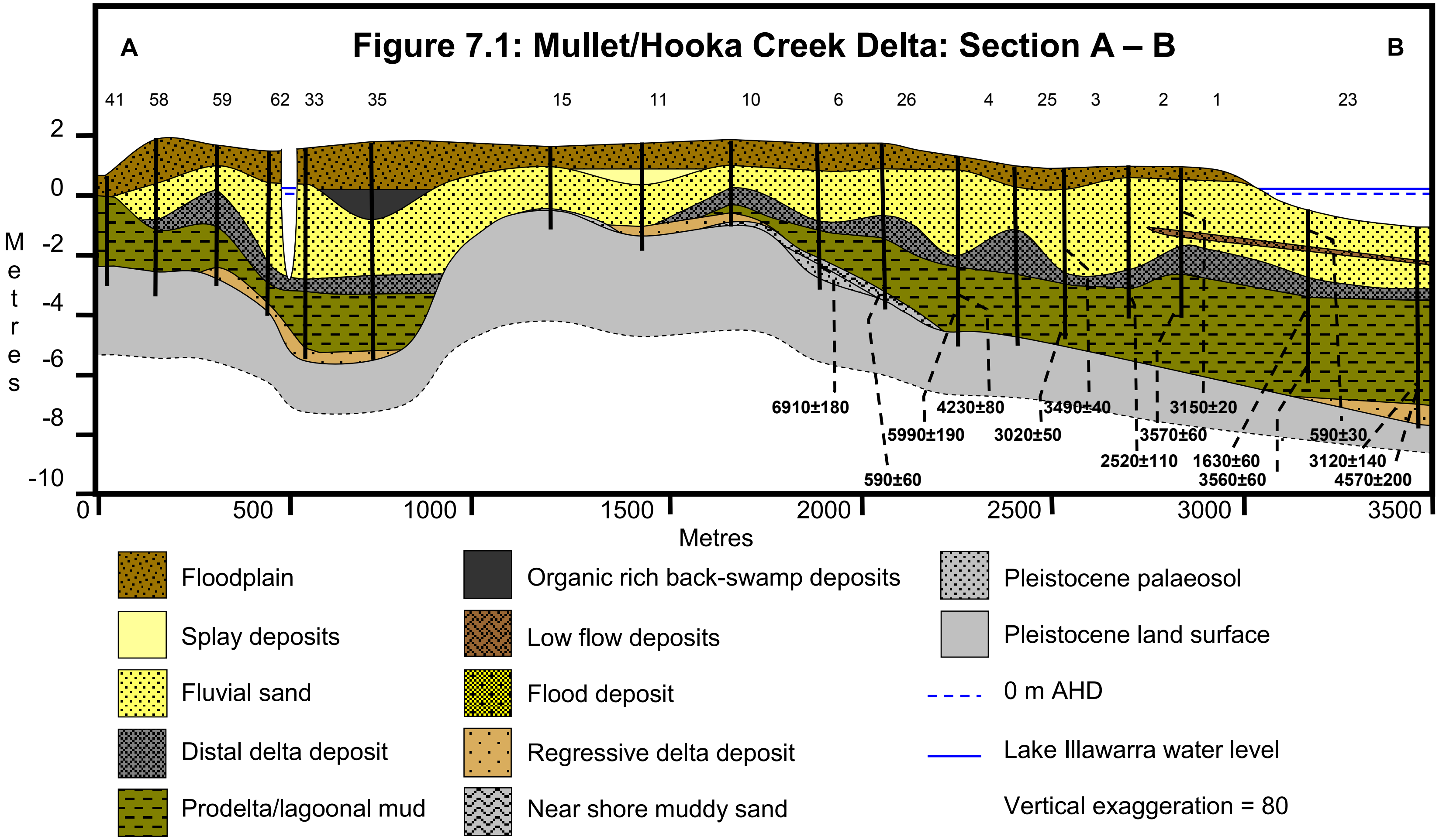
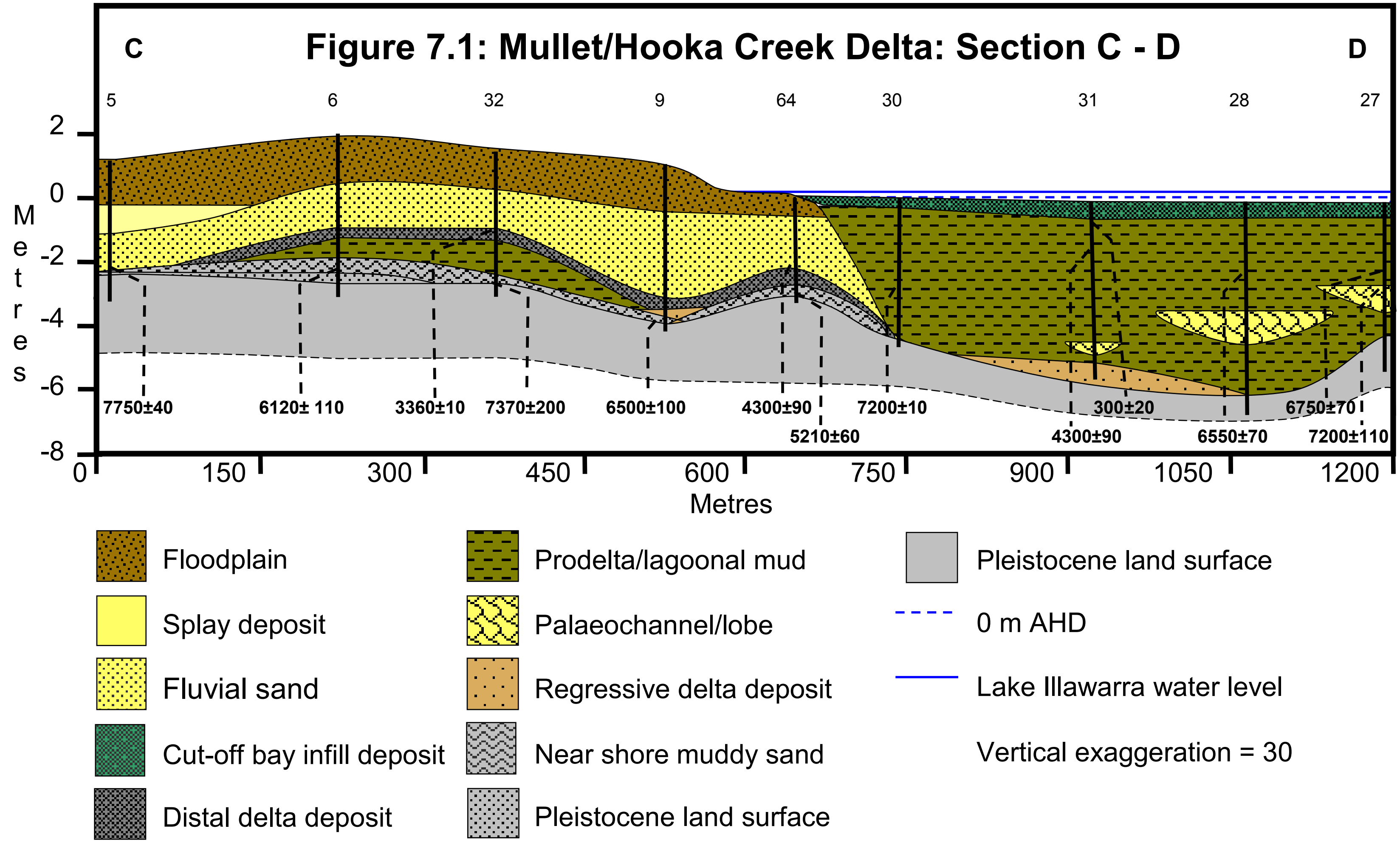


Figure 7.1: Mullet/Hooka Creek Delta: Section A – B

Figure 7.1: Mullet/Hooka Creek Delta: Section C - D



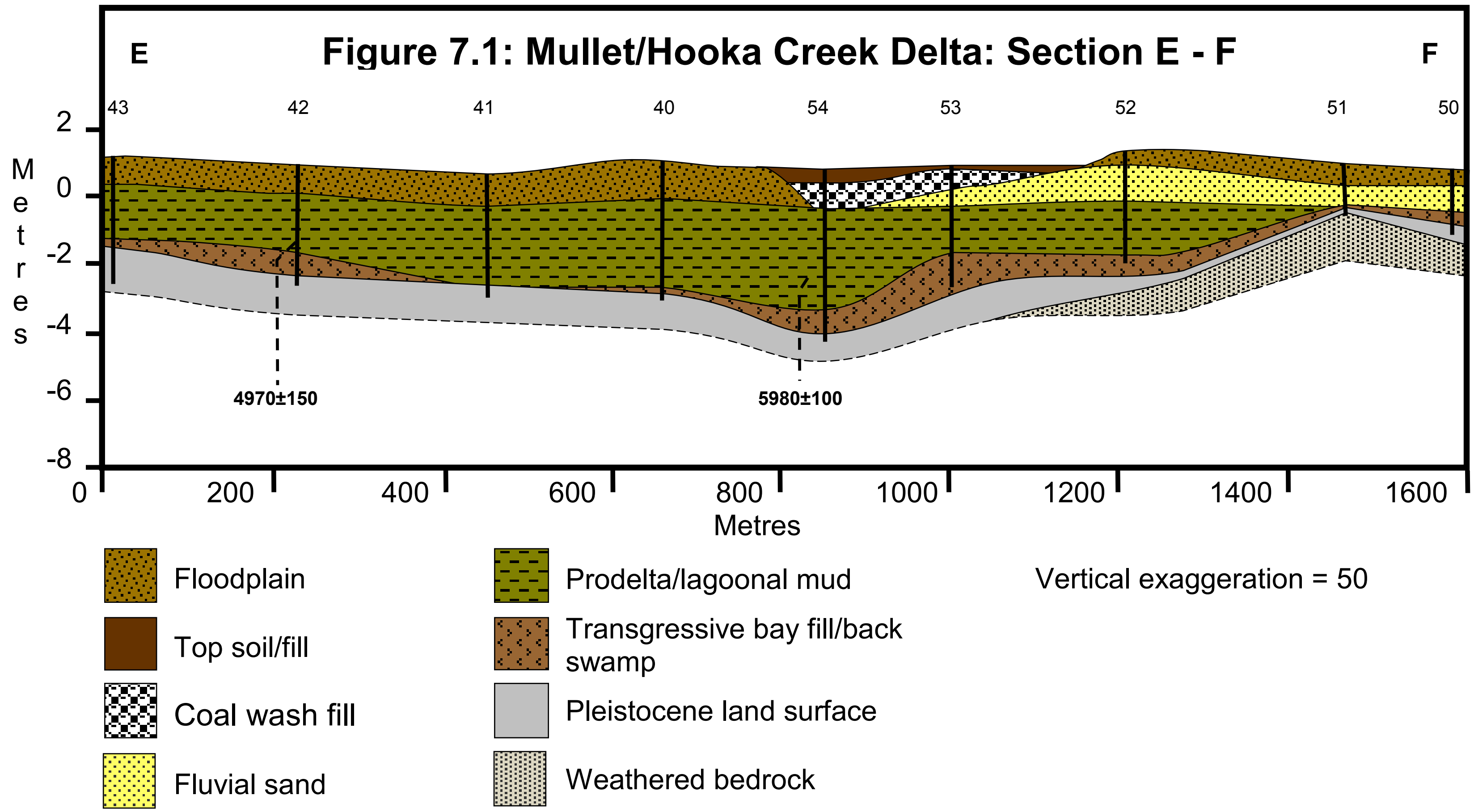


Figure 7.1: Mullet/Hooka Creek Delta: Section E - F

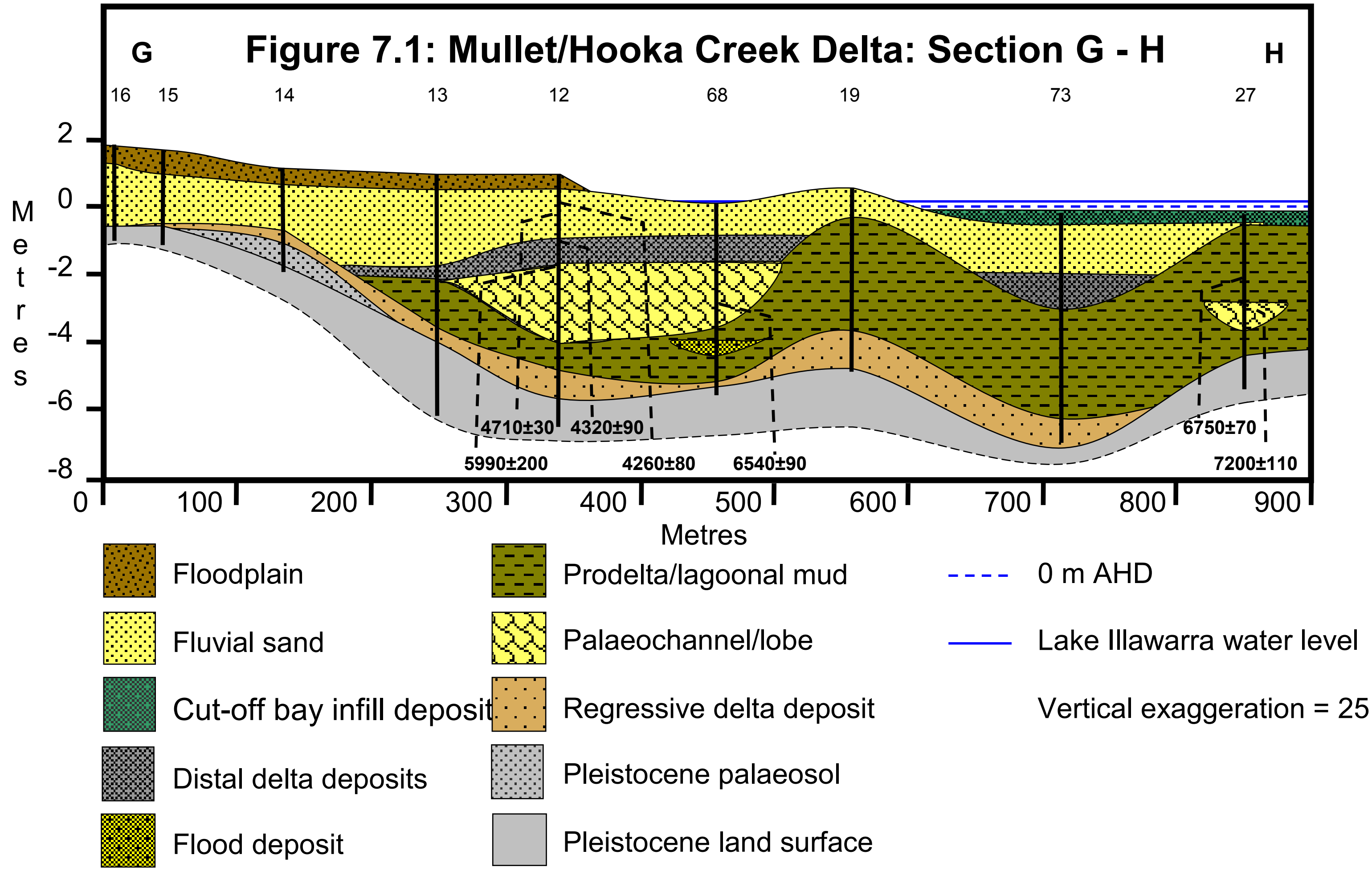


Figure 7.1: Mullet/Hooka Creek Delta: Section G - H
G
H
16
15
14
13
12
68
19
73
27
Metres
2
0
-2
-4
-6
-8
4710±30
4320±90
5990±200
4260±80
6540±90
6750±70
7200±110
0
100
200
300
400
500
600
700
800
900
Metres
Floodplain
Fluvial sand
Cut-off bay infill deposit
Distal delta deposits
Flood deposit
Prodelta/lagoonal mud
Palaeochannel/lobe
Regressive delta deposit
Pleistocene palaeosol
Pleistocene land surface
0 m AHD
Lake Illawarra water level
Vertical exaggeration = 25

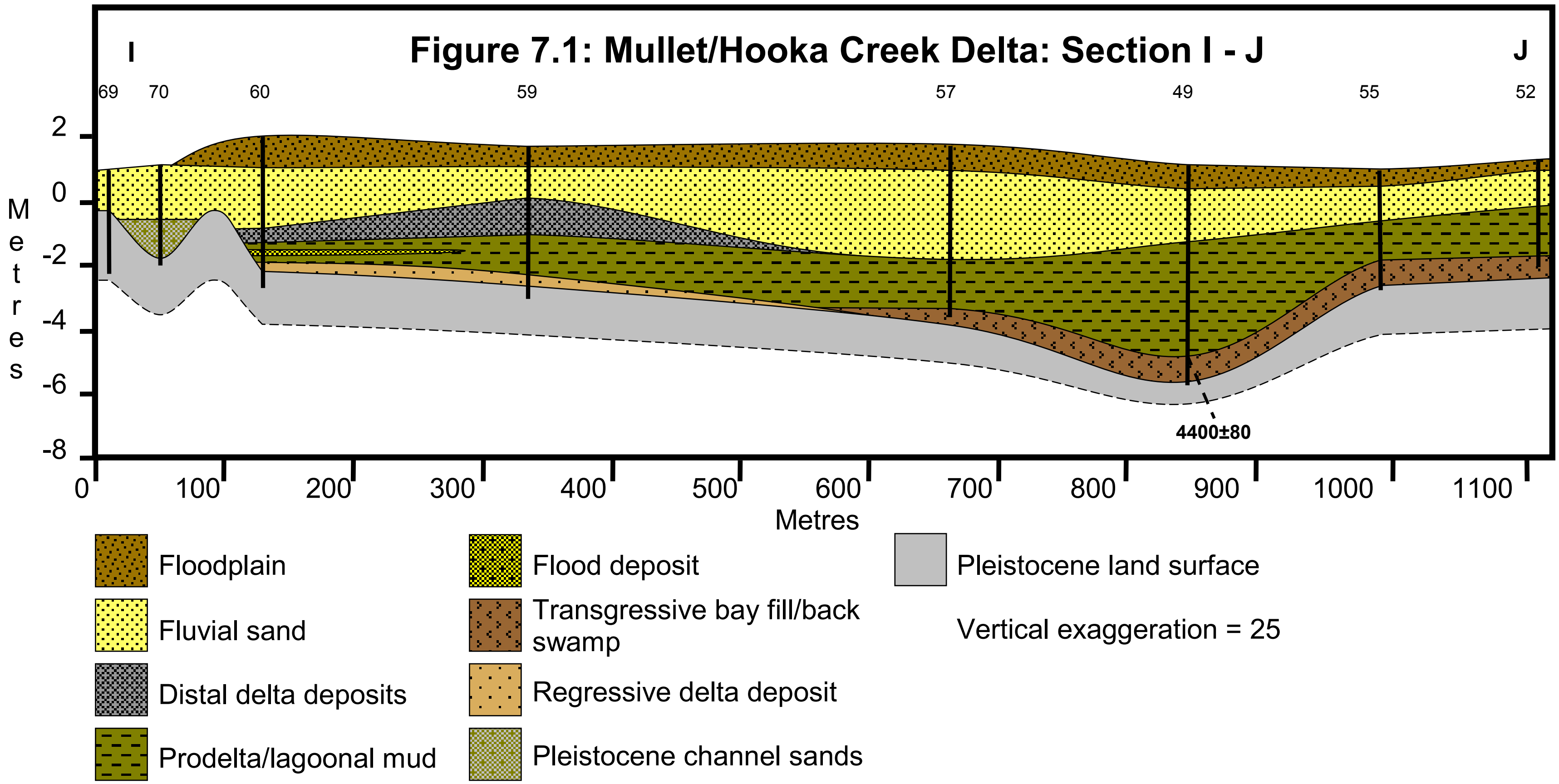


Figure 7.1: Mullet/Hooka Creek Delta: Section I - J
I
J
69
70
60
59
57
49
55
52
2
0
-2
-4
-6
-8
Metres
4400±80
0
100
200
300
400
500
600
700
800
900
1000
1100
Metres
Floodplain
Fluvial sand
Distal delta deposits
Prodelta/lagoonal mud
Flood deposit
Transgressive bay fill/back swamp
Regressive delta deposit
Pleistocene channel sands
Pleistocene land surface
Vertical exaggeration = 25

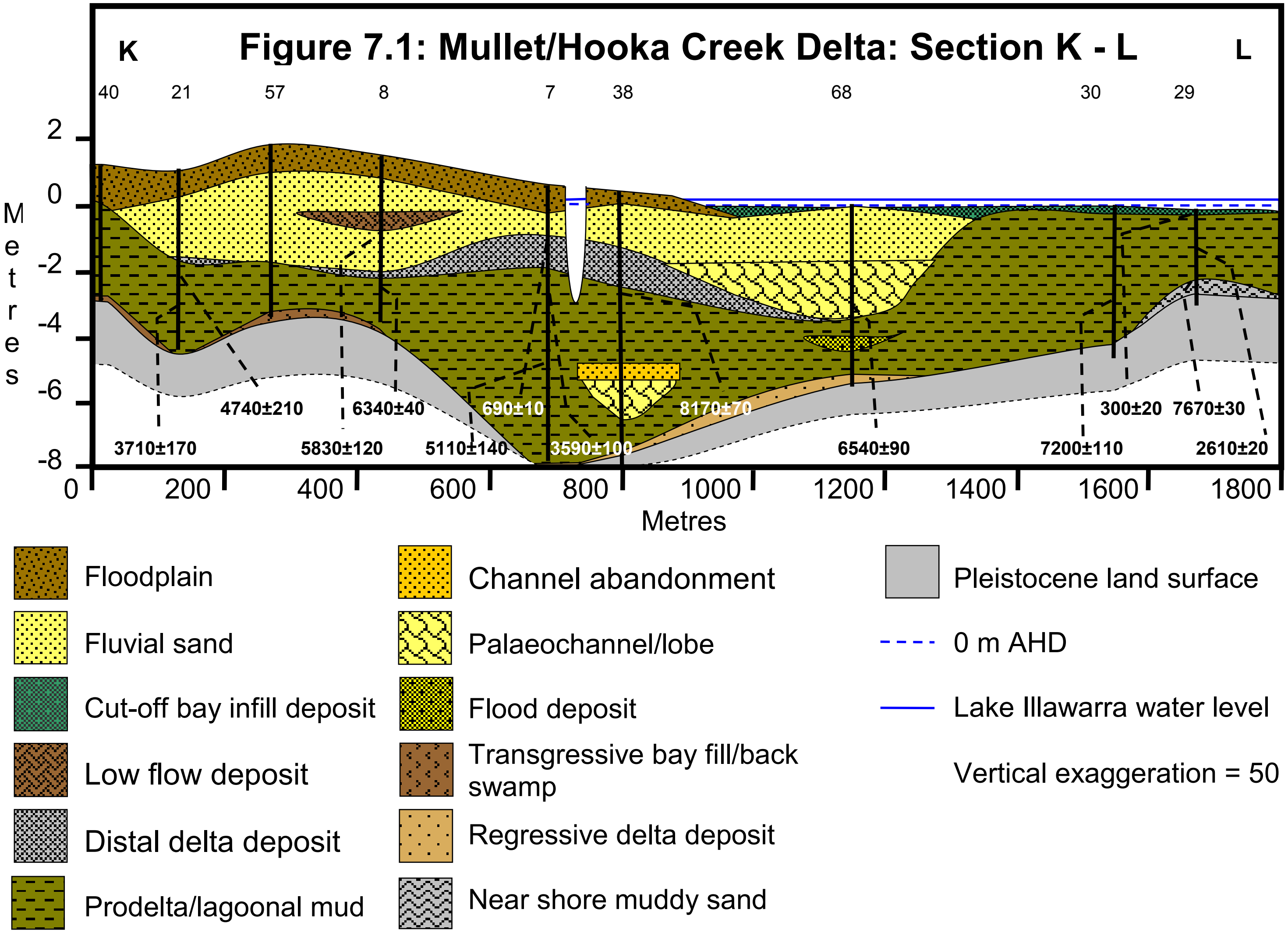


Figure 7.1: Mullet/Hooka Creek Delta: Section K - L

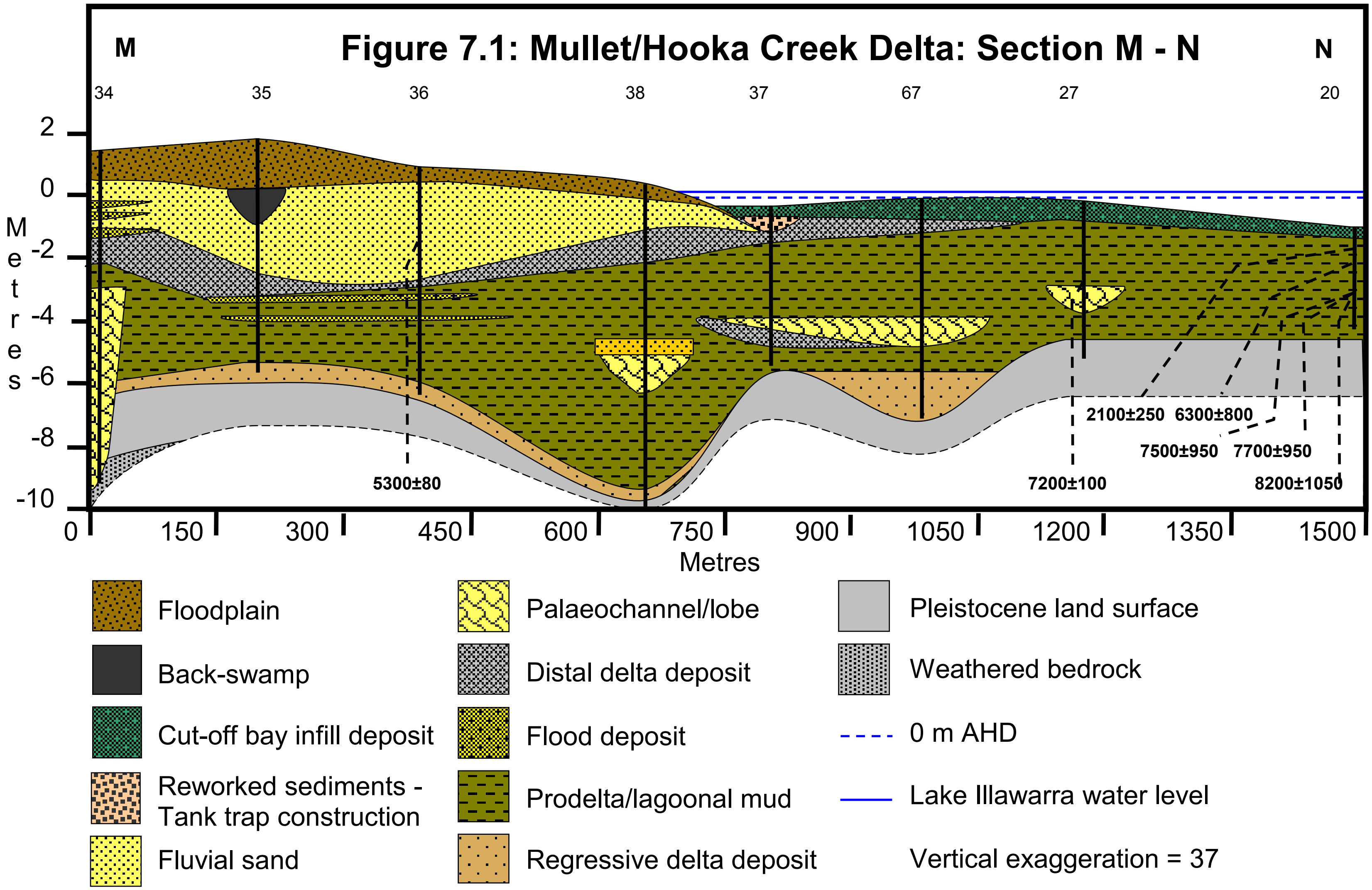


Figure 7.1: Mullet/Hooka Creek Delta: Section M - N

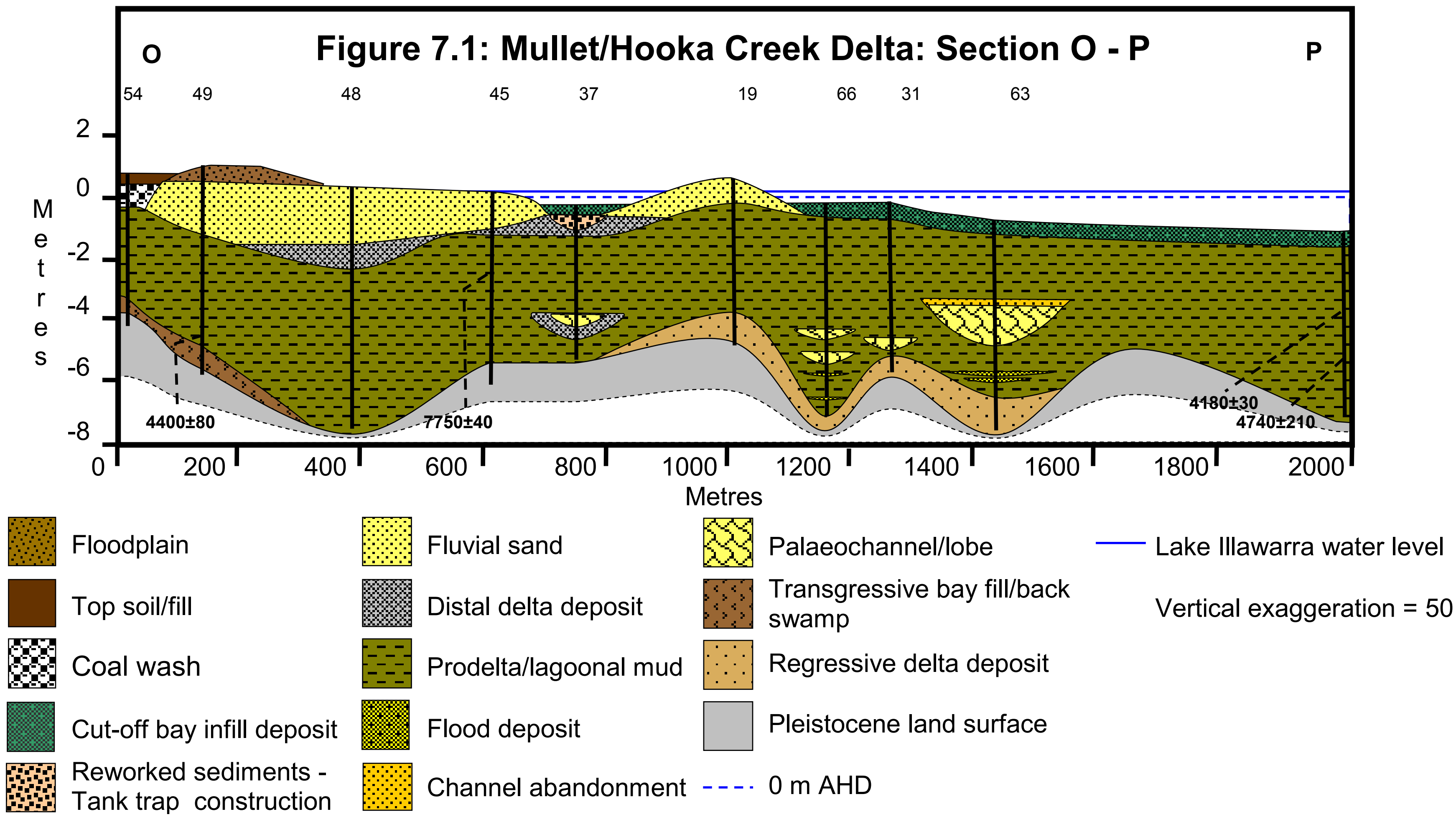
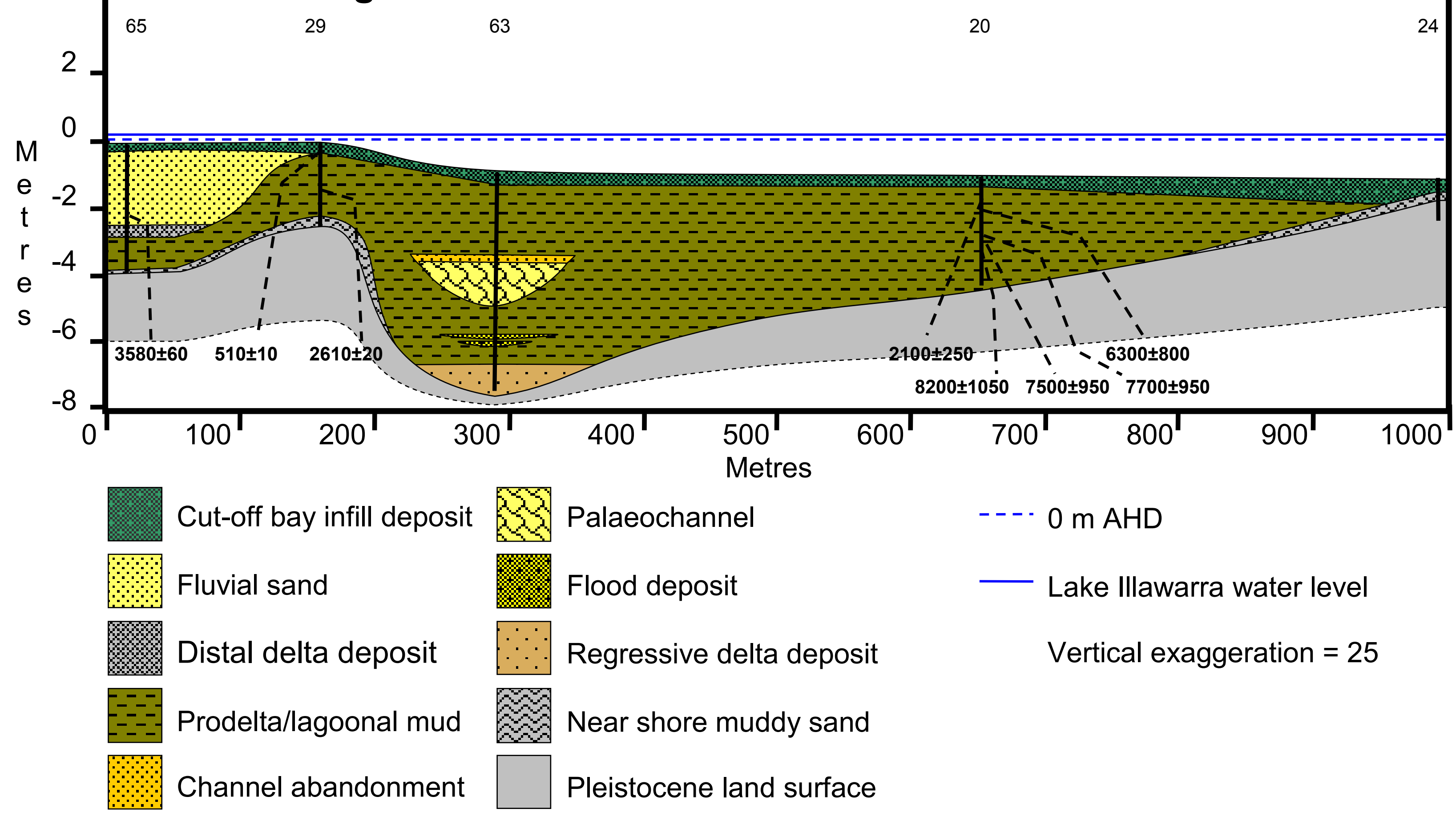


Figure 7.1: Mullet/Hooka Creek Delta: Section O - P

Figure 7.1: Mullet/Hooka Creek Delta: Section Q - R



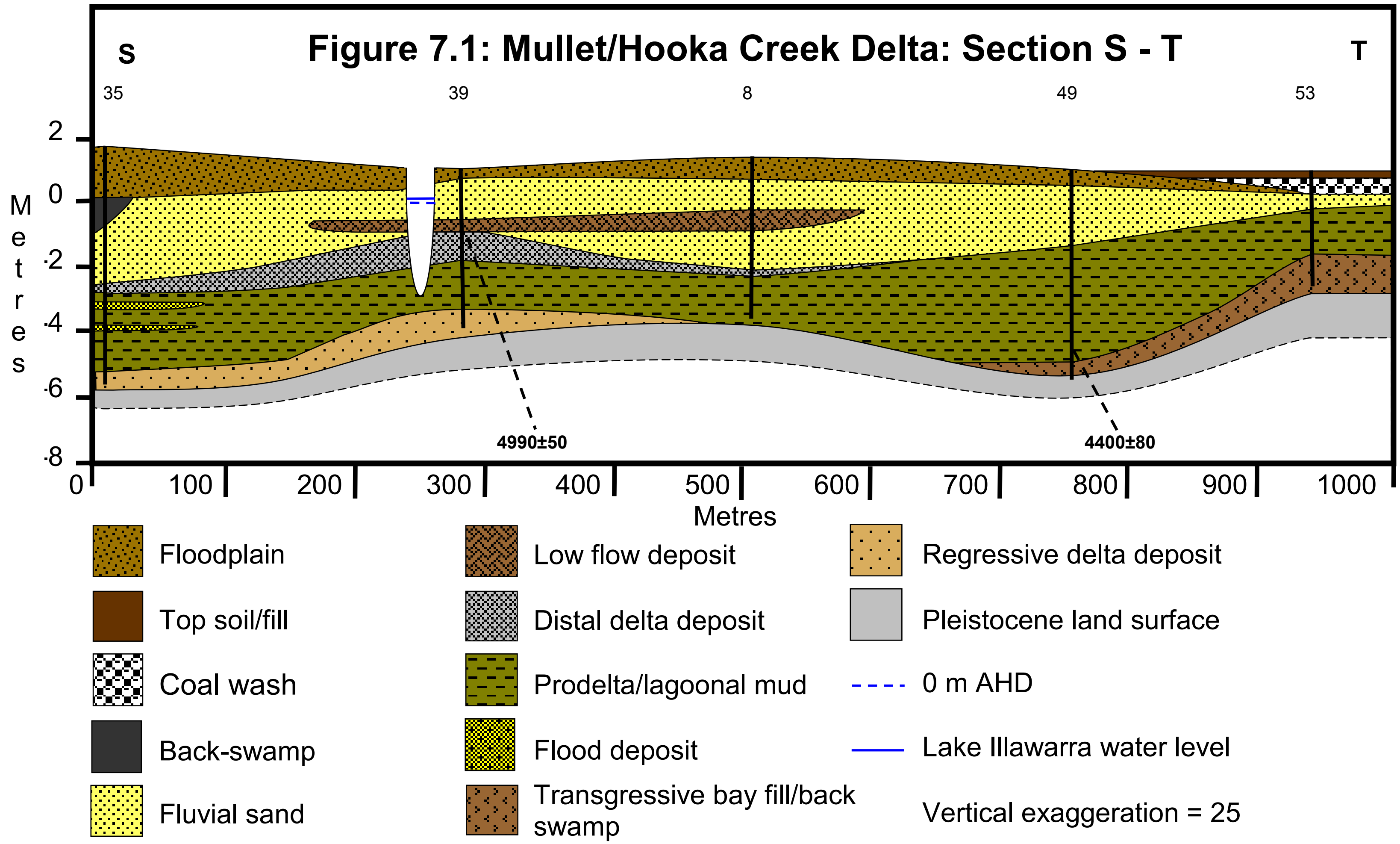


Figure 7.1: Mullet/Hooka Creek Delta: Section S - T

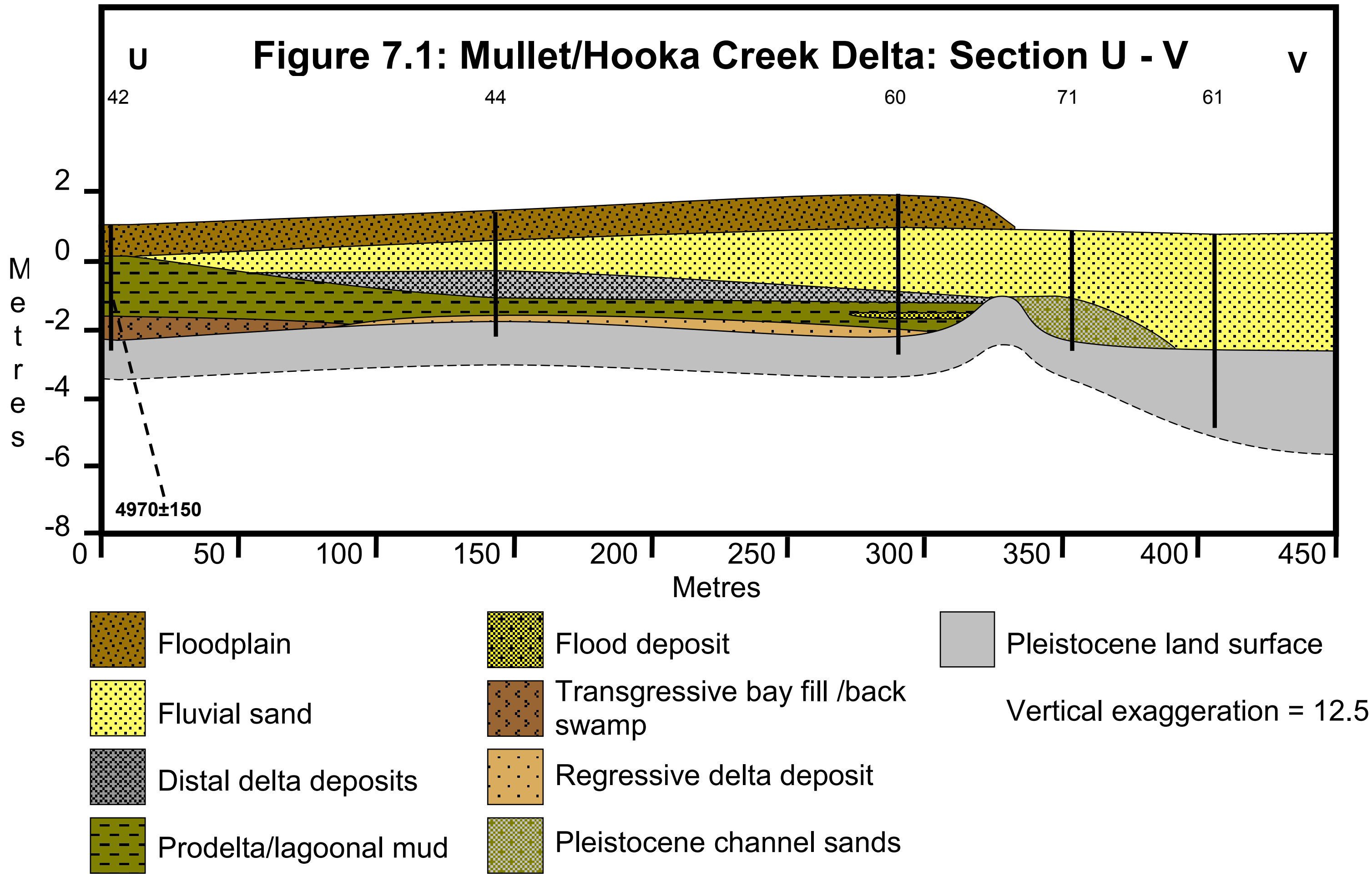


Figure 7.1: Mullet/Hooka Creek Delta: Section U - V

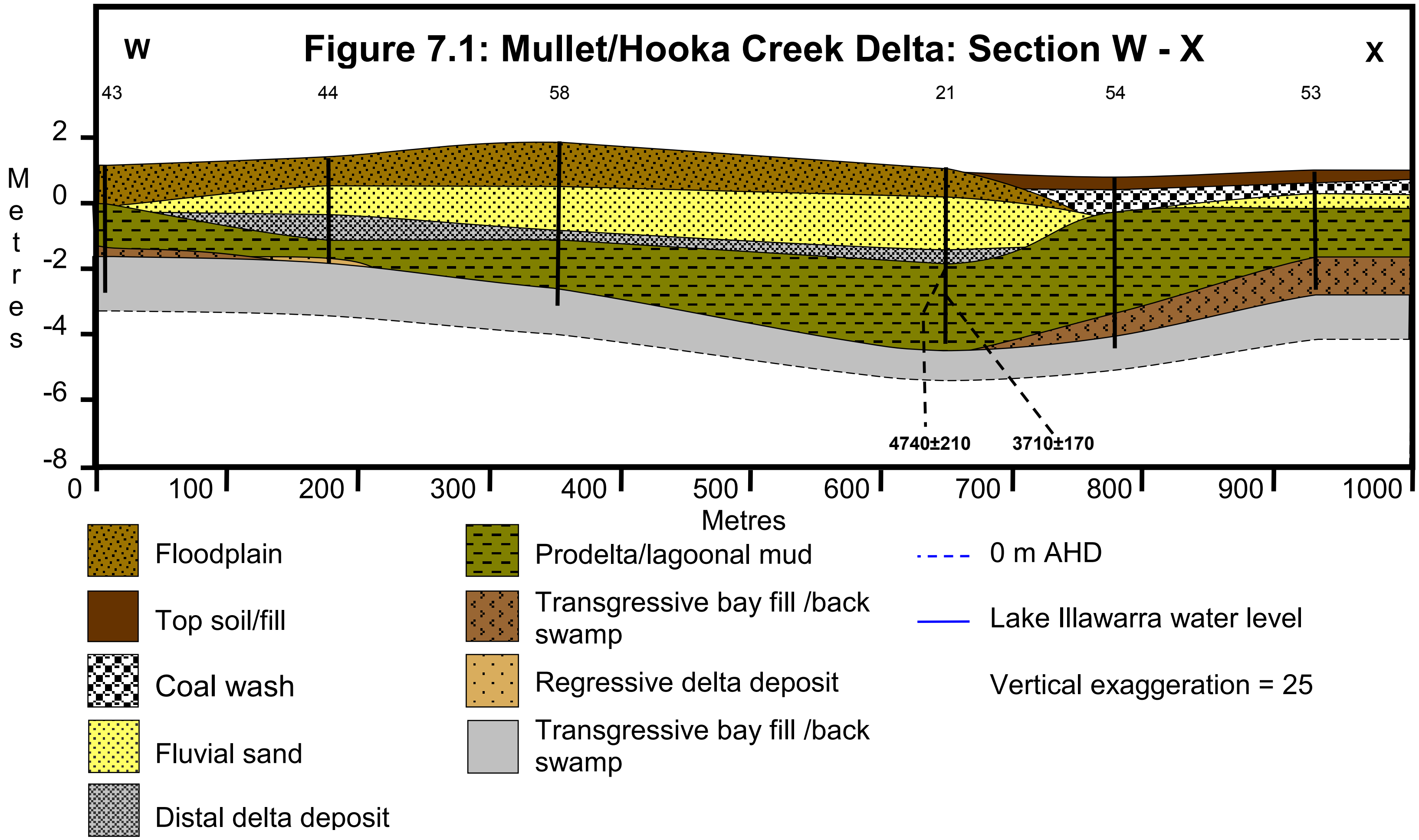


Figure 7.1: Mullet/Hooka Creek Delta: Section W - X

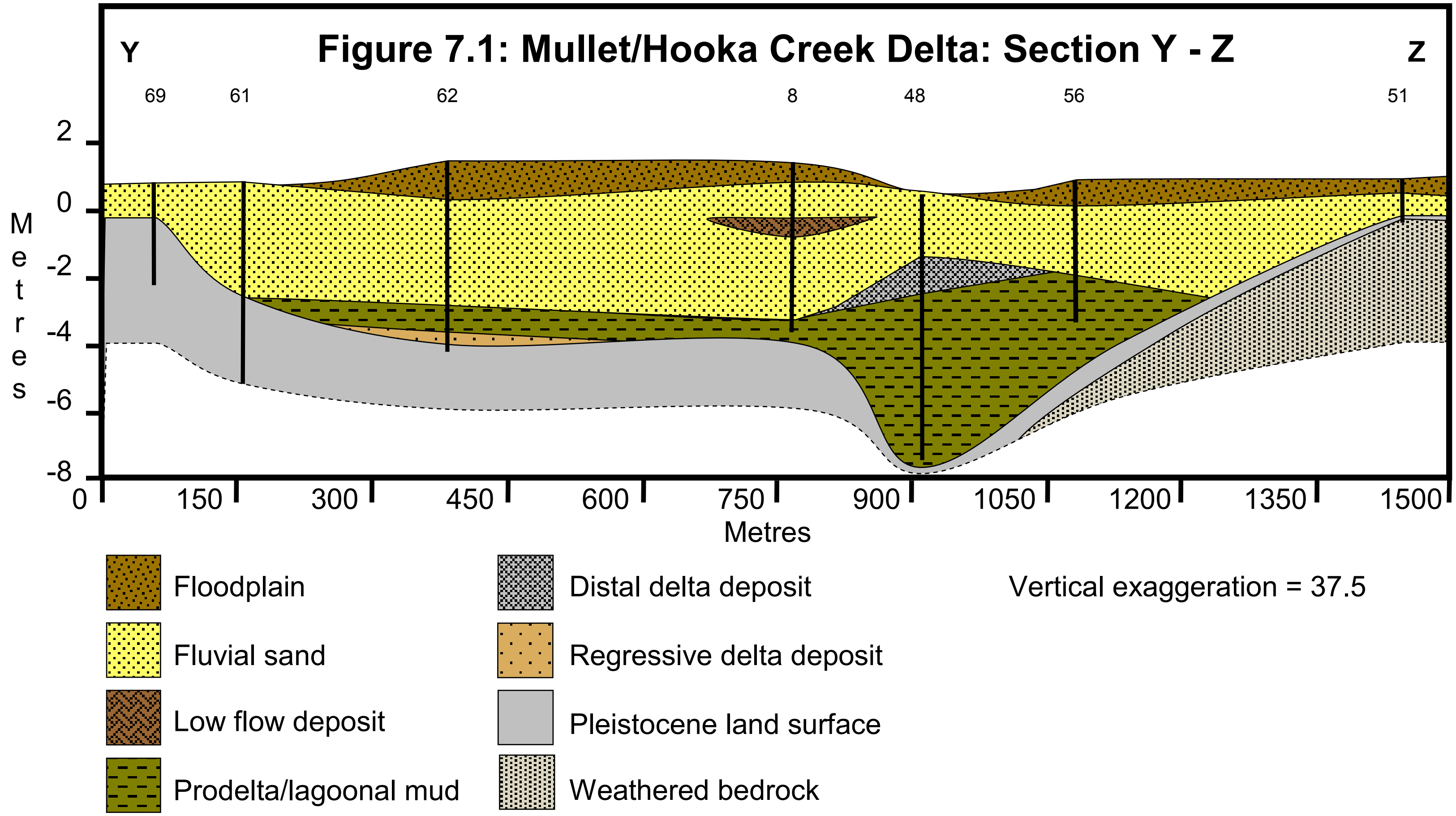


Figure 7.1: Mullet/Hooka Creek Delta: Section Y - Z

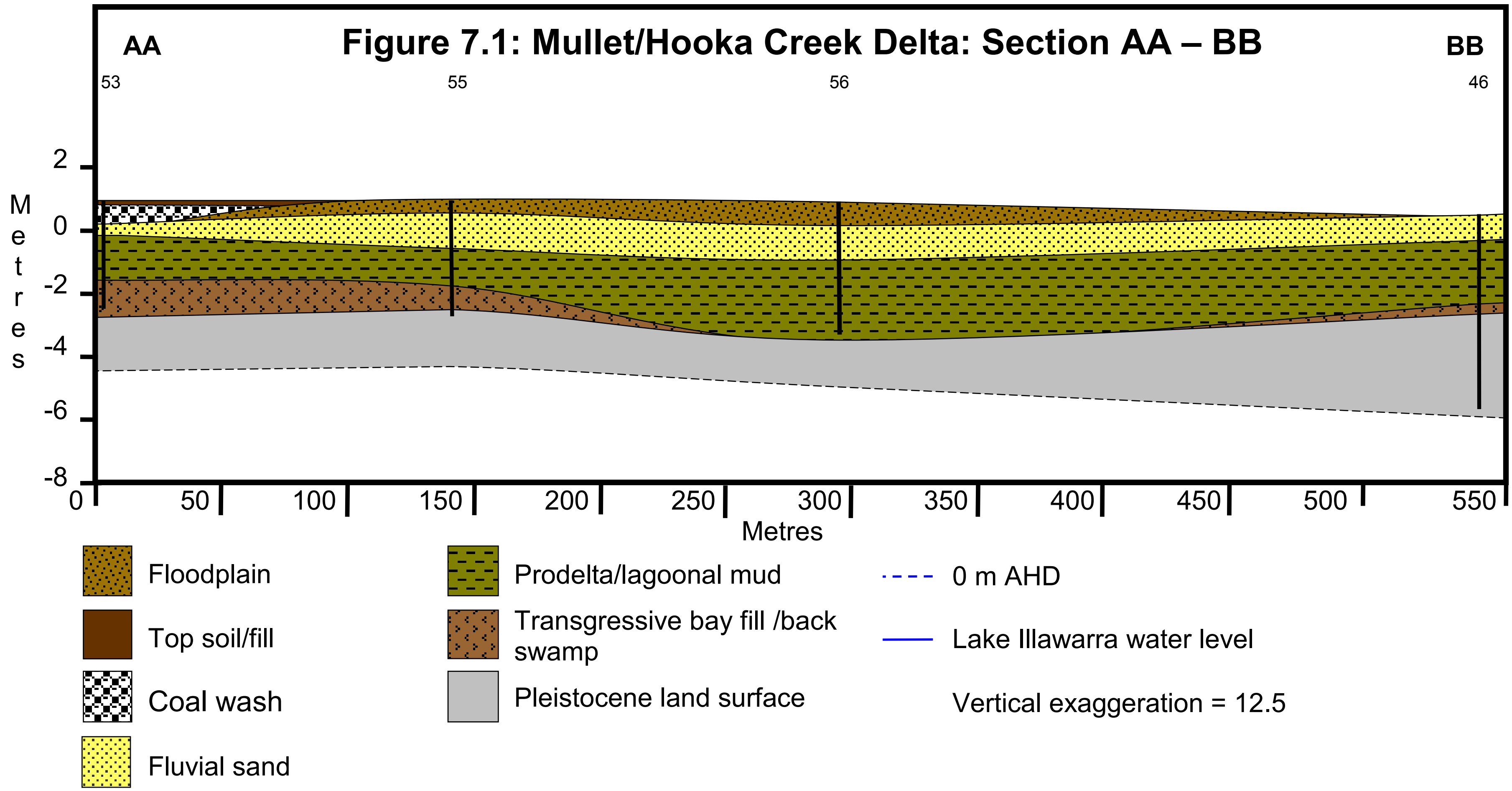


Figure 7.1: Mullet/Hooka Creek Delta: Section AA – BB

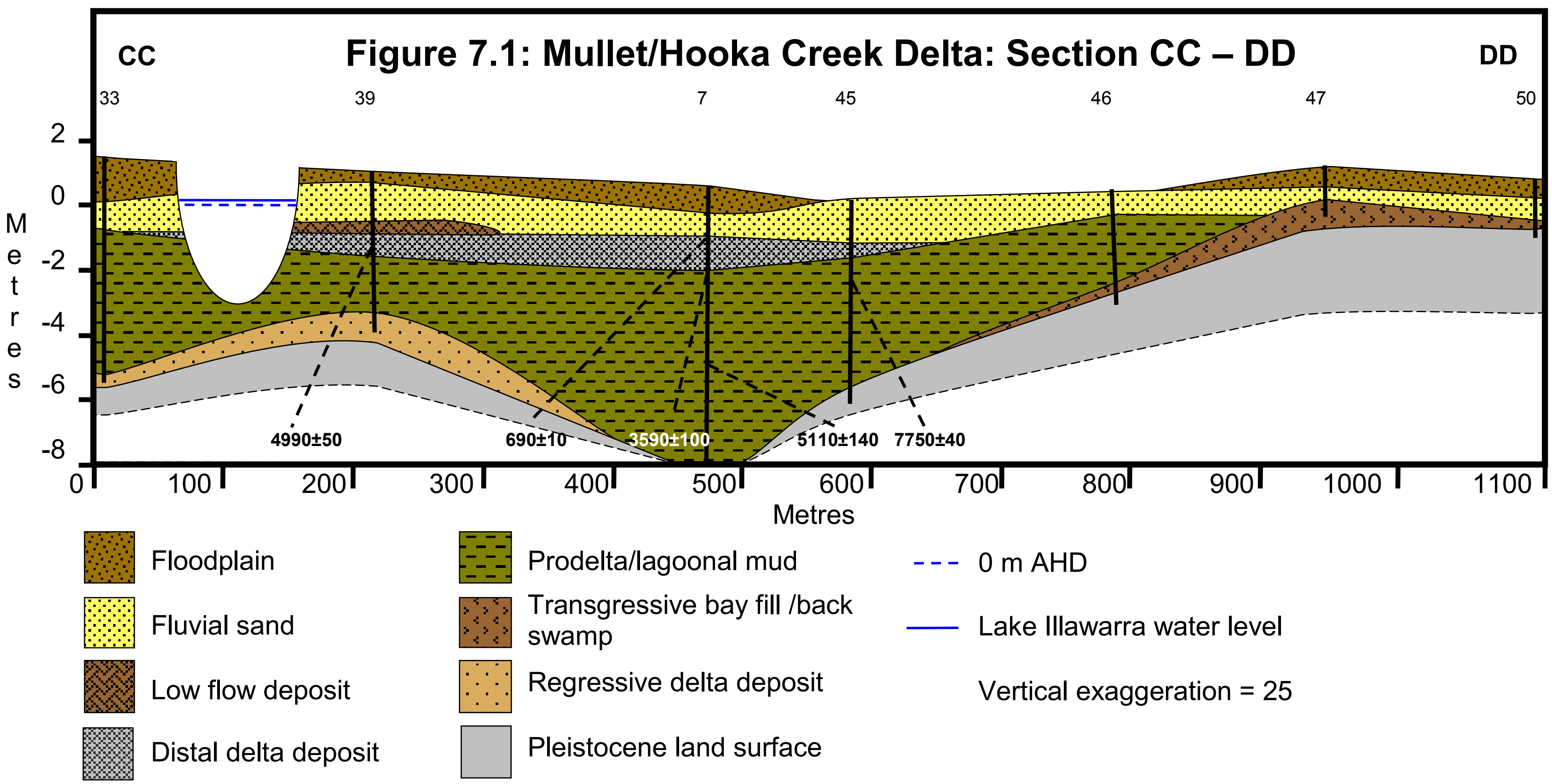


Figure 7.1: Mullet/Hooka Creek Delta: Section CC – DD

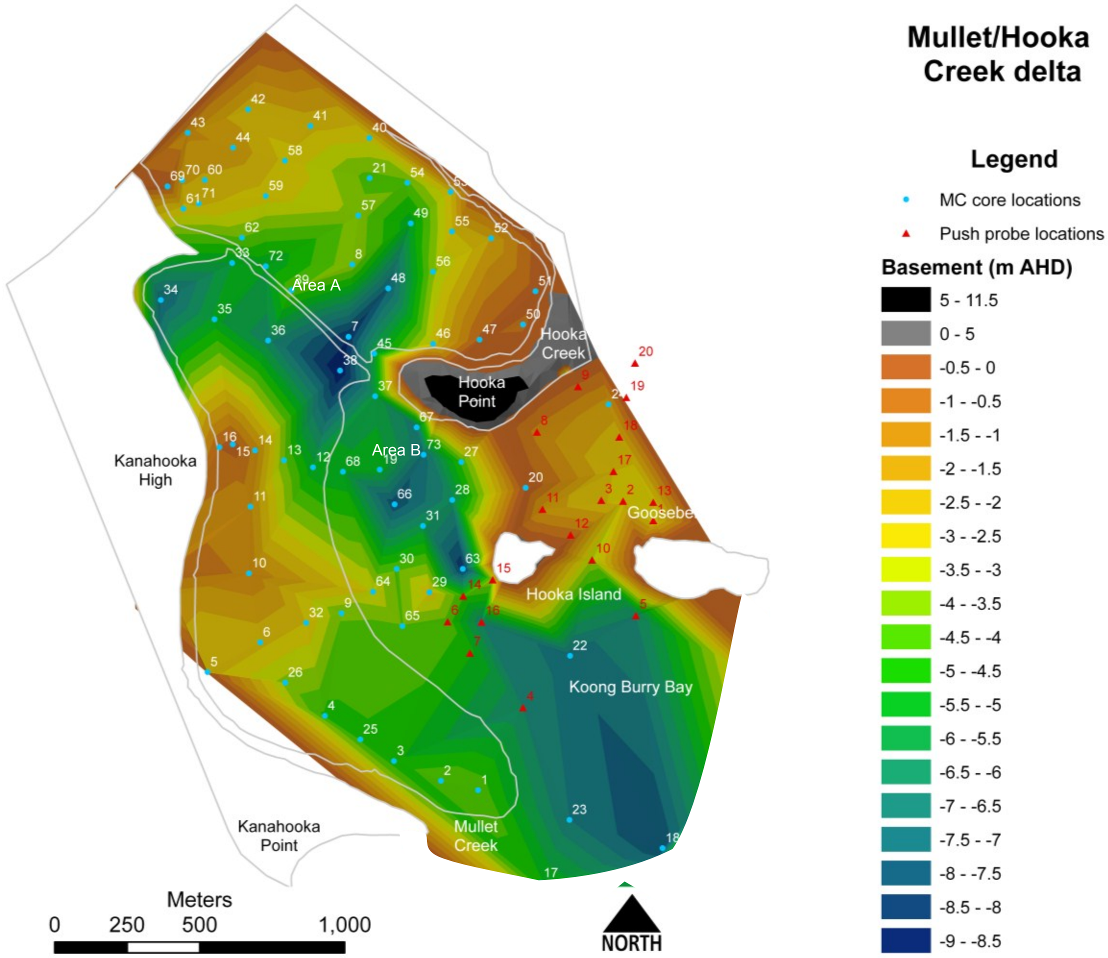


Figure 7.2: *TIN model Mullet/Hooka Creek palaeoreceiving basin morphology derived from the analysis of 73 subsurface vibracore/drill holes and 20 push probes. Note, care must be taken when assessing the models margins due to limited input data introducing edge effects.*

Sloss *et al.* (2005) suggested the main palaeochannel, within the Koong Burry Bay area, split into two channels proximal to Hooka Island as illustrated in Figure 6.3. However, cross/long sections C-D and Q-R (Figure 7.1) do not seam to support this. Instead, the data indicate that a single centrally located channel operated within Koong Burry Bay proximal to Hooka Island. The variance between the two models is likely due to the increased resolution of this study enabling the palaeoreceiving basin morphology to be

established more accurately, compared with the limited core data and seismic traces available to Sloss *et al.* (2005).

Figure 7.2 shows two deeper embayments existed within the main channel. The deepest embayment is located proximal to Hooka Point (Area A). The embayment is elongate in a north-northeasterly direction attaining a depth over 8 m AHD based on cores MC 7 and MC 48 which attained elevations of -8.2 m AHD and -8.19 m AHD, respectively. It is possible that this embayment formed at the palaeoconfluence between Mullet and Hooka Creeks. The north-northeasterly elongate nature of the embayment may represent the up-stream migration of a knick-point along the palaeo-Hooka Creek towards MC49.

It is interpreted that a second shallower embayment was located directly to the south-southeast of the larger embayment (Figure 7.2; Area B). The northerly and westerly margins of the embayment are the southern side of the Hooka Point high and the north-south orientated highs as discussed above. The eastern margin of the embayment is defined by the bedrock saddle between Hooka Point and Hooka Island (Figure 7.2). A narrow southwesterly orientated high intersected with probes 14 and 15 is attached to Hooka Island forming the southern margin of the embayment. The model indicates water within the embayment flowed through a narrow opening proximal to the location of push probe 14 (Figure 7.2). The area of lower elevation, between MC 30 and MC 65 is likely to be an artefact of the modelling process.

As previously discussed (Chapter 2) Coleman and Wright (1975) noted the inherited basin morphology is a key determinant for the morphology of present/modern deltas. Factors influencing this inherited morphology include, but are not limited to, lithology (rock type, structure, etc) of the under lying strata and the degree of incision by Pleistocene palaeochannels. At present, the influence of the underlying basement topography is not apparent within the Mullet/Hooka Creek study area (Figure 7.2). Instead the model indicates that the current channel cuts across palaeohighs located to

the west of the interpreted Pleistocene palaeochannel (Area C). However, the influence of the basement topography is likely to have been more pronounced during the initial stages of basin inundation and infilling.

The antecedent Pleistocene basement is overlain by a thin near shore muddy sand (Chapter 5, section 5.4). The majority of the cores which intersected the facies within this study area are located west of Hooka Island (Figure 7.3). The facies contour intervals derived from the cores (Figure 7.3) display a strong relationship with the underlying topography of the basement. This relationship between the facies and subsurface topography is also evident in the Mullet/Hooka Creek sections A-B, C-D, K-L and Q-R (Figure 7.1). As the Late Pleistocene/Early Holocene sea level rose the shoreline progressively moved in a landward direction resulting in the facies on-lapping the underlying basement.

Facies ages, as determined by amino acid racemisation and ^{14}C dating techniques, ranged from 5,210±60 years BP (MC 64) to 7,750±40 years BP (MC 5) with an average age of 5,406 years BP (Table 4.6b and 4.7; Figure 7.1, Volume 2, Appendix 5). These results are similar to the ages from the equivalent facies within the Macquarie Rivulet delta study area and those reported by Sloss *et al.* (2005, 2006a). This age range suggest deposition occurred during stage 1a and 2a of the Sloss *et al.* (2005, 2006a; Figure 3.7) model which is characterised by the transition from a restricted marine environment to a more sheltered estuarine environment as the Holocene barrier evolved.

The Pleistocene basement in the northeastern quadrant of the Mullet/Hooka Creek study area is overlain by the transgressive bay fill/back swamp facies (Figure 7.4). The stratigraphic relationship of this facies and surrounding facies is illustrated in Mullet/Hooka Creek Sections E-F, I-J, K-L, O-P, U-V, W-X, AA-BB and CC-DD (Figure 7.1). Based on the facies sedimentology (Chapter 5, section 5.5), it is inferred deposition occurred in a relatively shallow low energy back-water environment, such as a sub-embayment or back-swamp

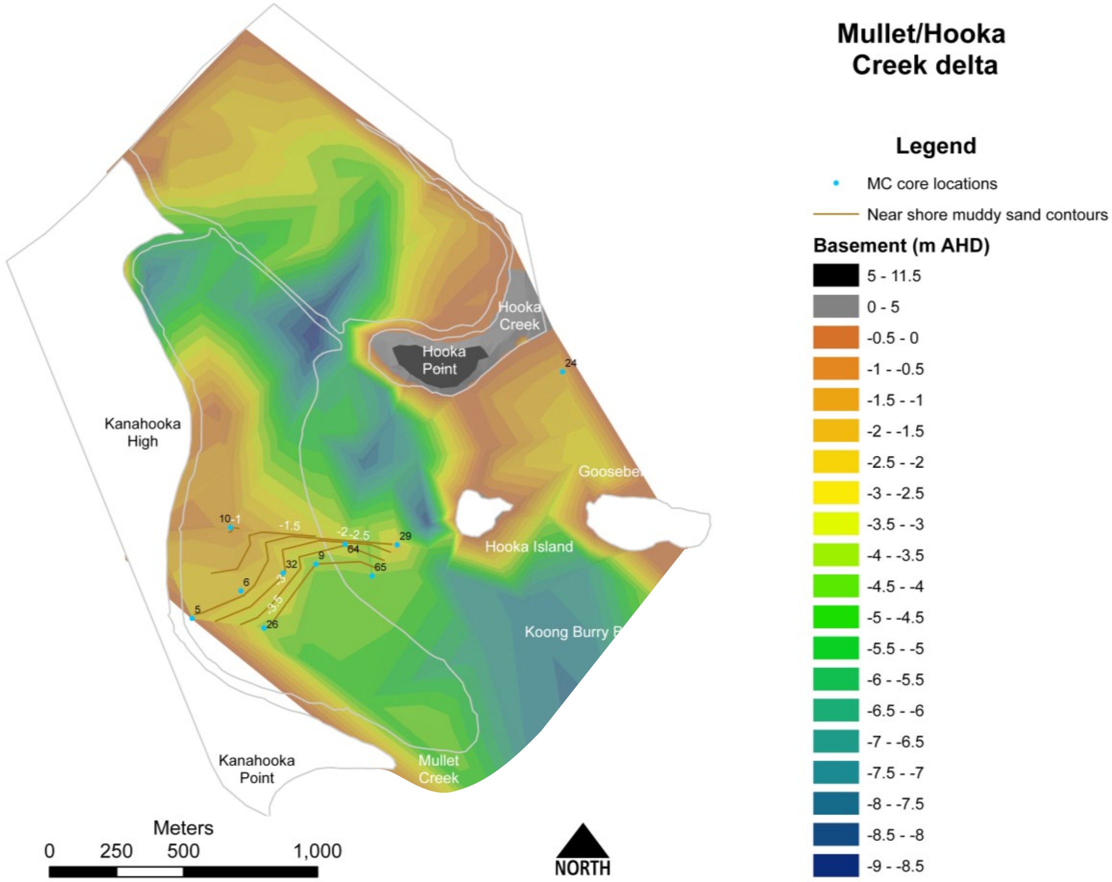


Figure 7.3: *Contour map illustrating the depth (m AHD) to the upper surface of the near shore muddy sand facies. The contours overlie the basement TIN model illustrated in Figure 7.2.*

Figure 7.4 and associated stratigraphic logs and long/cross-sections (Figure 7.1; Volume 2, Appendix 5) demonstrate that the maximum depth to the transgressive bay fill/back swamp facies upper surface occurs in the vicinity of MC 49 at a depth of -4.5 m AHD. From this location the depth to facies, relative to AHD, decreases steadily to the north-northwest and more sharply to the east and southeast, where the upper contact occurs at 0.2 m AHD (MC 47). The rapid decrease in depth to the east and southeast is related to the underlying Pleistocene topography and the bedrock high extending from the east-west orientated Hooka Point in the south, and which curves towards the north along the southeastern boundary of the study area (Figure 7.4). Facies thicknesses observed in the

cores ranged from approximately 0.1 m in MC 51 to 0.9 m in MC 53 with the majority of intersections in the vicinity of 0.2 m. Thinning of the facies within MC 47, 50 and 51 may also be attributable to down-cutting by the overlying fluvial sands (Figure 7.1; Volume 2, Appendix 5).

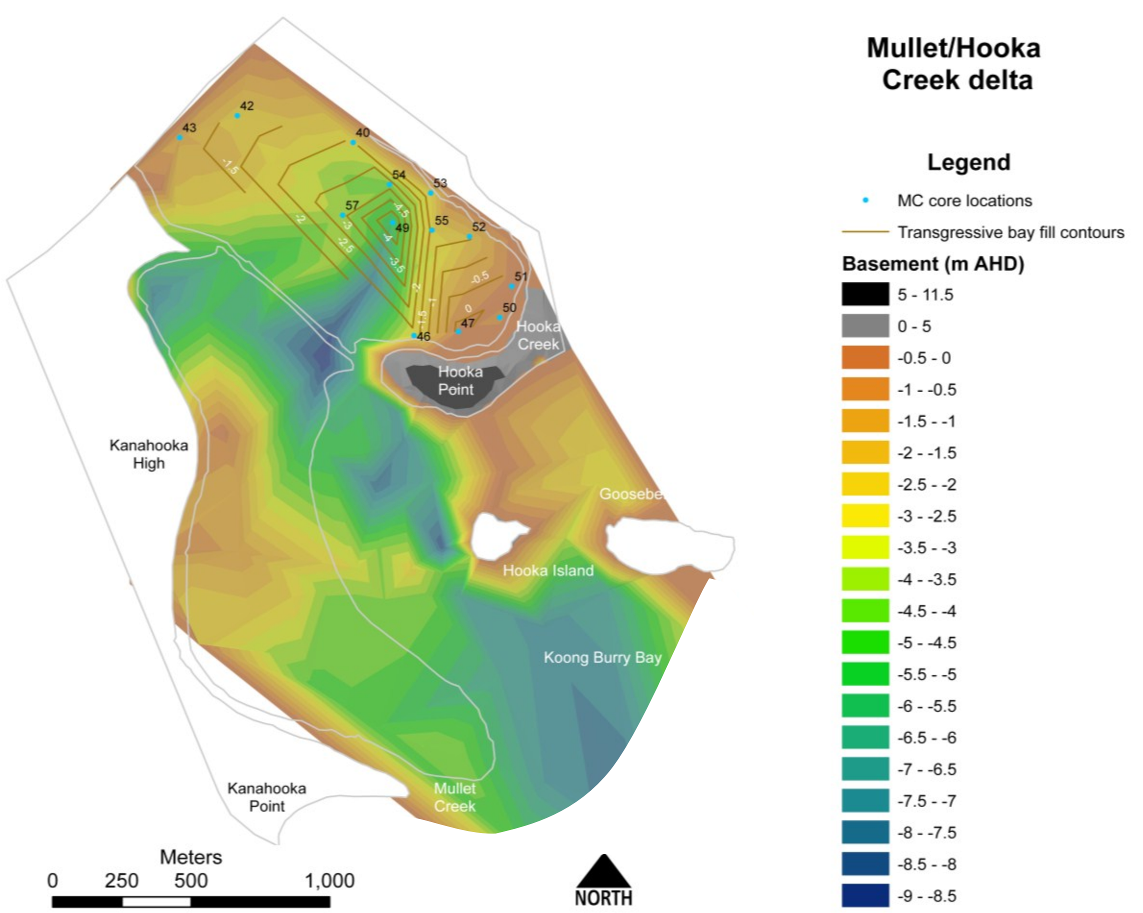


Figure 7.4: *Contour map illustrating the depth (m AHD) to the upper surface of the transgressive bay fill/ back-swamp facies. The contours overlie the basement TIN model illustrated in Figure 7.2.*

The lack of suitable material within the facies prevents the direct establishment of the facies time of deposition. Instead the relative age of the facies has been inferred from the overlying prodelta/lagoonal mud facies in MC 42 and 49. The articulate *Notospisula trigonella* within MC 42 and MC 49 yielded AAR ages of 4,970±150 years BP and 4,400±80 years BP(Table 4.6b) at +0.25 m and +0.40 m AHD above the facies contact.

Based on these ages, facies deposition would have commenced sometime prior to 5,000 years BP.

The minimum age of the transgressive bay fill/back swamp facies of c.a. 5 ka may be underestimated as water level during this time frame was in the vicinity of +1.5 m AHD based on the sea level curve published by Sloss *et al.* (2007; Figure 3.3). As discussed in Chapter 5, facies deposition is likely to have occurred in a shallow environment with probable water depths in the vicinity of 0.5 m to 1 m deep. The age depth relationship plot illustrated in Figure 7.5 suggests that the facies was deposited much earlier, between c.a. 7.7 ka and 8.5 ka. This depositional age range is more consistent with the depositional age of the near shore muddy sand facies (7750±40 years BP in MC 5), which is likely to have been deposited at a similar time.

Within the Mullet/Hooka Creek study area a thin compact organic-rich regressive delta facies was identified. As discussed in section 5.6, this facies displays the same sedimentary characteristics as the fluvial sand facies associated with the modern prograding delta with the exception of the reversed coarsening direction. The presence of this facies and its sedimentary characteristics, suggests sediment supply to the study area occurred at a rate slightly below the rate of sea level rise.

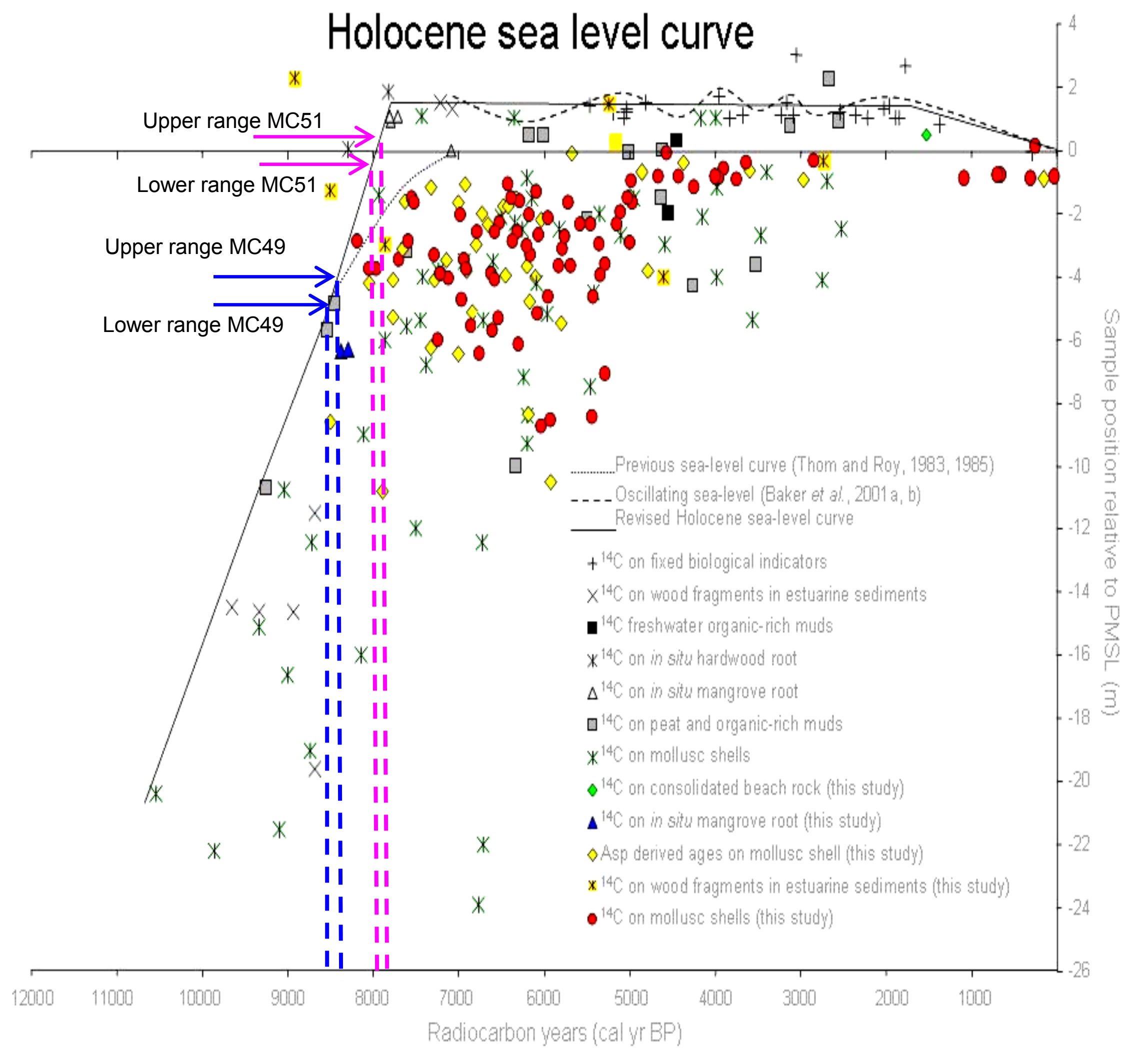


Figure 7.5: *Maximum and minimum transgressive bay fill/back swamp facies intersections overlayed on the Sloss (2005) sea level curve. The deepest facies intersection (MC49) and possible sea level range is highlighted in blue, where as the shallowest facies intersection (MC51) is highlighted in pink.*

Stratigraphically, the regressive delta facies is seen to overlie the Pleistocene basement and the near shore muddy sand facies, as evident on Mullet/Hooka Creek sections A-B, C-D, G-H to K-L, M-N to U-V, Y-Z and CC-DD (Figure 7.1). The facies was intersected in 22 cores, 21 of which were located proximal to the Pleistocene palaeochannel extending in a northwesterly direction from Hooka Island (Figure 7.6). Figure 7.6 indicates the facies ranges in depth from -1 m AHD located on the Pleistocene high to the west of Hooka

Island to -8 m AHD within the palaeochannel proximal to Hooka Island. The northern extent of the facies aligns with a levee evident in the modern floodplain (Figure 7.7). This levee may have formed the western margin of the regressive channel in this area.

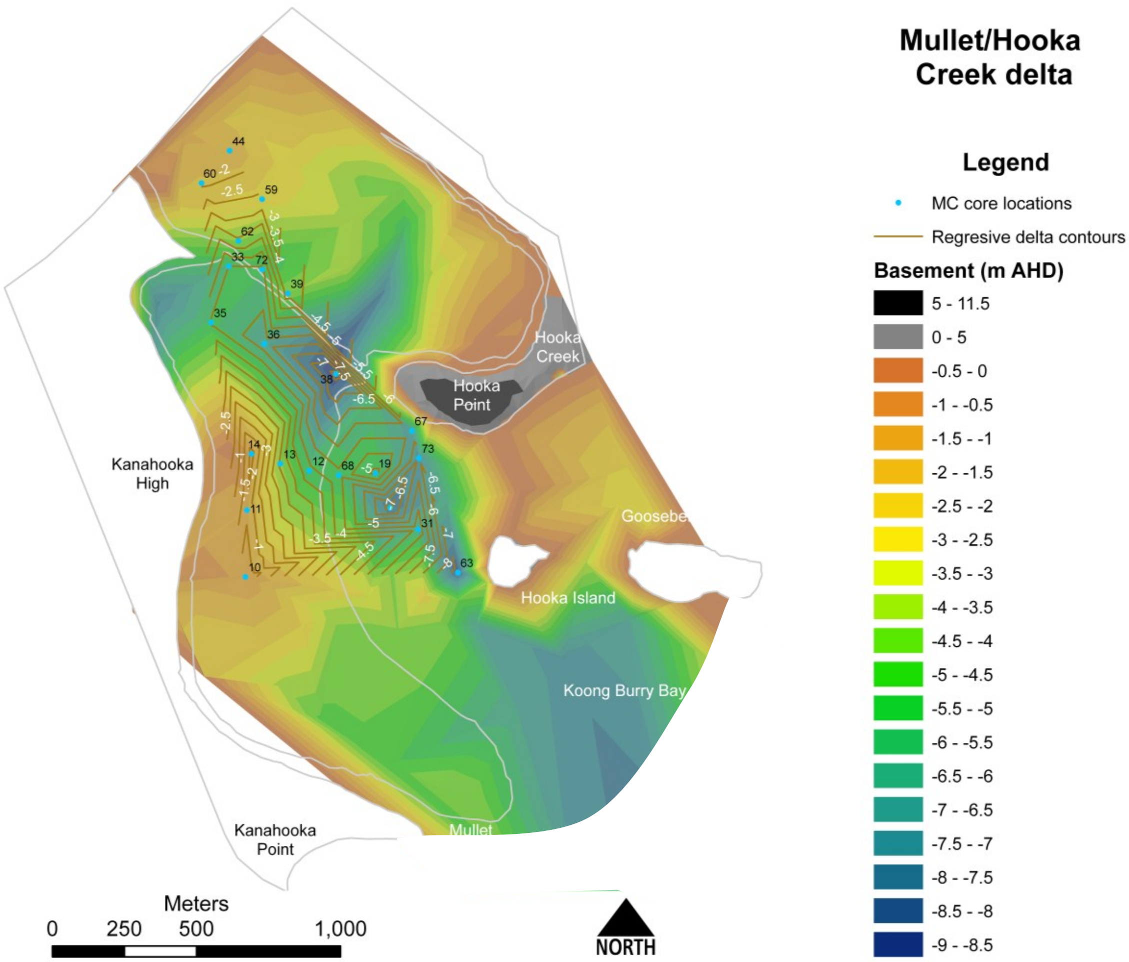


Figure 7.6: *Contour map illustrating the depth (m AHD) to the upper surface of the regressive delta facies. The contours overlie the basement TIN model illustrated in Figure 7.1.*

Figure 7.7: *The levee evident in the image is likely to have formed the western margin of the palaeochannel in this section of the study area. Note levee height decreases towards the northwest. Image looks towards the southeast.*

The regressive delta facies intersected in MC 38 is characterised by a succession of very compact alternating sand and organic-rich mud lamina (Section 5.6, Figure 5.6). The laminated nature of the facies in this core differs from the others which contained the facies. This variability may be attributable to the proximity of MC 38 to the confluence between the palaeo-Mullet Creek and palaeo-Hooka Creek channels. The coarser sandy laminae possibly represents periods of higher river energy whereas the organic-rich laminae represent periods of reduced energy. It is possible the organic-rich layers in the basal portion of the core may have been thicker than that preserved within the sedimentary record as the higher velocity sand laden flows could have scoured into the fine material. The increased thickness and frequency of the organic-rich mud laminae increase up section. The increased thickness and mud content are likely to reflect increasing water depth within the basin and the subsequent regression of the delta.

Applying the rule of superposition, the depositional time frame of this facies, which lacks material suitable for dating, can be inferred from ages derived from underlying and overlying facies. In this instance, the age of the facies could be inferred from ages obtained from cores where the regressive delta facies was intersected and where ages have been established for the overlying prodelta/lagoonal mud facies. As such, the prodelta/lagoonal mud facies in MC 67 indicates that deposition of the regressive delta facies in this portion of the study area had ceased by 7,540±30 years BP (Table 4.6b and

4.7; Volume 2, Appendix 5). However, as the articulate *Anadara trapezia* was removed from MC 67 3.59 m above the contact it is unlikely the derived age is valid. This age also exceeds four of the five ages established for the underlying near shore muddy sand facies (Table 4.6b and 4.7). Furthermore, as MC 67 is positioned adjacent to the tank trap channel which extends subaqueously towards Hooka Island, the age discrepancy may be attributable to anthropogenic reworking during the construction of the tank trap in the 1940s. The above issues highlight the difficulties in ascertaining robust and reliable ages in dynamic environments such as deltas and where anthropogenic modifications within the environment are likely to have occurred.

In this instance, plotting the depth to the upper surface of the facies while factoring in water depth on the sea level curve developed by Sloss (2005) was used to establish the time frame for facies deposition. When applying this methodology the sea level curve indicates deposition occurred between approximately 8, 000 and 9,000 years BP (Figure 7.8). However, this age range is greater than the maximum age determined using amino acid racemisation methodologies for the near shore muddy sand facies, which directly overlies the Pleistocene basement and is assumed to have been deposited at a similar time. As such this study is unable to determine the depositional time frame for this facies.

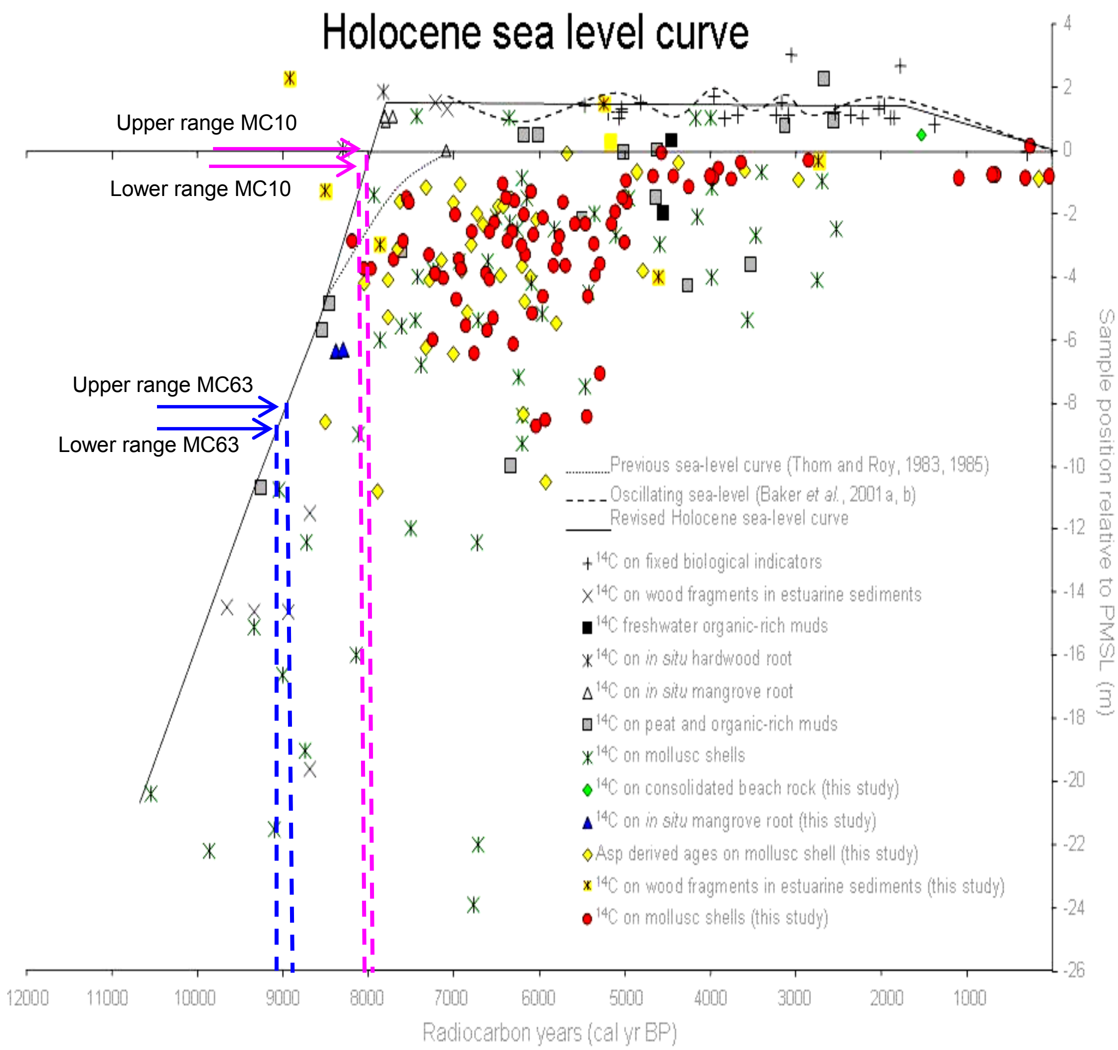


Figure 7.8: *Maximum and minimum regressive delta facies intersections overlayed on the sea level curve developed by Sloss (2005). The deepest facies intersection (MC10) and possible sea level range is highlighted in blue, where as the shallowest facies intersection (MC63) is highlighted in pink.*

As the receiving basin's water level increased evidence for the regressive delta would have likely extended to the west-northwest. However, beyond MC 44 there is no sedimentary evidence of the regressive delta within the study area. There are several possible explanations as to why the facies is not evident north of MC 44:

- the regressive delta avulsed proximal to this part of the study area;
- the facies was eroded by overlying facies;

- sediment supply to the area reduced; and/or
- increased rate of sea level rise drowned the regressive delta.

If the regressive delta avulsed there should be evidence of this avulsion within proximal cores such as MC 42, 43, 69 and 70 (Figure 4.3). As none of these cores contain any evidence of the facies it is unlikely the channel avulsed proximal to the study area. In the majority of cores where the facies was intersected it is overlain by prodelta/lagoonal mud. As this facies is very fine-grained and thus likely deposited in a low energy environment, it is unlikely the facies was eroded to the north of MC 44. Sediment supply to the modern prograding delta appears to have been relatively constant. Hence, this it is likely the sediment supply to the regressive delta was not reduced. Instead, it is more likely the rate of sea level rise increased to a point which exceeded the rate of sediment supply resulting in the delta being drowned.

7.2.2: Infilling the palaeoreceiving basin

The prodelta/lagoonal mud facies forms an essentially continuous layer covering a significant portion of the study area (Figure 7.9). Facies thickness is highly variable ranging from 0.44 m (MC 44) to 6.8 m (MC 63; Volume 2, Appendix 5). The thicker sequences intersected, such as in MC7, 28, 38, 48, 63 and 66, are associated with the deeper sub-embayments/pools within the Pleistocene palaeochannel system (Figure 7.9; Figure 7.1). The increased thickness of the facies in these areas is attributed to deeper water occurring earlier here than elsewhere within the study area.

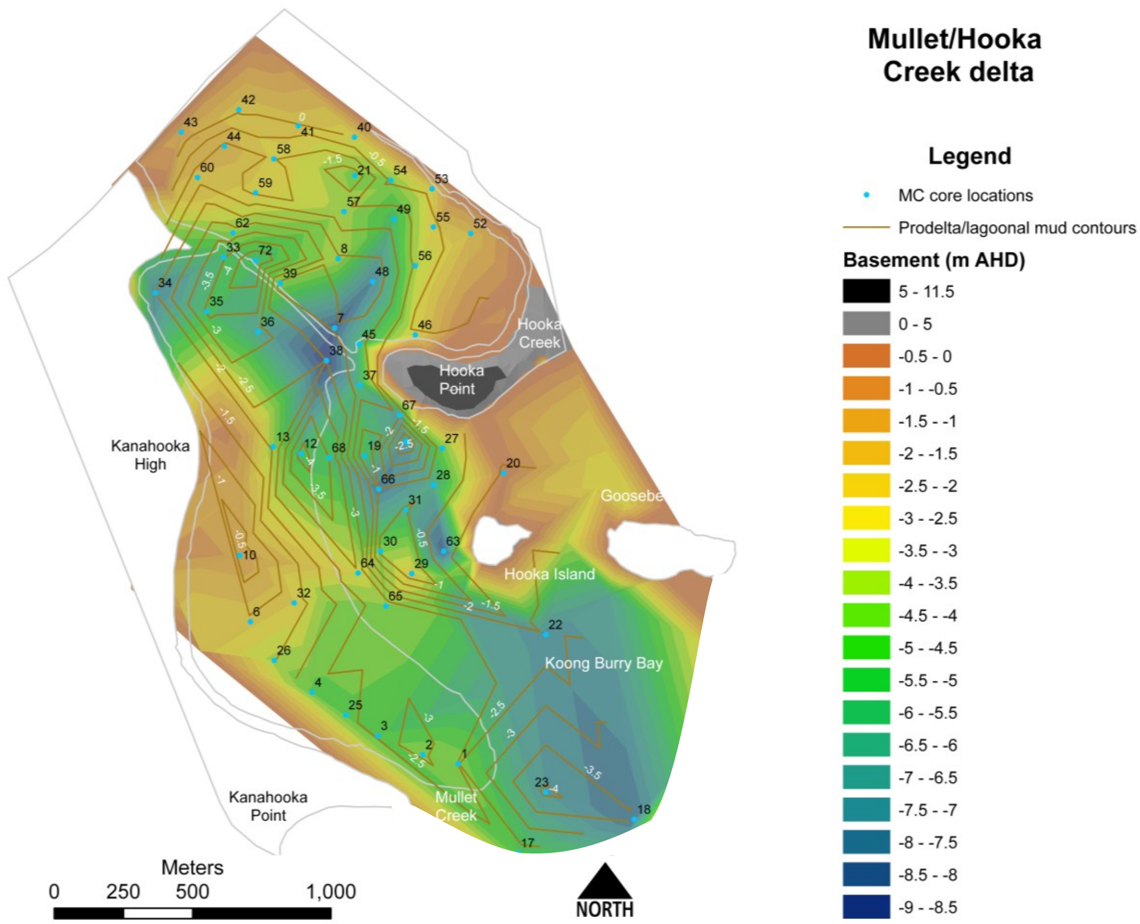


Figure 7.9: *Map illustrating the spatial distribution of the prodelta/lagoonal mud facies and relationship to the basement TIN model illustrated in Figure 7.1.*

Beyond the confines of the main Pleistocene palaeochannel the facies thins, as evident in cores MC 2, 6, 10, 12, 34, 44, 60, 62 and 72, where facies thickness is less than 1 m (Figure 7.1; Volume 2, Appendix 5). Thinning of the facies away from the central palaeochannel is primarily related to the maximum extent/depth of the Holocene sea level transgression relative to the underlying topography. As such, the maximum sea level obtained during this depositional period of approximately +1.5 m AHD (Figure 3.3) would have restricted the facies upper depositional limit to approximately -0.5 m AHD, based on a minimum facies depositional depth of 2 m. Significantly, this theoretical upper depositional limit is consistent with the maximum depth relative to AHD of all of the cores where the facies was intersected. Where the theoretical maximum upper

depositional limit was exceeded in MC 42 and 43 it was by no more than 0.37 m (Volume 2, Appendix 5).

Furthermore, fluvial erosion associated with delta progradation is also likely to be a contributing factor relating to the thinning of the facies away from this central palaeochannel. Where the facies thickness is <1 m, it is overlain by either the distal delta or the fluvial sand facies (Table 7.1). The facies in each of these cores had the potential to be thicker as the upper boundary of the facies is below the theoretical maximum depositional range of -0.5 m AHD. Based on the above, it is likely that the facies spatial distribution may have been more extensive than currently preserved within the sampled sedimentary record. However, Maher (2011) did not intersect the prodelta/lagoonal mud facies in her assessment of the evolution of the lower Mullet Creek.

Table 7.1: *Illustrates where the prodelta/lagoonal mud facies is <1 m thick and overlain by the distal delta or fluvial facies.*

MC	Prodelta facies top (AHD m)	Prodelta facies base (AHD m)	Prodelta facies thickness	Distal delta facies overlying
2	-3.092	-3.89	0.798	Yes
6	-1.095	-1.84	0.745	Yes
10	-0.09	-0.59	0.5	Yes
12	-4.197	-4.85	0.653	Yes
32	-1.271	-2.42	1.149	Yes
34	-2.009	-2.96	0.951	Yes
39	-1.813	-3.21	1.397	Yes
44	-1.116	-1.52	0.404	Yes
60	-1.296	-1.9	0.604	Yes
62	-2.743	-3.6	0.857	Yes
72	-4.5	-5.15	0.65	Yes

The prodelta/lagoonal mud facies contained a significant number of articulate *Notospisula trigonella* and *Anadara trapezia* suitable for geochronological analysis. A total of 43 samples from depths of -0.49 m to -5.25 m AHD were analysed. The 43 specimens were obtained from 39 of the 73 cores collected. The derived ages ranged from present to 8,200±1050 years BP (Table 4.6b and 4.7). Of the samples analysed MC 4, 20, 29 and 37 contained age inversions. The age inversion in MC 20 is covered by the

error margin associated with the two inverted dates. However, the inversions identified in the remaining cores exceeded the range of age errors. Ages exceeding 7 ka for the facies were not expected based on previous research undertaken by Sloss *et al.* (2005, 2006a and 2007). However, the five *Notospisula trigonella* and three *Anadara trapezia* were articulate indicating limited transportation. Significantly, three of the ages greater than 7 ka have been derived from MC 20 without inversion which further supports the accuracy of older than expected ages recorded for the facies as part of this study.

Long term sedimentation rates extrapolated from the AAR data in Table 4.6b range from 0.3 mm/year (MC 31) through to 4.5 mm/year (MC 20), with an average rate of 1.8 mm/year. The sedimentation rates determined in this study are consistent with the pre-European settlement rates reported by Sloss *et al.* (2011). Post-European settlement the sedimentation rate has increased as shown by the ^{210}Pb results from the study area (Table 4.8b). The minimum post-European sedimentation rate calculated is 3.8 mm/year with the maximum increasing to 6.6 mm/year for the upper 0.02 m of the core. Despite the maximum sedimentation rate being slightly lower than that reported by Sloss *et al.* (2011) the increase in sedimentation is most likely attributable to post-European modification of the catchment. These modern sedimentation rates may be understated as the weir farther upstream is likely to be impounding bedload and saltating sediment derived from the more developed parts of the catchment.

7.2.3: Fluvial progradation

The palaeochannel/channel abandonment facies was intersected in cores MC 12, 27, 28, 31, 34, 37, 38, 63, 67 and 68 (Volume 2, Appendix 5). Spatially, the facies is primarily located within the Koong Burry Bay area, proximal to Hooka Point (Figure 7.10). The facies is characterised by an overall coarsening upwards sequence occasionally overlain by a thinner fining upwards sequence (Chapter 5, section 5.7). Due to the coarse nature of the sediment and a lack of fauna, a high energy relatively shallow environment has been inferred.

The thickest deposits intersected occurred in cores MC 12, 34 and 38 (Volume 2, Appendix 5). The spatial distribution of these cores, facies thickness and subsequent channel gradients indicate the main Holocene fluvial channel followed a similar course to the Pleistocene palaeochannel, with a second channel located farther towards the southwest (Figure 7.10). Although it was not possible to directly link the majority of the intersected channels, it is possible that they represent various distributary channels formed due to the autocyclic processes of channel avulsion. The presence of these multiple channels would suggest the delta's initial morphology was more closely aligned to a fluvial/birdsfoot style of delta rather than the current cuspate wave dominated morphology. The morphological difference is likely to reflect the protection offered by Hooka Point and the Pleistocene palaeohighs to the west of Koong Burry Bay during the initial phase of progradation.

Establishing the depositional periods for the various channel facies intersected was problematic due to a general lack of suitable dating material. However, MC 63 and MC 68 contained material suitable for dating. MC 63 contained large articulate *Anadara trapezia* with minimal abrasion. The articulate nature, size and condition of the specimen would suggest it was in situ and, therefore, not transported from higher in the system. However, as the specimen was located within the palaeochannel facies Analysis of a valve from the specimen using ^{14}C methodologies yielded an age of 6,400±200 years BP (Table 4.7). This age suggests fluvial progradation commenced at least approximately 2800 years earlier than the 3.7 ka as previously suggested. This older than expected age highlights the inherent variability in the spatial and temporal distribution of facies within deltaic and estuarine environments. This variability provides further justification for the higher spatial resolution of this study when compared to previous studies of the delta's evolution.

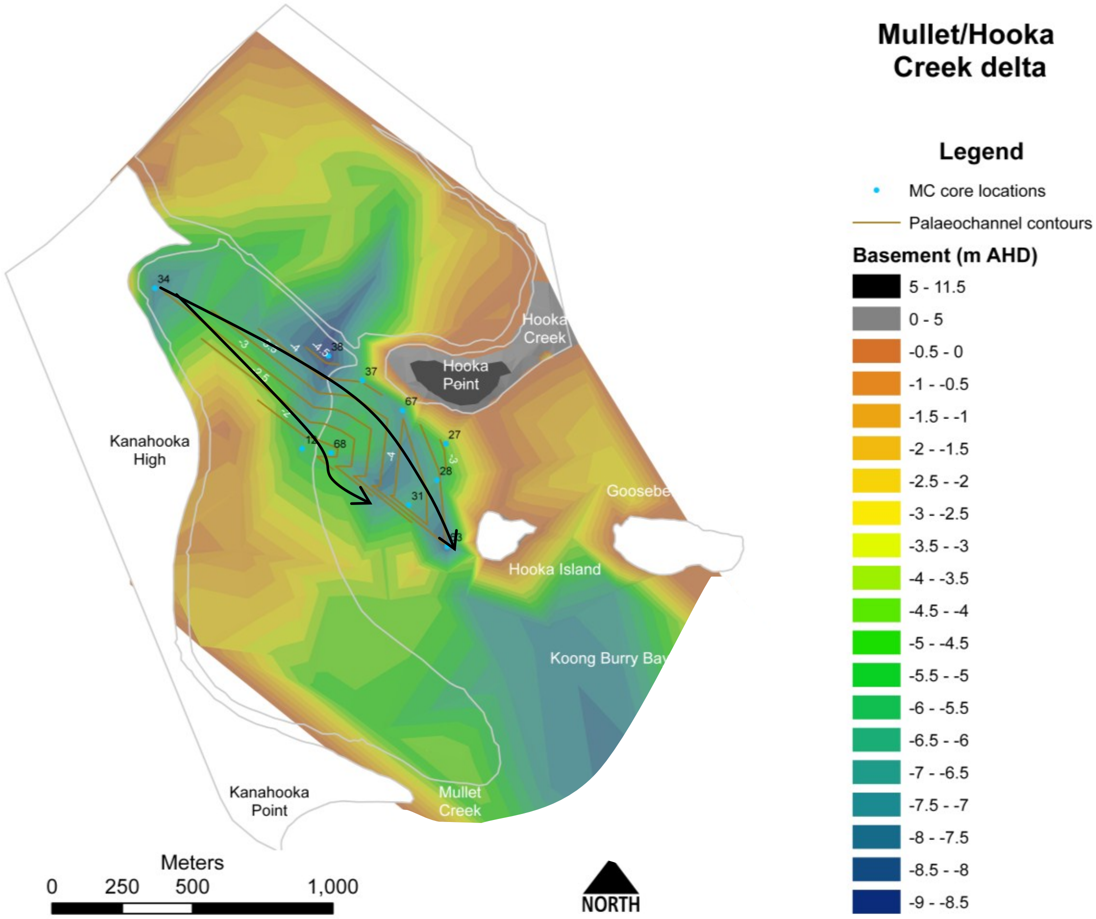


Figure 7.10: *Map illustrating the spatial distribution of the palaeochannel/lobe facies and relationship to the basement TIN model illustrated in Figure 7.1. Black arrow indicates the possible location of the palaeochannel(s). Location of channels is based on facies thickness and gradients. Note the strong correlation with the Pleistocene low.*

Within the study area relatively thin flood facies were intersected in cores MC 33 to 36, 59, 60, 63, 66 and 68 (Volume 2, Appendix 5). The majority of occurrences are associated with the prodelta/lagoonal mud facies however several occurrences are associated with the basal fluvial sequences (Figure 7.1). The sedimentological characteristics (Chapter 5, section 5.13.2) and stratigraphic relationships of the facies indicates it was deposited during periods of higher flow velocities, typically associated with flood periods, enabling the coarser sediments to be deposited in deeper water and/or erode into the underlying sediments.

Establishing the facies depositional time frame was not possible for several reasons. The sharp basal contact and coarse grain size suggest the facies was deposited rapidly in a high energy environment. These depositional conditions are typically not conducive for the habitation/preservation of specimens suitable for AAR or ^{14}C dating methodologies. Furthermore, the facies was intersected on multiple occasions at varied stratigraphic heights within each of the cores. The multiple intersections within the cores suggest facies deposition occurred over a wide temporal range.

Stabilisation of the Holocene sea level enabled the palaeodelta to again prograde into the study area as evidenced by the distal delta and fluvial sand facies intersected in 36 (Figure 7.11) and 56 (Figure 7.12) of the 72 cores from the study site (Volume 2, Appendix 5). The stratigraphic relationships between the two facies and the underlying facies are evident in the Mullet/Hooka Creek sections (Figure 7.1). Typically, the fluvial sand facies overlies the distal delta facies which in turn overlies the prodelta/lagoonal mud facies. However, in 17 cores (MC 14-16, 19, 33, 46, 49-53, 55-57, 69-71; Volume 2, Appendix 4 and 5) the fluvial sand was in direct contact with the prodelta/lagoonal mud. The lack of the intermediate distal delta facies in these cores is likely attributable to erosion by the coarser grained fluvial sand facies.

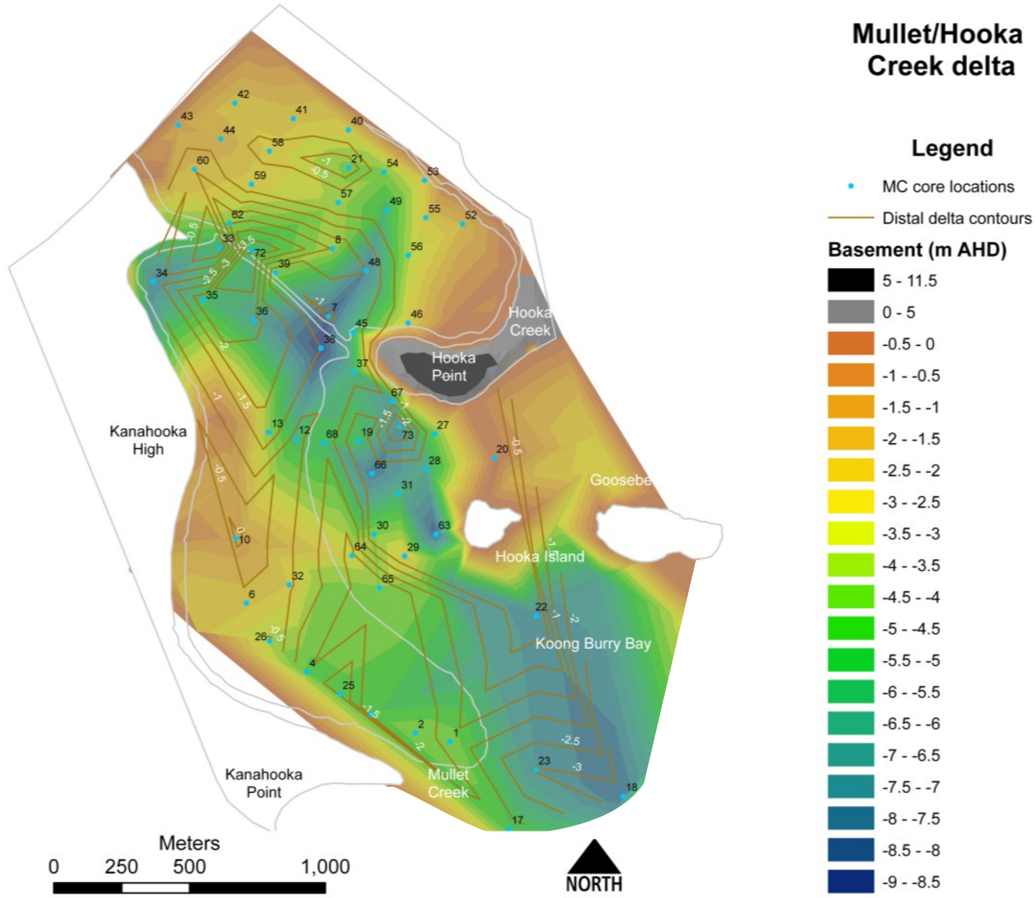


Figure 7.11: *Map illustrating the spatial distribution of the distal delta facies and relationship to the basement TIN model illustrated in Figure 7.1*

The distal delta and fluvial sand facies contained a total of 25 specimens suitable for geochronological analysis utilising AAR and ^{14}C techniques (Table 4.6b and 4.7). The scarcity of material within the facies is likely to be attributable to the higher energy levels associated with delta progradation reworking the specimens post-mortem, disarticulating specimens and breaking up the valves. The higher energy levels and higher water velocity also appear to have reduced the faunal diversity and quantity within the two facies. Specimens from the distal delta facies yielded ages ranging from 690±10 years BP (MC 7) to 8,170±70 years BP (MC 38, Table 4.6b). Specimens from the fluvial sand facies yielded ages from 590±30 years BP (MC 23) to 7890±150 years BP (MC 13, Table 4.6b). Analysis of the derived ages for the two facies suggests the main phase of fluvial deposition commenced *ca.* 6.5 ka. This commencement age range is slightly

older than the age range established for the Macquarie Rivulet study area. The earlier facies ages are likely to reflect the increased number of samples dated from the Mullet/Hooka Creek study site in comparison to the Macquarie Rivulet study site.

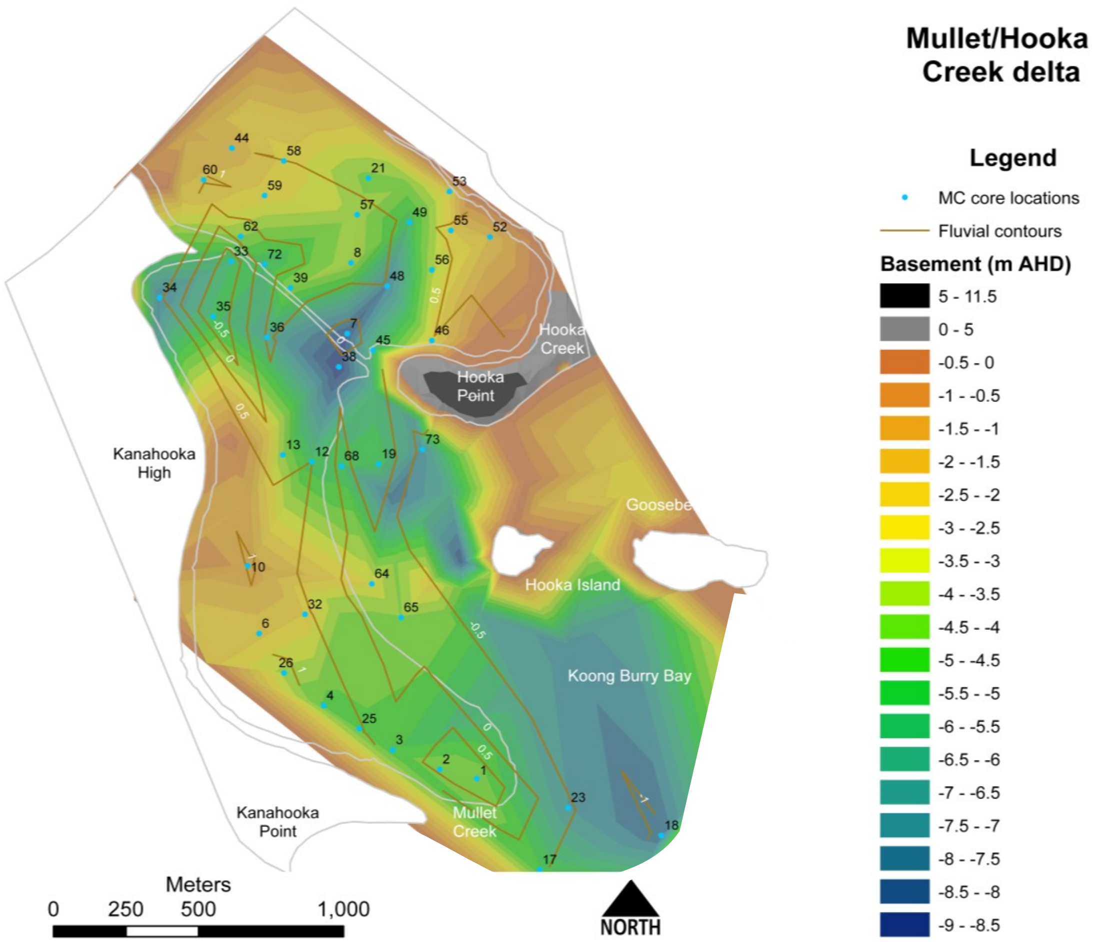


Figure 7.12: *Map illustrating the spatial distribution of the fluvial sand facies and relationship to the basement TIN model illustrated in Figure 7.1*

The thickness of the two facies is highly variable across the study area. The distal delta facies is relatively thin with thickness ranging from 0.15 m (MC 36) to 1.2 m (MC 25) and with an average thickness of 0.61 m. The limited thickness of the facies is likely to be attributed to the facies being eroded and/or reworked as the coarser fluvial sequence was deposited. Furthermore, the Mullet/Hooka Creek sections (Figure 7.1) suggest the inherited morphology of the receiving basin had limited impact on the location and

thickness of the distal delta facies as the receiving basin lows had been in filled with earlier sedimentary deposits.

Typically the fluvial sand facies is thicker than the distal delta facies with 52 (92%) occurrences exceeding the average thickness of the distal delta facies. The minimum facies thickness intersected was 0.3 m (MC 50), a maximum thickness of 3.8 m (MC 72) and an average thickness of 1.7 m. The top three thickest deposits (MC 36, 61 and 72) have a strong association with the location of the Pleistocene palaeochannel. The increased thickness of the facies in these cores is likely to represent an extended depositional time frame caused by the depositional low associated with the remnant Pleistocene palaeochannel. Cores containing deposits <1 m thick are primarily located near Hooka Creek. The reduced thickness of this facies in these areas is possibly attributed to the area being isolated by the primary distributary channel forming an interdistributary bay. However, in MC 10 (0.95 m thick) the reduced thickness is more likely attributable to the core's position with respect to the underlying Pleistocene palaeohigh in the antecedent surface (Figure 7.12).

The derived ages suggest the delta initially prograded in a northeasterly direction in a similar orientation to the previously active palaeochannel and underlying Pleistocene palaeochannel. During this initial progradation phase the fluvially derived sediments in the northern portion of the study area were probably derived from several distributary channels. While the delta was sheltered by Hooka and Kanahooka Points the delta is likely to have exhibited morphological characteristics consistent with a fluvial/birdsfoot style of delta as the influence of wind waves, which have shaped the current Mullet Creek delta lobe, would have been limited.

Coleman and Wright (1975) noted the inherited morphology of the receiving basin is one of the key determinants for the morphology of present/modern delta. Accordingly, Hean and Nanson (1985) had attributed the significant directional change, near the upstream end of the tank trap and core MC 33 (Figure 7.13), to the presence of

Pleistocene terraces. However, this study has found no evidence to support this assertion. Instead the directional change is attributed to the reorientation/rotation of the channel that is inferred to have occurred in response to the sea level regression *ca.* 2 ka (Figure 3.3). It is likely that exposure of the high stand delta and associated mouth bar deposits, would have blocked the high stand distributary channel(s) entering Kong Burry Bay. This blockage may have caused the distributary channel(s) to avulse/deflect in a southerly direction. Subsequent westerly point bar migration has emphasised this initial directional change. The capacity for the delta to prograde in this direction was limited by the presence of the Kanahooka high resulting in the delta again altering is progradation direction towards the east. Significantly, this observed reorientation of the Mullet Creek channel is not consistent with Coleman and Wright's (1975) findings as the channel had to cut across the palaeohigh evident in Figure 7.2 between MC 10 and MC 15. This cross-cutting relationship is also evident in Mullet/Hooka Creek delta section A-B, C-D and G-H (Figure 7.1). These two examples, illustrate the capacity of deltas to move beyond the confines of the inherited receiving basin morphology.

Anthropogenic modifications of Mullet Creek both upstream and within the study area have significantly altered the modern sedimentological and morphological evolution of the delta. The two key modifications which impacted on the delta's evolution are the construction of the upstream weir in the early 1900's and the tank trap in 1941. The upstream weir limited the amount of coarse sediment transported and deposited at the delta mouth. This has resulted in the modern fluvial deposits being muddier and finer grained than pre-European deposits. Tank trap construction shortened Mullet Creek by approximately 2.8 km resulting in much of the down stream transported sediment being deposited in Kong Burry Bay instead of at the mouth of Mullet Creek. Additional details about the morphological implications of these changes are discussed in Chapter 8.

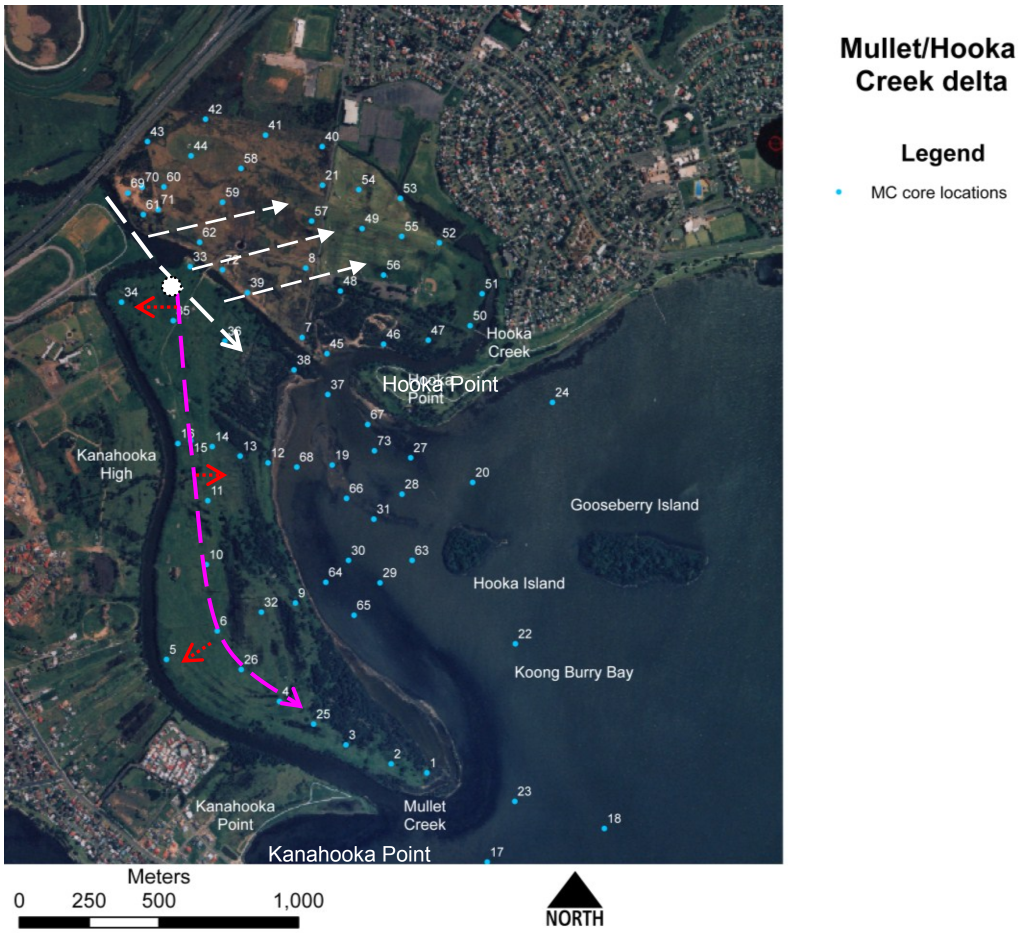


Figure 7.13*: The possible morphological evolution of the Mullet/Hooka Creek channels is illustrated based on the cores (illustrated) where geochronological data were obtained from the distal delta and fluvial facies. The white dashed line represents the initial phase of fluvially dominated delta development. The pink lines illustrate the migration path of the delta as it transitions to a wave-dominated cuspate delta morphology. The red dotted lines illustrate the direction of point bar migration.*

7.2.4: Floodplain and levee development

The well developed levees and floodplains within the study area are likely to have developed primarily from the vertical accretion of the Mullet/Hooka Creek distributary channels as they migrated through the study area. Levee morphology within the study area is typically flat with levee crests which that gently taper into the floodplain. This

morphology is similar to the B-type levee observed in the eastern portion of the Macquarie Rivulet study area (Figure 6.11).

Due to the lack of specimens suitable for geochronological analysis, establishment of the depositional timeframe was not possible. However, as the facies formed in shallow water to subaerial environments deposition is likely to have occurred relatively recently, as sea level fell within the receiving basin since *ca.* 2 ka, based on the Holocene sea level curve published by Sloss *et al.* (2007).

7.3: Hooka Creek

Initial assessment of aerial photographs and topographic maps (Figure 4.6) indicated that Hooka Creek may have been a remnant Pleistocene palaeochannel of Mullet Creek. However, the TIN model (Figure 7.2, Area A) and cross/long-sections, such as CC-DD, E-F, I-J, S-T, U-V and W-X (Figure 7.1) do not support this. Instead, this study shows that Hooka Creek operated concurrently with Mullet Creek draining the area to the north.

As discussed in section 7.2.1, 7.2.2 and 7.2.3 the antecedent Pleistocene substrate, proximal to Hooka Creek, is overlain by the transgressive bay fill/back-swamp facies which is then overlain by the prodelta/lagoonal mud facies. The prevalence of mud within the Hooka Creek area (Figure 7.14) indicates that the area was likely to have been a calm aquatic environment consistent with the depositional conditions described in section 7.2.1 for the transgressive bay fill/back-swamp facies. The prodelta/lagoonal mud facies is in turn overlain by the fluvial and floodplain facies in the eastern portion of the study area (area A, Figure 7.14) and the floodplain/levee facies in the western portion of the study area (area B, Figure 7.14). The lack of fluvial sediments within the western-most portion of the study area indicates that the delta had prograded beyond the western margin of the study area. It is possible the western portion of the study area may have had characteristics similar to a cut-off embayment, such as Tullarwalla Lagoon, St Georges Basin (Hopley and Jones 2006), but on a smaller scale.

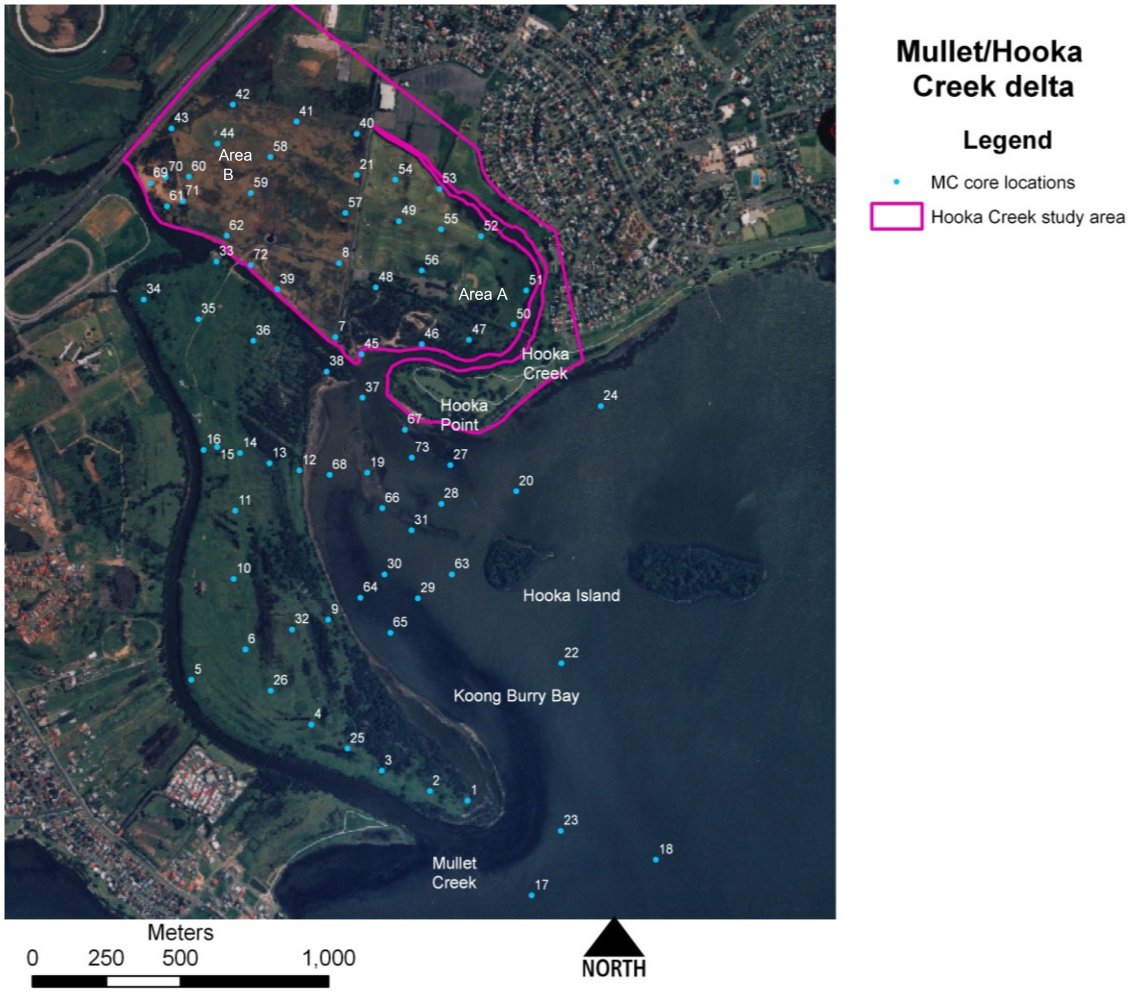


***Figure 7.14**: The Hooka Creek component of the Mullet/Hooka Creek study area.*

Furthermore, the lack of fluvial sediments/facies within cores MC 40, 41, 42 and 43 (Volume 2, Appendix 5; Figure 7.1 section E-F; Figure 7.14) indicates that the apparent connection with Mullet Creek, evident in the aerial photographs and topographic maps (Figure 4.6), is a surface feature. This channel represents a modern high flow flood activated channel. It is also likely this channel formed as sea level fell, and exposed the western portion of the study area. The sea level fall is likely to have resulted in the formation of a knickpoint. The down cutting and the inland migration of the knickpoint would have formed the Hooka Creek channel. It is likely that the current shape of the channel was controlled by the channels proximity to Hooka Point, a bedrock high.

Establishing a precise age for the commencement of Hooka Creek's evolution was not possible. However, this study indicates Hooka Creek is relatively young and likely to have formed during the late Holocene. The late Holocene age is inferred as Hooka Creek appears to have incised into the prodelta/lagoonal mud, fluvial and floodplain facies in the eastern portion of the study area (Figure 7.1 section E-F; Figure 7.14 area A). Furthermore, as the creek has incised into the Pleistocene substrate near its confluence with Kong Burry Bay it is likely the channels' position has been relatively stable throughout its evolution. Down-cutting of this nature would have only been possible as sea level fell at *c a.* 2 ka (Figure 3.3).

7.4: Chapter summary

The Holocene evolution of Mullet/Hooka Creek delta has been established from the high resolution assessment of 73 sedimentary cores, the construction of 15 long/cross sections and 85 age determinations. The initial evolution of the delta was controlled by the inherited basin morphology, particularly the palaeochannel.

As water level within the receiving basin rose the regressive delta facies was deposited primarily in the palaeochannel with the near shore sandy mud facies being deposited on the palaeohigh to the west of the channel. These basal sediments were subsequently overlain by prodelta/lagoonal mud deposits. The sedimentary core and geochronological data indicates that fluvial deposition was occurring at *ca.* 6.5 to 7 ka. This initial phase of fluvial activity appears to have been drowned within the study area as water levels continued to increase within the basin indicated by the overlying prodelta/lagoonal mud. Stabilisation of water level within the basin enabled the delta to again prograde into the study area. Initial delta morphology was likely to have been consistent with a fluvial/birdsfoot style of delta.

This study has demonstrated the significant direction change near the upstream end of the tank trap is not attributable to underlying Pleistocene highs as previously suggested by Hean and Nanson (1985). Instead this change is attributed to the distributary channel

avulsing towards the west as a consequence of the sea level fall. Once the delta prograded beyond the shelter provided by Hooka and Kanahooka Point the delta's morphology appears to have transitioned to that of a wave dominated delta.

The scarcity of specimens within the deltaic sequences and the overlapping depositional time frames obtained from the various facies highlights the complexities associated with establishing the evolution of even small fluvial deltas. Specifically, the overlapping depositional time frames established in this study illustrate that multiple deposition environments have occurred occur simultaneously, as they do in the modern environment.

Chapter 8

GIS Based Analysis of Recent Morphological Change/Delta Growth: Methods, Results and Discussion

8.1: Introduction

When developing management strategies/policies for fluvio-deltaic environments it is essential that a detailed understanding of their past morphological evolution, in response to catchment modification, is gained. However, the dynamic nature of the systems, along with their sedimentary history, makes establishing these changes problematic. On a temporal scale these changes may occur rapidly in response to a single trigger event or occur over a longer period in response to environmental factors, such as the sedimentary regime and subsidence. Hopley and Jones (2006) and Hopley *et al.* (2007) noted many of the conventional geophysical techniques, such as seismic and ground penetrating radar, are often ineffective in these environments due to the gaseous and muddy nature of the sediments. In such a dynamic environment, the calculated sedimentation rates are highly variable which invariably impacts on the interpretation of the results, particularly with young deposits. For example, prodelta sedimentation rates calculated for Lake Illawarra in previous studies indicate sedimentation rates between 2-16 mm/yr (Chenhall *et al.* 1995; Payne *et al*. 1997; Jones and Chenhall 2001; Sloss *et al*. 2004). Furthermore, conducting geochronological assessments is time consuming and costly and the continual reworking of upper deltaic sediments limit the amount of material suitable for dating. Thus, an alternative method to determine the recent morphological evolution of the deltas assessed in this study was sort.

Geographic information systems (GIS), remotely sensed and photogrammetric data along with historical maps can be used to effectively monitor and assess environmental

change. Yeh and Li (1997), Yang *et al. (*1999), Calzadilla *et al.* (2002) and Weng (2002) demonstrated geologically young and rapidly evolving sedimentary environments, such as deltas, could be monitored by analysing photogrammetric and remotely sensed data in a GIS framework. Furthermore, the use of maps, both recent and historical, to monitor morphological changes to deltaic environments has been illustrated by the assessment of the Po delta by Cooreggiari *et al.* (2005) , the Danube delta by Giosan *et al.* (2005) and the Godavari delta by Rao *et al.* (2005).

This chapter establishes the modern morphological evolution of the Macquarie Rivulet and Mullet/Hooka Creek deltas, based on the analysis of historical maps and aerial photography within a GIS framework. Moreover, the chapter relates the observed morphological changes to natural processes, such as flood events, and anthropogenic modification of the deltas' respective catchments. The chapter also evaluates the validity of the technique as a tool which environmental managers can use when developing strategies/policies for these environments.

8.2: Land use patterns: Macquarie Rivulet and Mullet/Hooka Creek catchments

Prior to European settlement the catchments of Macquarie Rivulet and Mullet/Hooka Creek were inhabited by aborigines of the Wadi Wadi language group who are believed to have had minimal impact on the catchments (Hopley *et al*. 2007). European cedar cutters, from the early 1800s, are the first recorded Europeans to impact on the respective catchments. In 1816 much of the land surrounding Lake Illawarra was surveyed and clearing commenced for agricultural purposes such as the growing of wheat, oats and potatoes (McDonald 1976; Lake Illawarra Authority 2005). However, initially the clearing occurred slowly due to the dense vegetation and the limited number of people working the land (Lake Illawarra Authority 2012). By the late 1800s dairy farming and pasture improvement had replaced crop propagation. The 1920s saw the initial phase of urban development commence with the further subdivision of the larger land grants (McDonald 1976). The available aerial photographs suggest the rate of

urban development was fairly static until the 1960s. An analysis of census data from Albion Park Rail and Albion Park (Macquarie Rivulet catchment) and the Dapto/West Dapto area (Figure. 8.1) indicates between 1986 and 1996 the numbers of dwellings constructed annually increased significantly with more moderate growth occurring to present. However, it is proposed an additional 19,000 homes will be constructed within the Macquarie Rivulet and Mullet/Hooka Creek catchments by 2050 (Wollongong City Council 2007).

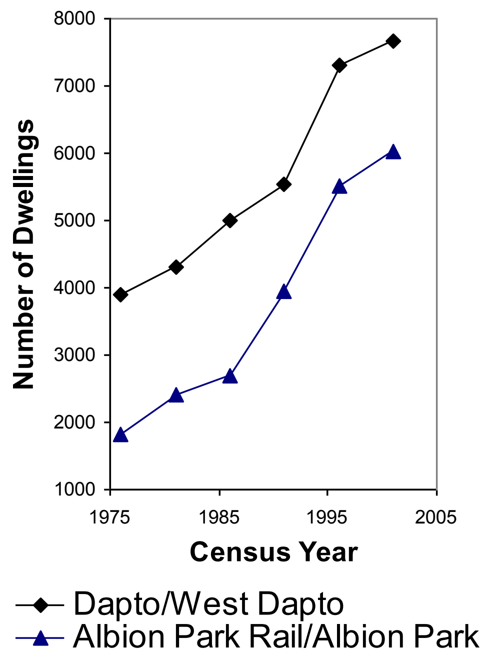


Figure 8.1: *Number of dwellings constructed between 1976 and 2001 in Albion Park Rail and Albion Park (Macquarie Rivulet catchment) and the Dapto/West Dapto area (Mullet/Hooka Creek catchment) based on Australian census data.*

8.3: Data collection

Historical parish maps, in conjunction with aerial photographs, were used to establish the modern morphological evolution of the Macquarie Rivulet and Mullet/Hooka Creek deltas. The primary consideration when identifying potential data sources was to ensure that complete spatial coverage of the delta being analysed occurred within a single map or image. Hopley *et al.* (2007) noted by doing this, processing errors associated with the

merger of multiple images is removed, thus the quality of the final analysis is enhanced. The other criterion applied when selecting images was the scale at which they were produced or captured. Experimentation conducted by Hopley *et al.* (2007) suggested the ideal scale for the assessment was 1:25,000, however, it was possible to work with scales as small as 1:40,000. A total of four maps and ten aerial photographs for Macquarie Rivulet delta (Table 8.1) and 1 map and nine aerial photographs for the Mullet/Hooka Creek delta (Table 8.2) were selected based on these criteria.

Table 8.1: *Maps and aerial photographs used to assess modern morphological changes of the Macquarie Rivulet delta and the associated image processing data.*

Year	Type	County	Parish	Photo	No of GCP's	RMS error (m)	Total delta area (ha)	Rate of Increase (%)
1834	Map				0	0		0
1892	Map	Camden	Calderwood		35	6.97605	145.701	0
1916	Map	Camden	Calderwood		35	8.6753	146.006	0.21
1927	Map	Camden	Calderwood		46	11.1982	146.11	0.07
1938	Photo			Aerial Mosaic South Coast NSW Lake Illawarra section	34	5.67609	152.372	4.29
1948	Photo			GW171, run 27, photo 103	30	6.24758	152.612	0.16
1961	Photo			NSW 1063, run 3 photo 5012	35	5.73824	153.324	0.47
1963	Photo			NSW 1189, run 1K, photo 5107	30	6.26866	155.382	1.34
1974	Photo			NSW 2288, run 1, photo 141	51	7.52601	153.383	-1.29
1981	Photo			NSW 2928, run 60, photo 96	43	7.31811	156.163	1.81
1984	Photo			NSW 3388, run 1, photo 1	24	7.62911	157.a25	0.62
1993	Photo			NSW 4108, run 2, photo 113	22	8.54661	159.812	1.71
2002	Photo			NSW 4730, run 2, photo 164	20	9.5962	159.948	0.09
2006	Photo			WCC rectified composite	49	7.3762	160.027	0.05

Table 8.2: *Maps and aerial photographs used to assess modern morphological changes of the Mullet/Hooka Creek delta and the associated image processing data.*

Year	Type	County	Parish	Photo	No of GCPs	RMS error (m)	Total delta area (ha)	Rate of Increase (%)
1916	Map	Camden	Kembla		262	5.89184	289.5142	0
1948	Photo			NSW 201, run 3 photo 9	133	5.80308	291.2661	0.61
1955	Photo			NSW 595, run 4 photo 50	159	5.86219	292.9231	0.57
1963	Photo			NSW 1139, run 6 photo 5012	72	5.02868	289.1528	-1.29
1975	Photo			NSW 2299, run 8 photo 4	75	4.86992	288.7435	-0.14
1982	Photo			NSW 2997, run 23b photo 157	101	4.96747	289.2111	0.16
1984	Photo			NSW 3367, run 3 photo 17	79	6.43251	288.8725	-0.12
1990	Photo			NSW 3753, run 23 photo 104	83	4.36383	288.9653	0.03
2002	Photo			NSW 4600, run 13 photo 7	211	3.76874	289.2080	0.08
2006	Photo			NSW 4956, run 14 photo 151	97	5.76534	289.5688	0.12

8.4: Image scanning, georeferencing and results

Digital processing of the selected maps and aerial photographs was based on the methodology proposed by Hughes *et al.* (2006). Initially, the maps and aerial photographs were scanned at 600 dpi and saved as Tif files. Experimentation in this study found scanning at a higher resolution significantly increased data handling and storage issues while not providing any significant benefits in relation to the quality of the final digitised image. The digitised images were georeferenced with ArcGIS version 9.2 georeferencing tools.

Georeferencing was selected over the more complex aerotriagulation and orthorectification techniques as the topographic variability, and thus distortions within

the original maps and aerial photographs are minimal within the study sites. Moreover, the georeferencing process enabled the concentration of ground control points (GCPs) around the specific points of interest which provided increased accuracy on the low-relief deltaic floodplains (Calzadilla *et al.* 2002; Hughes *et al.* 2006).

The selected digital images were georeferenced using image to image techniques following Calzadilla *et al.* (2002). Calzadilla *et al.* (2002) demonstrated that, if care was taken, image to image techniques ensured the accurate correlation of spatial features over time. In this study, the most recent images from the two sites were georeferenced using the GCPs derived from the established Illawarra roads and the Illawarra wetlands vector data sets, created by the School of Earth and Environmental Sciences, University of Wollongong, in 1993. Based on Hughes *et al.* (2006) recommendations, a combination of hard (Princes Highway, Hooka Creek Road and the South Coast railway line) and soft (stable natural features of the deltaic environments, i.e. trees) GCPs were used in the georeferencing process. With the accurate georeferencing of the 2006 images, individual polygons/shape files denoting the morphological shape of the deltas were on-screen digitised at a scale no smaller than 1:2,500. The resulting polygons/shape file was then used to georeference the 2002 images of the deltas. This technique was then applied to all earlier images.

To accurately georeference the Macquarie Rivulet and Mullet/Hooka Creek images between 20 to 51 GCPs and 72 to 262 GCPs respectively were identified and selected (Table 8.1 and 8.2). It is probable the additional number of GCPs required for the Mullet/Hooka Creek images reflects the increased size of the study area. The resulting root mean (RMS) errors for the sites ranged from 5.67 m to 11.19 m for Macquarie Rivulet and from 3.77 m to 6.43 m for Mullet/Hooka Creek (Table 8.1 and 8.2). For both of the deltas the RMS errors fall well under the acceptable range of 25 to 40 m, determined by the scale of the original maps and aerial photographs. Second-order or quadratic transformations were then applied to all of the images, following Hughes *et al.*

(2006). It is important to note the 1834 map could not be accurately georeferenced as it is a sketch map, not a surveyed map, which was reproduced in a report on the progress of infrastructure in New South Wales (Figure 6.8; Mitchell 1856).

The delineated delta boundary files, generated during the image to image georeferencing process, were then used to calculate the sub-aerial extent of the deltas at a given time using X Tools Pro (Table 8.1 and 8.2). The calculated areas showed the growth and percentage increase of Macquarie Rivulet and Mullet/Hooka Creek deltas for the period 1892 to 2006 and 1916 to 2006 respectively (Figure 8.2 and 8.3).

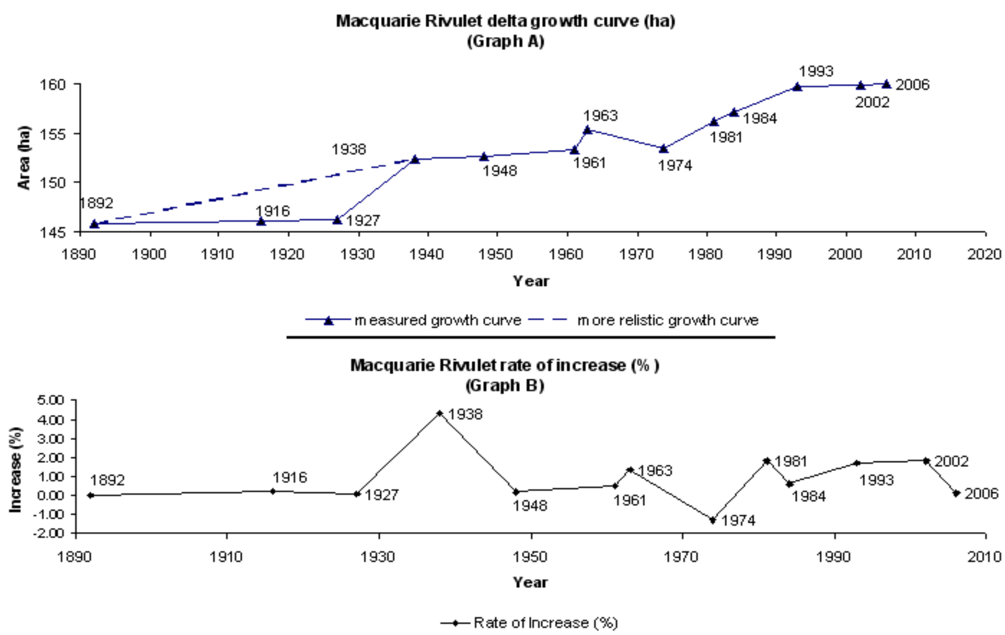
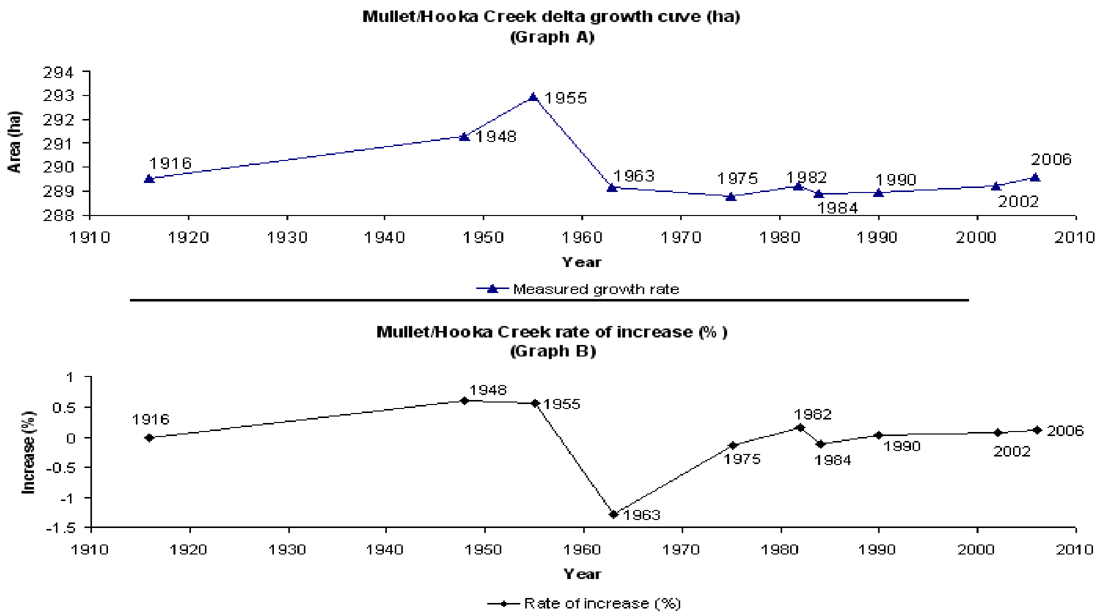


Figure 8.2: *Graphs illustrating (a) growth of the Macquarie Rivulet delta area and (b) rate of increase in percent between 1892 and 2006 (after Hopley et al 2007).*



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***igure 8.3:** Graphs illustrating (a) growth of the Mullet/Hooka Creek delta area and (b) rate of increase in percent between 1916 and 2006.*

8.5: Macquarie Rivulet delta

Between 1816 and the mid 1800s, clearing of Macquarie Rivulet's catchment occurred slowly due to the dense vegetation and the limited availability of people to work the land. Due to the minimal land disturbance it is probable the delta's morphology, during the early part of the 1800s, remained relatively static and was similar to that illustrated by the 1834 sketch map (Mitchell 1856). Based on this map, Macquarie Rivulet delta's morphology was characterised by two cuspate lobes prograding in an east-southeast direction at the time (Figure 8.4a). The cuspate morphology of the delta represented in the 1834 map was also recognised by Young (1976) in a map produced in 1857. This cuspate morphology is generally associated with a wave dominated delta where the sediment is rapidly reworked by wave action. However, in the case of Macquarie Rivulet the cuspate morphology more likely reflects a limited sediment supply.

Several triangular shaped distributary mouth bars are evident in the 1892 map of the Macquarie Rivulet delta (Figure 8.4b). These bars form due to the frictional interaction between the outflowing water and the sediment interface, with the outflowing water only being able to expand horizontally (Sutter 1994; Reading and Collinson 1996). The development of the bars resulted in the bifurcation of the channel and the delta adopted a morphology more consistent with a fluvial-dominated birdsfoot delta (Coleman and Wright 1975; Bhattacharya and Walker 1992; Haslett 2000). The observed morphological changes suggest the sediment load of Macquarie Rivulet increased. The increased sediment load is likely to be the result of tilling of the cleared lands for agricultural purposes and continued deforestation of the catchment.

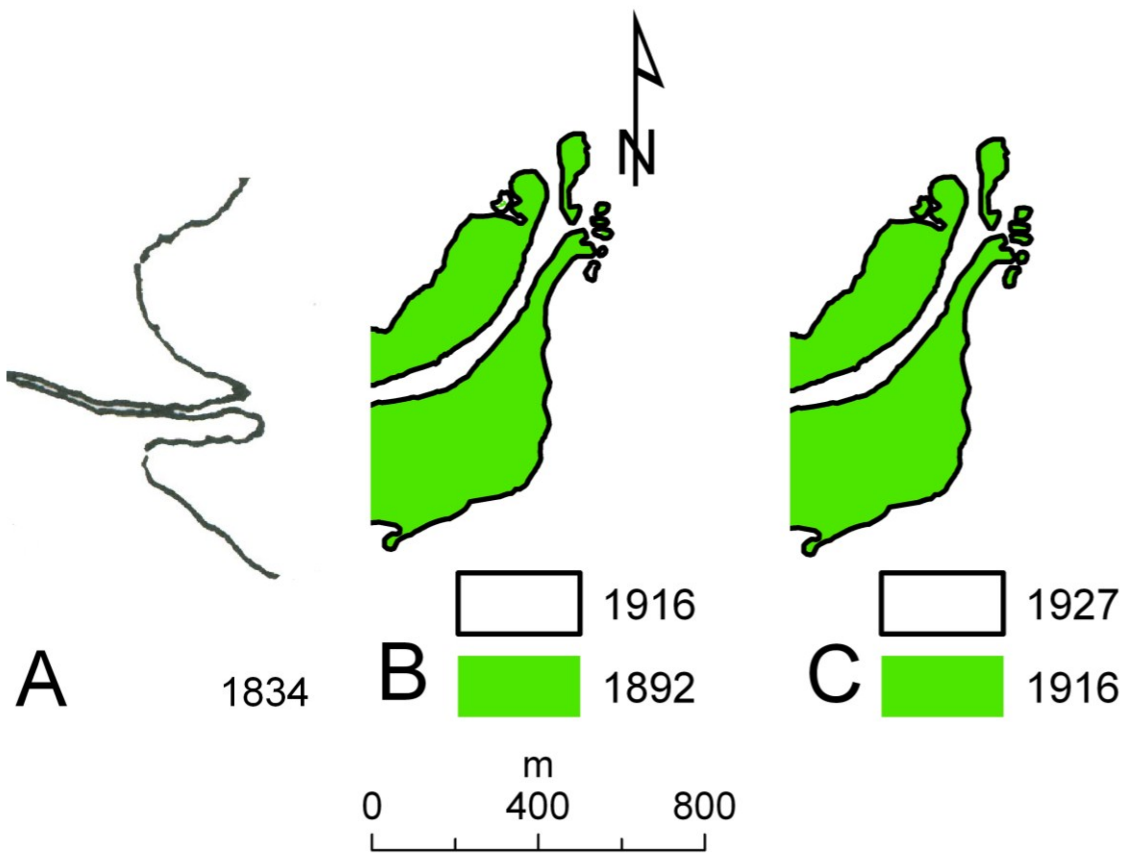

Figure 8.4: *The extensive morphological differences in the Macquarie Rivulet delta between (a) 1834, (b) 1892-1916 and (c) 1916-1927 are illustrated. Note the 1834 image is not georeferenced, since it appears to be a reprint of a sketch map (after Hopley et al 2007).*

Morphologically, the delta remained relatively stable between 1892 and 1927, when compared to the extensive morphological changes which occurred prior to 1892. During the 35 year period assessed, the delta increased from 145.701 ha (1892) to 146.006 ha (1916) and to 146.110 ha (1927; Table 8.1). By 1927, a new small subaerially exposed bar to the south of the northeast-oriented channel mouth and an increase in the size of the other subaerially exposed bars, which were observed in the 1892 map, were recognised (Figure 8.4b-c).The minimal change to the morphology and area of the delta between 1892 and 1927 probably reflects a lack of new survey data during this period. By the late 1920 to 1930s, the focus on land clearing had ceased, with many farmers now concerned with pasture improvement as dairy farming replaced crop production (Young 1976; Lake Illawarra Authority 2005).

Between 1927 and 1938 a significant increase in delta area is apparent (Figure 8.5a). During this period the delta increased from 146.110 ha (1927) to 152.372 ha (1938) an increase of 6.262 ha or 4.3% (Figure 8.2; Table 8.1). Over the 11 year period the central distributary mouth bar had increased in size considerably. The northern lobe of the bar had begun to hook back in a northerly to northwesterly direction, the southern lobe had prograded in a northeasterly direction, and the small distributary islands appear to have been reworked and incorporated into the southern lobe (Figure 8.5a). These morphological differences can probably be attributed to the 1927 assessment being based on a parish map whereas the 1938 assessment is based on a georeferenced aerial photograph. The dashed line in Figure 8.2 is likely to reflect a more realistic growth curve of the delta between 1892 and 1938.

Young (1976) noted Macquarie Rivulet delta decreased in size between 1938 and 1948. However, this study suggests the delta increased slightly in size from 152.372 ha to 152.612 ha, an increase of 0.24 ha or 0.16% (Figure 8.2; Table 8.1). This discrepancy can be attributed to the increased accuracy of digital mapping techniques. Over the 10

years, the main morphological change consisted of the development of a long thin subaerial levee prograding in an easterly direction from the slightly enlarged distributary mouth bar (Figure 8.5b). Other morphological changes included the expansion of the northern lobe in a north-northwest direction and the reworking of the southernmost levee's tip landwards (Figure 8.5b) by the northeasterly wind-waves.

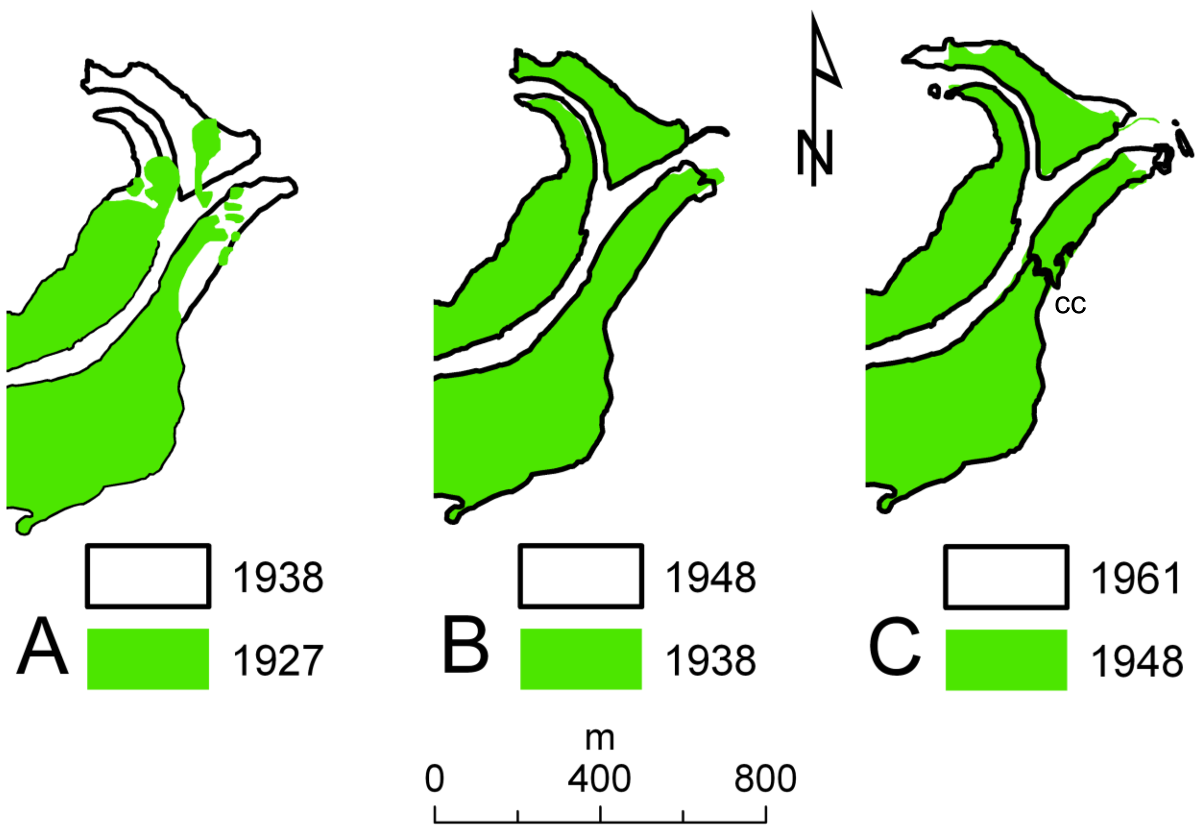

Figure 8.5: *Morphological differences in the Macquarie Rivulet delta between (a) 1927 - 1938, (b) 1938 - 1948 and (c) 1948 - 1961. The black outline represents the more recent morphology. CC, crevasse channel (after Hopley et al 2007).*

Between 1948 and 1961, the area of the delta increased from 152.612 ha (1948) to 153.324 ha (1961), an increase of 0.712 ha or 0.47% (Figure 8.2; Table 8.1). Macquarie Rivulet delta prograded towards the northeast and the northwest with the deposition of sediment at the mouths of both distributary channels (Figure 8.5c). Moreover, Figure

8.5c illustrates the extension of the southern lobe of the delta and the formation of several distributary mouth bars. The eastern levee on the northern lobe has been reworked towards the west by northeasterly wind-waves (Figure 8.5c). Continued sedimentation resulted in the northwestern and eastern ends of the large distributary mouth bar prograding westwards and northwards, respectively (Figure 8.5c). During this period a narrow crevasse splay channel developed, splitting the southern lobe (Figure 8.5c). Due to the temporal difference between the two images, it is not possible to indicate more precisely when this channel first developed. However, during this period, six major flood events were recorded, and it is probable the channel's development can be attributed to the combined effect of one or more of these events.

Between 1961 and 1963, the delta increased in size from 153.324 ha (1961) to 155.382 ha (1963), an increase of 2.058 ha or 1.34% (Figure 8.2; Table 8.1). The most prominent morphological change observed was the expansion of the crevasse splay channel splitting the southern lobe (Figure 8.6a). This expansion can be attributed to the two flood events that occurred during the period. The northeastern-most portion of the southern lobe and distributary mouth bar associated with the southern channel, increased in size significantly (Figure 8.6a). The northern distributary channel continued to actively transport and deposit sediment at the delta front resulting in the expansion of the large distributary mouth bar and the smaller mid channel mouth bar (Figure 8.6a). In addition to the expansion of the mouth bars, the northern lobe of the delta extended slightly. The observed increase in area of the delta, particularly to the southern lobe, is likely to reflect the deposition of sediment reworked from the cutting of the crevasse splay. Moreover, analysis of the aerial photographs from the 1960s suggests urban and commercial development in the lower Macquarie Rivulet catchment area increased. It is probable that the increased development within the catchment destabilised the readily erodible soils, identified by Hazelton (1993), and contributed additional sediment to the delta.

Significant expansion of the crevasse splay channel occurred between 1963 and 1974 (Figure 8.6b). This increase can be attributed to the six major flood events which occurred over the 11 year period. Overall, the delta decreased in size by 1.999 ha from 155.382 ha (1963) to 153.383 ha (1974), a decrease of 1.29% (Table 8.1). By 1974, the crevasse splay had become the primary outlet and site of sedimentation for the delta. This was due to extensive shoaling at the point where the northeastern and northern channel bifurcated, limiting water and sediment flows through these two channels. However, elevated water levels, associated with flood events, would reactivate these channels temporarily. Due to the reduced sediment loads, minimal morphological changes to the northeastern and northern channels and the large distributary mouth bar were observed. However, the distributary mouth bar associated with the northern distributary channel evident in 1963 had been reworked by 1974 (Figure 8.6b). It is likely the reworking of the bar was a due to the combined effects of wind-wave reworking and temporary reactivation of the northern distributary channel during flood events.

Between 1974 and 1981, the delta increased by 2.78 ha or 1.81% from 153.383 ha (1974) to 156.163 ha (1981; Figure 8.2; Table 8.1). By 1981, extensive shoaling blocked the northeastern and northern distributary channels joining the northeastern-most portion of the southern lobe to the northern lobe and the large mouth bar (Figure 8.6c). This resulted in the southeastern channel, previously referred to as the crevasse splay channel, becoming the only active distributary channel of the delta during periods of normal flow.

Sedimentation resulted in the development of a large east-northeast-trending distributary mouth bar (Figure 8.6c), and by 1981 a large spit-like levee extended from the most easterly point of the southern lobe. This spit-like feature was oriented in a northeast direction with a large sediment accumulation observed at its easternmost tip (Figure 8.6c). Additional spilt-like levees formed on the southern side of the northern lobe of the delta and were oriented in a northeast direction (Figure 8.6c). The

orientation of these features is due to sediment reworking in shallow water by northeasterly wind-waves.

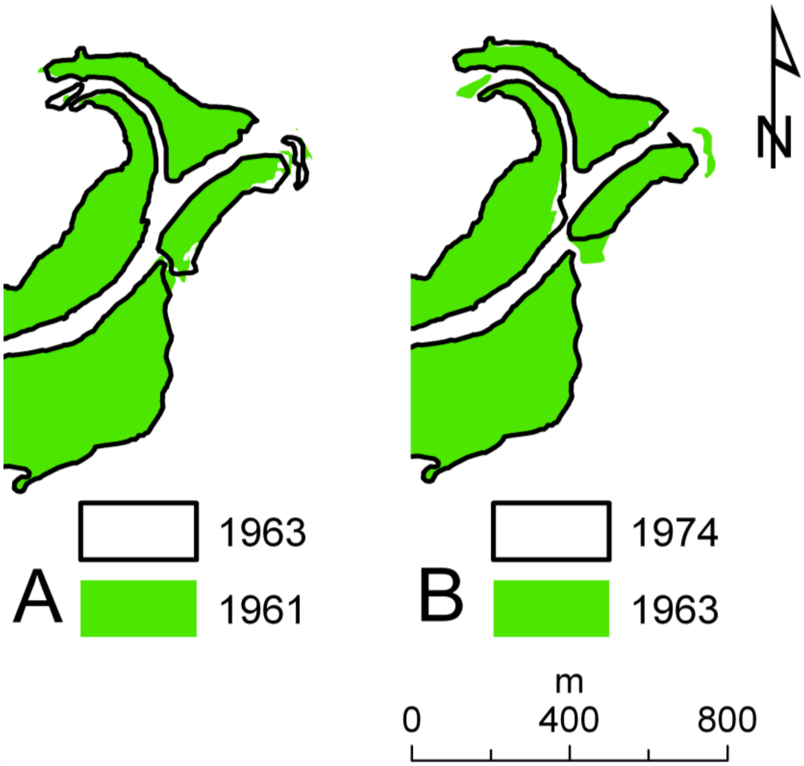

Figure 8.6*: Morphological differences in the Macquarie Rivulet delta between (a) 1961 - 1963, (b) 1963 - 1974 and (c) 1974 - 1981 (after Hopley et al. 2007).*

Over the three years between 1981 and 1984, the delta increased in size from 156.163 ha (1981) to 157.145 ha (1984) equating to an additional 0.982 ha of land (Figure 8.2; Table 8.1). This increase can be attributed to the progradation of a levee extending from the northern end of the southern lobe. The development of the levee resulted in a reduction in the distributary channel width, and the mouth became oriented more towards the east (Figure 8.7a). The development of the levee may be linked with the large flood event which occurred in February 1984 within the adjacent Mullet/Hooka Creek catchment (Wollongong City Council 2012). Moreover, the progradation of this levee resulted in the formation of a small cut-off embayment (Figure 8.7a).

Between 1984 and 1993 significant morphological changes were observed (Figure 8.7a) with these morphological changes causing the delta to increase in area by 1.71% from 157.a25 ha (1984) to 159.812 ha (1993; Figure 8.2; Table 8.1). These changes are likely to reflect additional sediment loads due to continued urban development (Figure 8.1) and the occurrence of six flood events, including the extreme 1984 event. The 1984 flood resulted in larger than average amounts of sediment being eroded and deposited in a short time (Hean and Nanson 1985).

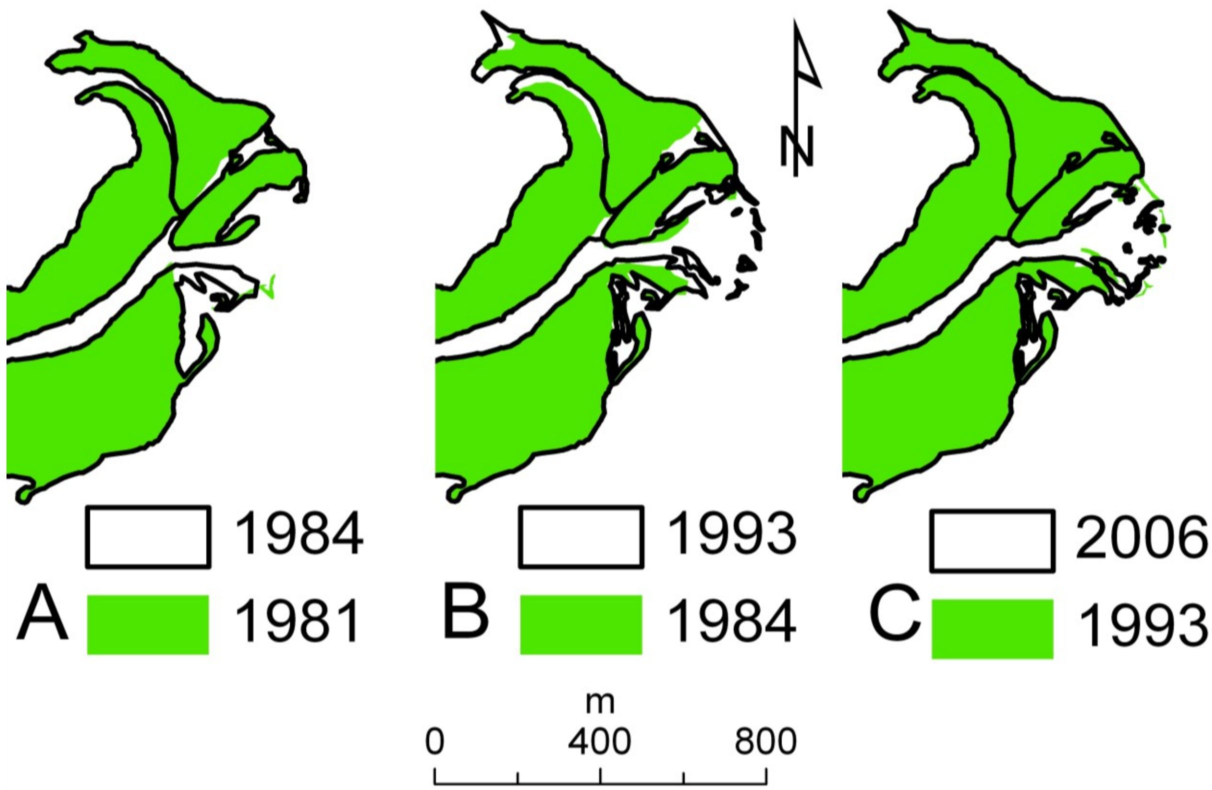

Figure 8.7: *Morphological differences in the Macquarie Rivulet delta between (a) 1981 - 1984, (b) 1984 - 1993 and (c) 1993 - 2006. The black outline represents the more recent morphology (after Hopley et al 2007).*

One of the most striking morphological changes was the development of a large triangular extension off the northernmost tip of the north lobe of the delta (Figure 8.7b). The shape and orientation of the extension indicate it was the result of sediment

reworking by the northeasterly wind-waves. The sediment forming this extension was likely derived from the extensive delta plain and front present in the relatively shallow water surrounding the delta.

The levee extending from the southern lobe continued to accumulate sediment and increase in size. Approximately 15 m to the northeast of the levee, a large elongate mouth bar developed. In addition to this bar, several other smaller bars formed (Figure 8.7b). Another key morphological change is the further extension of the southwestern levee on the northern lobe, which formed a small back-swamp (Figure 8.7b). By 1984, a new levee had developed and was prograding from the southeastern tip of the northern lobe. Initially, this levee may have been a subaerially exposed mouth bar which accreted with time and was subsequently connected to the main lobe of the delta. Continued sedimentation in the small cut-off embayment, first observed in 1984, resulted in the formation of small subaerially exposed bars within it (Figure 8.7b).

Between 1993 and 2006 Macquarie Rivulet delta's growth rate slowed significantly. Over the 13 year period, the delta increase by 0.136 ha or 0.09% from 159.812 (1993) to 159.948 ha (2002) and a further 0.05% to 160.027 ha (2006; Figure 8.2; Table 8.1). The reduced growth rate indicates decreased sediment availability. This decrease is likely to reflect a combination of the occurrence of only one significant flood event, a decline in the average number of homes constructed in the catchment, improved sediment control measures for building sites, subsidence of the rapidly deposited northeasterly edge of the northern levee and subaqueous deposition. The subsidence of the levee is evident due to the die back of trees along the margin of the subaerial portion of the delta (Figure 8.8). By 2006, continued shoaling resulted in complete and partial infilling of the northeastern and the northern channels. This resulted in the integration of the large distributary mouth bar and the northeastern portion of the former southern lobe into the northern lobe (Figure 8.7c). Over the 13 year period, the southern levee

increased in size along with the construction of a parallel elongate mouth bar (Figure 8.7c).

Figure 8.8: *Die back of trees along the northeastern margin of the northern lobe of Macquarie Rivulet. The die back is likely the result of the rapidly deposited sediments subsiding increasing water and salinity levels within the substrate.*

8.6: Mullet/Hooka Creek delta

Between 1916 and 1948 the GIS analysis indicated that the delta increased in size by 1.75 ha or 0.61% (Figure 8.3; Table 8.2). This increase in subaerially exposed land is concentrated in the Koong Burry Bay area (Figure 8.9a) and can be attributed to two main factors. The most significant factor was the construction of the tank trap in 1941 by the Australian Army. The tank trap connected Mullet Creek to Koong Burry Bay via a 660 m long channel with an average width of 15 m in 1948. It was not possible to ascertain the original depth of the trap, however, it is believed the trap would have been a minimum of 2.5 m deep for it to effectively limit tanks crossing. Based on this depth assumption, a minimum of 24,750 m^3 of sediment would have been excavated to produce the trap. It is likely some of the increase in the delta's area can be attributed to the disposal of the excavated material proximal to the site. Potential areas where the spoil may have been dumped are along the east-southeastern shore line of Currungoba Peninsula, the southeastern and western bank at the entrance to Hooka Creek and the

small elongate island off the eastern bank of Hooka Creek (Figure 8.9a). However, it was not possible to confirm this as suitable spatial data was unavailable as were documents pertaining to construction of the trap from the military. Furthermore, the subsequent increase in hydraulic gradient and water velocity, due to the construction of the tank trap, would have more efficiently transported any entrained sediment into the lake via the trap rather than via the lower reach of Mullet Creek.

The other factor which may have contributed to the observed increase in area and morphological differences is that the 1916 polygon/shape file is based on a georeferenced parish map whereas the 1948 polygon/shape file is based on a georeferenced aerial photograph. It is not possible to calculate the extent of the apparent artificial growth of the delta due to the differing data types. This discrepancy was also noted by Hopley *et al.* (2007) when they assessed the recent morphological evolution of the Macquarie Rivulet delta.

Over the 32 years between 1916 and 1948 two channel mouth bars developed in Koong Burry Bay (Figure 8.9a). The crescent or lunette shape of the larger mouth bar is often associated with inertia-dominated systems, where the outflowing water and the receiving basins water are able to mix adequately in both horizontal and vertical space (Sutter 1994; Reading and Collinson 1996). However, Koong Burry Bay is very shallow for approximately 1 km into the lake, which is not conducive to the development of inertia-dominated channel mouths. It is more likely the lunette shape is the result of reworking by southeasterly wind-waves which occur throughout the year.

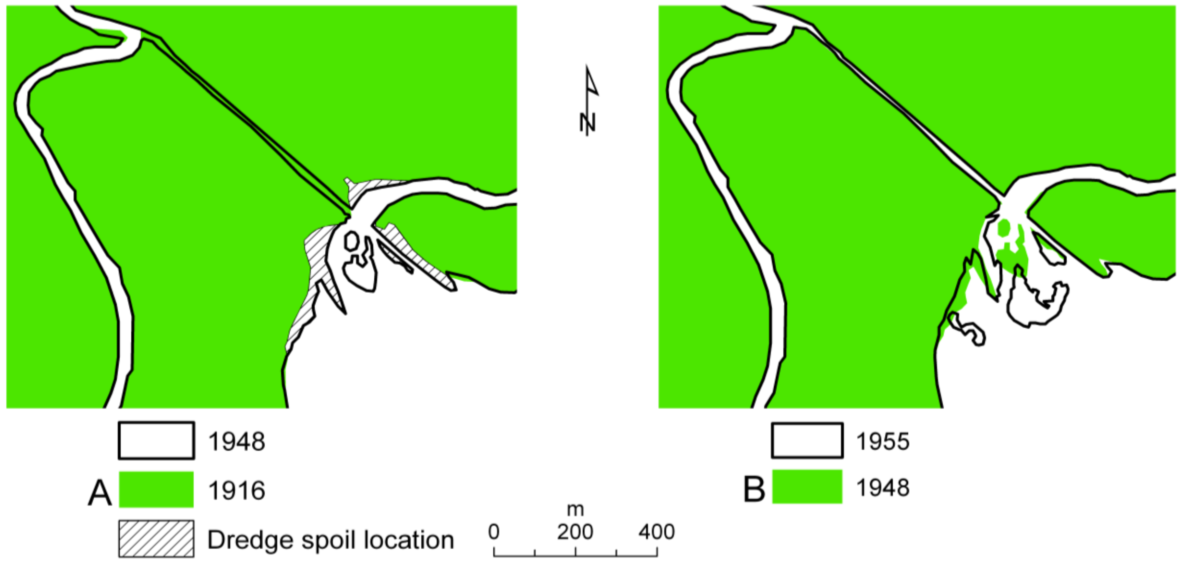

Figure 8.9: *The extensive morphological differences in the Mullet/Hooka Creek delta between (a) 1916-1948 and (b) 1948-1955 are illustrated. The cross hatching in Figure a indicates the probable location of the dredge spoil (after Hopley and Jones 2007).*

Assessing the impact of the upstream weir's construction across Mullet Creek in the early 1900s on the delta's growth was not possible due to poor temporal coverage of the spatial data. However, it is believed the construction of the weir would have significantly limited the amount of sediment transported to the delta's mouth. In particular, the coarser grained sediments transported via saltation and bed-load processes would be trapped, whereas the finer grained sediment transported in suspension would have overtopped the wall. The fine-grained nature of the sediment entering the lake would not have been deposited until the velocity of the entering water plume decreased to a point which facilitated mixing with saline water and flocculation of the suspended sediment.

From 1948 to 1955 the delta increased in area by 1.66 ha or 0.57% (Figure 8.3; Table 8.2). The majority of this increase is associated with the subaerial expansion of the large levee extending from the southeastern mouth of the tank trap in a south-southeasterly

direction (Figure 8.9b). In addition to the growth of this levee a secondary smaller bar has developed to the south of the levee. The large mouth bar evident in the 1948 image has been reworked towards the southeast and has increased in size significantly (Figure 8.9b). The small southeast to northwest orientated levee-like bar has also increased in size over the seven years. The overall birdsfoot morphology of the bars within Koong Burry Bay are characteristic of a friction-dominated channel mouth which is commonly associated with fluvial dominated systems entering relatively shallow water (Sutter 1994; Reading and Collinson 1996). The emergence of the large levee, the reworking and increase in size of the mouth bars evident in 1948 and the development of other bars suggest additional sediment was introduced to the system. This additional sedimentation can be attributed to the construction of the tank trap which enabled sediment to bypass the lower reach of Mullet Creek.

Between 1955 and 1963 the delta's morphology was significantly modified (Figure 8.10a). During this time the delta decreased in area by 3.77 ha or 1.29% (Figure 8.3; Table 8.2). The absence of the large levee evident in the 1955 image accounts for much of the decrease in area (Figure 8.10a). The rapid formation of the levee resulted in it being relatively unconsolidated and highly susceptible to reworking by flood events and wind waves. During this eight year period five significant flood events occurred. The impact of these flood events on Koong Burry Bay would have been enhanced by the presence of the tank trap. Prior to the construction of the trap, floodwaters would have flowed around a very tight bend in Mullet Creek and continued for another 2.7 km to the lake. The construction of the trap bypassed this directional change, reduced the sinuosity and length of the flow path resulting in the floodwaters entering the lake at higher velocities and with increased erosion potential. Other observed morphological changes in the Koong Burry Bay/Hooka Creek area included the reworking and slight extension of the bar orientated parallel to the tank trap and the erosion of the small spit near the mouth of Hooka Creek. A levee-like extension of the southern bank of Mullet Creek at the upstream entrance to the tank trap developed (Figure.8a). This levee would

have further limited the amount of sediment transported down the main channel of Mullet Creek.

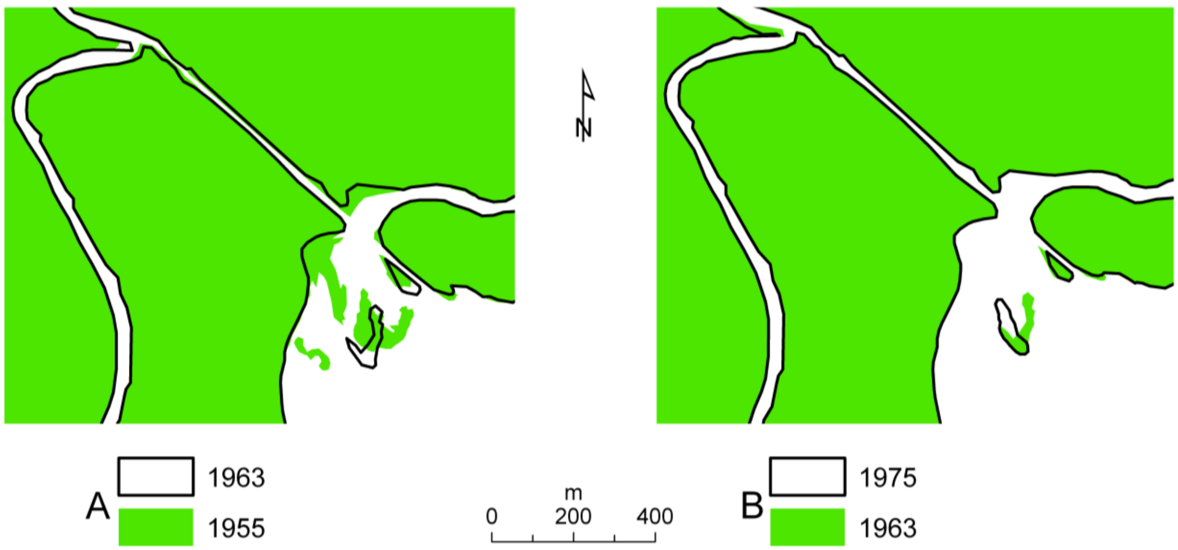

Figure 8.10: *The morphological differences in the Mullet/Hooka Creek delta between (a) 1955-1963 and (b) 1963-1975 are illustrated (after Hopley and Jones 2007).*

Between 1963 and 1975 a further seven flood events occurred which reduced the size of the delta by a further 0.41 ha or 0.14% (Figures 8.3 and 8.10b; Table 8.2). Morphologically, the levee at the junction of Mullet Creek and the entrance to the tank trap decreased in size significantly. It is probable the tank trap was not large enough to carry full flood flows thus forcing excess floodwaters down the lower Mullet Creek channel and eroding the levee. The other significant morphological change was the reworking of the tank trap's main mouth bar towards the southwest (Figure 8.10b).

After 1975 the Mullet/Hooka Creek delta moved into a constructive phase with the delta increasing in size for each of the assessed periods, with the exception of the 1982-1984 period. Between 1975 and 1982 the Mullet/Hooka Creek delta increased in sized from 288.74 ha to 289.21 ha an increase of 0.16% (Figure 8.3; Table 8.2). The observed increase is associated with the increased size of the large mouth bar in Koong Burry Bay

(Figure 8.11a). Over the seven years the bar increased in length by 30 m and in width by 25 m at its widest point. The orientation of the northwestern part of the bar is likely the result of waters discharging from Hooka Creek. Furthermore, a small bar has developed near the eastern edge of the large bar. It is probable this constructive phase of the delta is related to increased urbanisation in the Dapto/West Dapto area (Figure 8.1).

Between 1984 and 2006 minimal morphological changes were observed (Figure 8.11b). However, between 1982 and 1984 the delta decreased in size by 0.34 ha or 0.12% (Figure 8.3; Table 8.2). This decrease in the delta's area can be directly attributed to the extreme 1984 flood event which was concentrated in the Mullet Creek catchment. The intense rainfall and subsequent flooding caused significant channel erosion, particularly in the steeper-gradient upper to mid reaches of the catchment (Hean and Nanson 1985). Much of the eroded sediment was deposited upstream of the rail and freeway embankments and on the floodplains of Mullet Creek. The reduced sinuosity and increased hydraulic gradient of the tank trap would not have dissipated the floodwater's energy, resulting in the floodwaters entering the lake with relatively high erosive power. Morphologically, the floods reworked the small bar near the eastern edge of the large bar, eroded the western bank of Hooka Creek and altered the sharp bend in Mullet Creek at the tank trap's upstream end.

Between 1984 and 1990 urban development within the catchment increased and would have contributed additional sediment to the delta (Figure 8.1). However, the GIS analysis indicates the morphology and size of the Mullet/Hooka Creek delta remained relatively stable with an area increase of 0.09 ha or 0.03% (Figure 8.3; Table 8.2). The limited change to the deltas morphology is likely to be an artefact of the 1984 flood event. The flood would have scoured into the channel's base creating a sediment sink which required infilling prior to sediment delivery to the delta front resuming. Inhibited growth of a delta due to the creation of a sediment sink has also been documented by Hopley (2004).

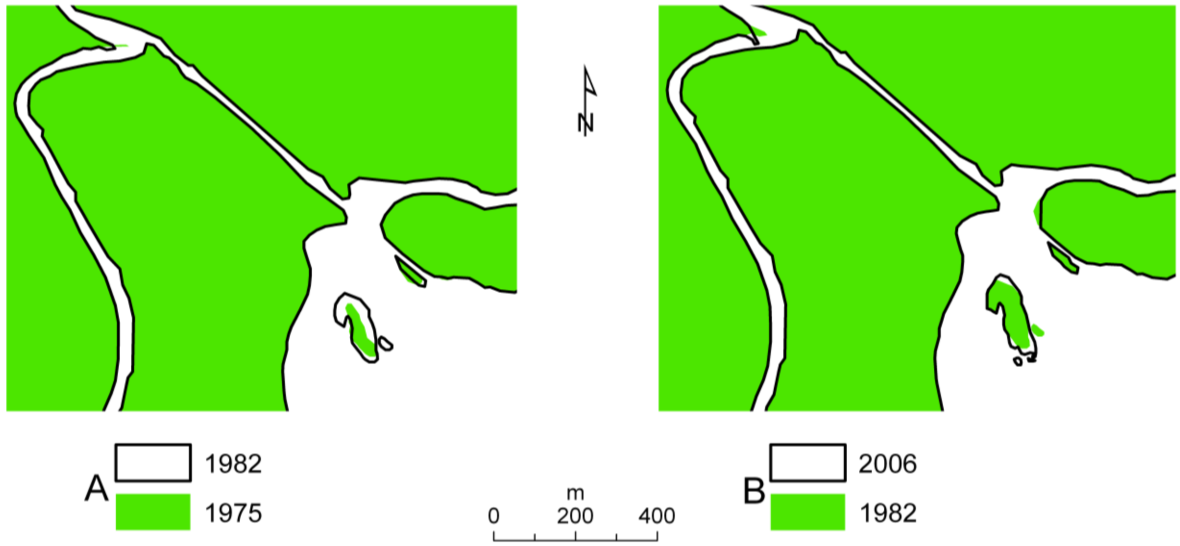

Figure 8.11: *The morphological differences in the Mullet/Hooka Creek delta between (a) 1975-1982 and (b) 1982-2006 are illustrated (after Hopley and Jones 2007).*

From 1990 to 2002 the Mullet/Hooka Creek delta increased it's subaerial footprint by 0.24 ha or 0.08% (Figure 8.3; Table 8.2). The growth of the delta was concentrated in the Koong Burry Bay area at the mouth of the tank trap. The large bar orientated parallel to the Currungoba Peninsula remained stable between 1984 and 1990 but increased in size slightly between 1990 and 2002, with its overall length increasing from approximately 186 m to 220 m. During the period approximately 2150 dwellings were constructed (Figure 8.1) in the Mullet/Hooka Creek catchment, in particular the West Dapto area. The construction of so many dwellings is likely to have generated significant amounts of free sediment which could be transported to the delta. However, the restricted growth of the delta suggests the four offline wetlands (Rob 1, 2 and 3; Reed 1), constructed in the early 1990's with a combined capacity of ~123,000 m^3 (Sinclair Knight and Partners 1992), were absorbing the majority of the freely available sediment associated with the rapid urbanisation of the West Dapto area.

Over the four years between 2002 and 2006 the delta's subaerial area increased by 0.36 ha or 0.12% (Figure 8.3; Table 8.2). This observed increase in area, given the continued urban expansion of the West Dapto area (Figure 8.1), is minimal. The lack of observed growth is likely to reflect the morphology of Koong Burry Bay, the active receiving basin. The broad and sheltered nature of the bay enables the sediment laden water to laterally expand which results in the sediment being deposited across a broad subaqueous plain which is slowly accreting. The major morphological changes through this period consisted of the development of two small bars at the southeastern end of the large bar (Figure 8.11b). These bars may be the result of sediment transported to the delta mouth during the 2003 flood event.

8.7: Deltaic growth comparison

Both the Macquarie Rivulet and the Mullet/Hooka Creek deltas have responded in similar ways. The observed changes can be attributed to a combination of both anthropogenic and natural factors. Over the period analysed, Macquarie Rivulet has an average higher percentage rate of growth than Mullet/Hooka Creek. As the regional geology, soil landscapes and catchment land use patterns are similar it is unlikely these factors are responsible for the differing growth rates. The differences are more likely to reflect the extensive floodplain stripping, identified by Hean and Nanson (1985) within the Macquarie Rivulet catchment.

Between the late 1940s and mid 1950s both deltas increased in size steadily. In both instances, the increase in deltaic area can be attributed to the initial phases of urban development. Post mid 1950s the Mullet Creek delta decreased in area up until the early 1960's. This pattern differs from Macquarie Rivulet which shows a steady increase in delta area to 1961 with a spike in growth to 1963. This pattern is then reversed with Mullet/Hooka Creek increasing in size and Macquarie Rivulet decreasing in size up till the late 1970s. In the early 1980s Mullet/Hooka Creek decreased in area while Macquarie Rivulet increased in area due to the 1984 extreme flood event. This event

was an erosive event for the Mullet/Hooka Creek delta whereas it was a depositional event for the Macquarie Rivulet delta, as the storm event was concentrated in the Mullet/Hooka Creek catchment. These observed discrepancies highlight the localised nature of storm events for the region.

From the mid 1980s up until early 2000s both deltas increased in area reflecting an increased rate of urban development and land clearing within the catchment areas. However, in both instances the rate of delta growth decreased in the early 1990s. The decreased growth rate is likely to be attributed to the implementation and enforcement of sediment control measures within the areas being developed. These measures ranged from the installation of site-specific sediment fences to the construction of large sediment traps, which are now used as water quality control ponds. From 2002 to 2006 the annual growth rate of Macquarie Rivulet delta decreased, whereas the Mullet/Hooka Creek delta increased slightly. This discrepancy can be attributed to the fact that development within the Macquarie Rivulet catchment slowed significantly whereas development continued within the Mullet/Hooka Creek catchment. Furthermore, subsidence of the northeastern edge of Macquarie Rivulet's northern levee is also likely to be a contributing factor.

8.8: Technique evaluation

The study illustrates that an integrated approach to mapping based on historical parish maps and aerial photographs within a GIS framework can be used to effectively track past morphological changes on a delta system, such as the Macquarie Rivulet and Mullet/Hooka Creek deltas, with reasonable accuracy. However, care needs to be taken when assessing the validity of historical maps. The temporal distribution of suitable photogrammetric data also controls the precision of interpretation since multiple flood events may occur between photographic records. In the future such studies could be enhanced by the use of higher frequency satellite data.

An understanding of the rates and causes of changes in delta areas provides a measure of the soil loss from the catchment, due to changing land use patterns, as well as flood magnitude and frequency. As such, it provides an additional tool which can be used in developing catchment management plans, especially when combined with the rates of prodelta sediment accumulation (e.g. Chenhall *et al*. 1995; Hopley and Jones 2006). This GIS mapping approach, assuming data of sufficient quality and from suitable time periods is available, could be applied to other deltas, both in Australia and overseas, providing valuable information.

8.9: Chapter summary

Overall, both Macquarie Rivulet and Mullet/Hooka Creek deltas have increased in area significantly, despite periods of negative growth. Both the positive and negative increases in area and associated morphological changes have occurred in response to a combination of anthropogenic catchment modifications and natural factors. Some of the key factors contributing to the observed changes include land clearing, urban/commercial development, floods, wind-waves, bank stability, regional geology and erodible soils. Furthermore, the research highlights the growth and the associated morphological changes in both deltas appear to have stronger links to their respective catchments rather then the receiving basin.

Chapter 9

Potential impacts of Climate Change and Anthropogenic Activities on Delta Evolution

9.1: Introduction

Deltas are dynamic environments which rapidly respond to broader changes within the catchment and receiving basins. This response is attributable to deltas evolving at the fluvial/estuarine interface where many interacting factors, including relative sea level, fluvial discharge, sedimentation rates and wave and tidal influences, shape their morphology. This chapter presents and discusses some of the potential impacts of climate change and anthropogenic activities on the evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas. The chapter also highlights issues in the planning process which often overlooks the implications of catchment modification downstream and on the deltas themselves. The information presented in this chapter is based on the detailed morphological and sedimentological evidence presented in Chapters five to eight of this thesis. The chapter also makes recommendations with respect to further research required and to the future management of the deltas.

9.2: Climate Change

Broadly, climate change has wide ranging environmental, economic and political implications from a local to global context (DCC 2009, IPCC 2012, Fatoric and Chelleri, 2012). Wardekker *et al.* (2010) noted climate change implications will pose significant challenges within deltaic environments, such as inundation and channel avulsion. Numerous organisations such as universities and government departments have and continue to conduct research to identify and better understand the impacts of climate change. This enhanced understanding will increase our capacity to assess the vulnerability of an area to the impacts and, therefore, determine effective adaptation and management strategies.

However, specific assessment of the potential climatic impacts on deltas is lacking and where it has occurred it is typically focussed on the urbanised/developed continental scale deltas with abundant sediment supply. For example, Wardekker *et al*.'s (2010) study discussed the implications of climate change on deltas near Rotterdam at the mouths of the Rhine, Nieuwe Mass and Nieuwe Waterweg. Specifically, the study assessed the impact of sea level rise, altered wind regimes and rainfall events and subsequent river discharge variations. Based on the authors' assessments they developed a series of six resilience principles (homeostasis, omnivory, high flux, flatness, buffering and redundancy) which enable the local decision makers to operationalise the concepts, thus reducing the delta's vulnerability to climate change impacts. Gu *et al.* (2011) assessed climate change impacts on urbanisation of the Yangtze River delta. This study noted sea level rise, increased flooding and the associated reduction in developable land as key issues. However, unlike Wardekker *et al.* (2010), this study did not discuss ways in which the delta could be managed. As with the previously noted studies (Fatoric and Chelleri 2012) climate change will have a significant impact on the Ebro delta. The key areas addressed by this study include changes in hydrology, altered sedimentation patterns, impacts of waves and increased sea level. The study also presented possible management strategies to limit the impact of climate change on the delta.

In 2009 the Department of Climate Change (DCC) published the findings from its initial first-pass assessment of the risks posed by climate change around the Australian Coastline. The key climate change areas addressed in the report included sea level change (historical and projected), extreme events, inundation risk and erosion risk. The following section discusses these aspects and their potential impact on the Macquarie Rivulet and Mullet/Hooka Creek delta geomorphological evolution into the future.

9.2.1: Sea level change

As illustrated in Chapters five to seven, sea level has played a critical role in the sedimentological and morphological evolution of Lake Illawarra and its deltas during the Holocene. Specifically, the research has presented geochronological and facies evidence,

relative to the sea level envelope published by Sloss *et al.* (2007), which suggests the deltas regressed as the late Pleistocene/early Holocene sea level rose inundating the receiving basin and study areas. With the stabilisation and subsequent sea level fall the two deltas were able to actively prograde into the study area. The preservation of the regressive sequence, in places, and subsequent prograded sequences suggest that delta sedimentation was at times able to keep pace with and/or exceed the rate of sea level rise.

Analysis of tide data from Fort Denison (Sydney, New South Wales) and Fremantle (West Australia) by Church *et al.* (2006a) indicated that the average rate of sea level rise in Australia is less than the global average. Specifically, the study showed sea level rise in Australia occurred at 1.3 mm/year compared to the global average of 1.8 mm/year. The discrepancy between the two rates has been attributed to reduced sea level associated with El Niño events as documented by Hopler *et al.* (2005). However, DCC (2009) noted the rate of rise between the early 1990's and 2008 is similar to the global average for southern and eastern Australia (Figure 9.1) while the rates of rise for the western and north-western portion of Australia are more than double the global average due to climate change and local short term variability (Figure 9.1; DCC 2009).

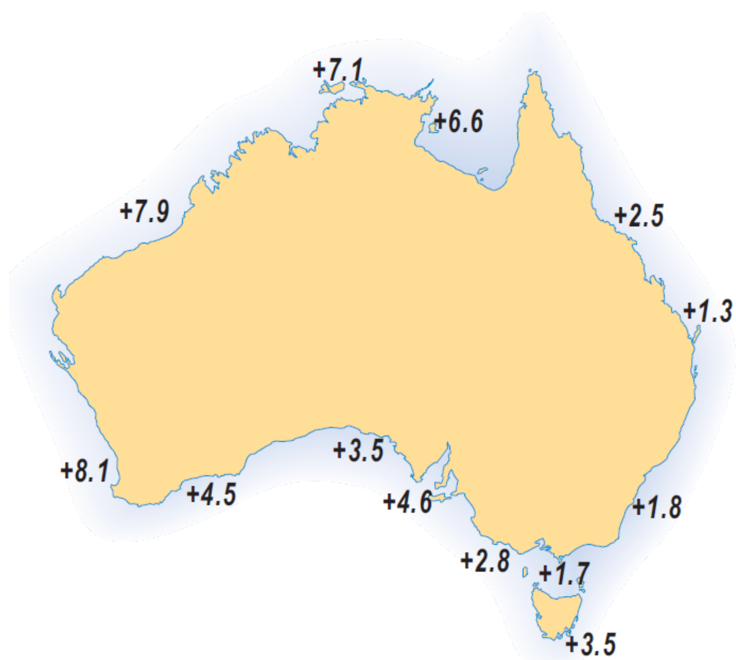

Figure 9.1: *Local sea-level rise (mm/year) from the early 1990s to 2008 (DCC 2009).*

In 2007 the CSIRO and the BOM (CSIRO 2007b) developed three sea level rise scenarios for Australia (Table 9.1). DCC (2009) noted that since these models were developed sea level rise projections of up to 1.9 m have been suggested with a mid range of 1.1-1.2 m. Based on the new research the DCC adopted the mid range figure of 1.1 m rise by 2100 for its assessment of climate change risk to the Australian coastline. However, the blanket application of this 1.1 m rise to the Australian coastline does not reflect the variability in the rate of rise as reflected in Figure 9.1 and discussed by Lewis *et al.* (2012).

Table 9.1: *CSIRO and BOM (2007b) sea level rise scenarios.*

Year	**Scenario 1:** Unavoidable sea level rise	**Scenario 2:** upper IPCC AR4 projections	**Scenario 3:** upper IPCC AR4 projections plus new research on icesheets
2030	0.132	0.146	0.200
2070	0.333	0.471	0.700
2100	0.496	0.819	1.100

As part of its response to climate change the NSW Government developed the NSW Sea Level Rise Policy (DECCW 2009) which is given effect through SEPP71 – Coastal Protection and the Environmental Planning and Assessment Act 1979. The policy document establishes sea level rise benchmarks of +0.4 m and +0.9 m by 2050 and 2100, respectively, above 1990 levels. These benchmarks equate to average annual increases of 6.6 mm/year to 2050 increasing to 10 mm/year by 2100 along the NSW coastline. These sea level rise projections have been adopted for the study, due to the Macquarie Rivulet and Mullet/Hooka Creek deltas geographic location. Furthermore the 2100 projected level is similar to that adopted by the DCC (2009).

Despite the high sedimentation rates observed proximal to the delta mouths (up to 31.25 mm/year in MR 33, Table 4.6a) the two deltas will be vulnerable to sea level rise as the rate of vertical accretion once subaerial exposure occurs is much lower. Accurately establishing the degree of vulnerability, specifically the inundation extent and morphological response of the two deltas is a complex process, due to the large

number of variables which occur within deltaic environments, and is beyond the scope of this research project. Despite this, simplistic first pass 'bucket fill' inundation models for the two deltas are presented and discussed below (Figure 9.2 and 9.3). The base digital elevation model (DEM) utilised in the development of the bucket-fill inundation models is based on high resolution LiDAR data (Figures 4.6, 4.7) which is reported to have accuracies of 0.15 m in the vertical and 0.06 m in the horizontal. The use of high resolution LiDAR data to develop the DEM increases the topographic accuracy of the model over the lower resolution SPOT3D DEM utilised by the DCC (2009). The NSW Sea Level Rise Policy (DECCW 2009) 2050 and 2100 projected sea level rise scenarios assuming a 0m AHD baseline and the same scenarios assuming a 0.25 m baseline to reflect the current elevated water level within Lake Illawarra were then overlain on the resultant DEM. Despite the simplistic nature of the models presented, the 'bucket fill' approach adopted in this study provides a fast, cost effective method to establish the possible impacts of inundation in coastal areas. Additionally, DCC (2009) noted the approach provides generally robust outputs. It is important to note this 'bucket fill' approach cannot model morphological changes which may result directly from sea level inundation or other climate change responses including, but not limited to, altered rainfall and wind wave patterns. Furthermore, the models can not predict the hydrostatic implications associated with inundation of the relatively unconsolidated deltaic sediments. However, if the models are viewed with this in mind they do provide a high level insight into the extent of inundation under the sea level rise scenarios and potential locations of delta avulsions.

By 2050 large areas of Macquarie Rivulet delta will be inundated if the 0.4 m rise is realised (Figure 9.2). In contrast, Mullet/Hooka Creek delta is likely to experience less inundation based on the same scenario. However, by 2100 large areas of the Mullet/Hooka Creek delta near the tank trap will be inundated (Figure 9.3) with additional inundation occurring to a lesser extent on the Macquarie Rivulet delta. By 2100 The Macquarie Rivulet inundation model (Figure 9.2) indicates thinning of the southern lobe has occurred in one location. This thinning may be the point at which a crevasse splay develops resulting in the delta avulsing towards the south. Furthermore,

the actual inundation extent may be greater than illustrated in Figures 9.1 and 9.2 as the current rate of subsidence is not known and the hydrostatic implications of additional water has not been incorporated into the model. However, inundation of the two deltas will likely result in the delta front being abandoned and the delta regressing as occurred in the late Pleistocene/early Holocene transgressive event (refer to Chapters five to seven). It is important to note the projected annualised rate of sea level rise is less than those associated with the late Pleistocene/early Holocene transgressive event.

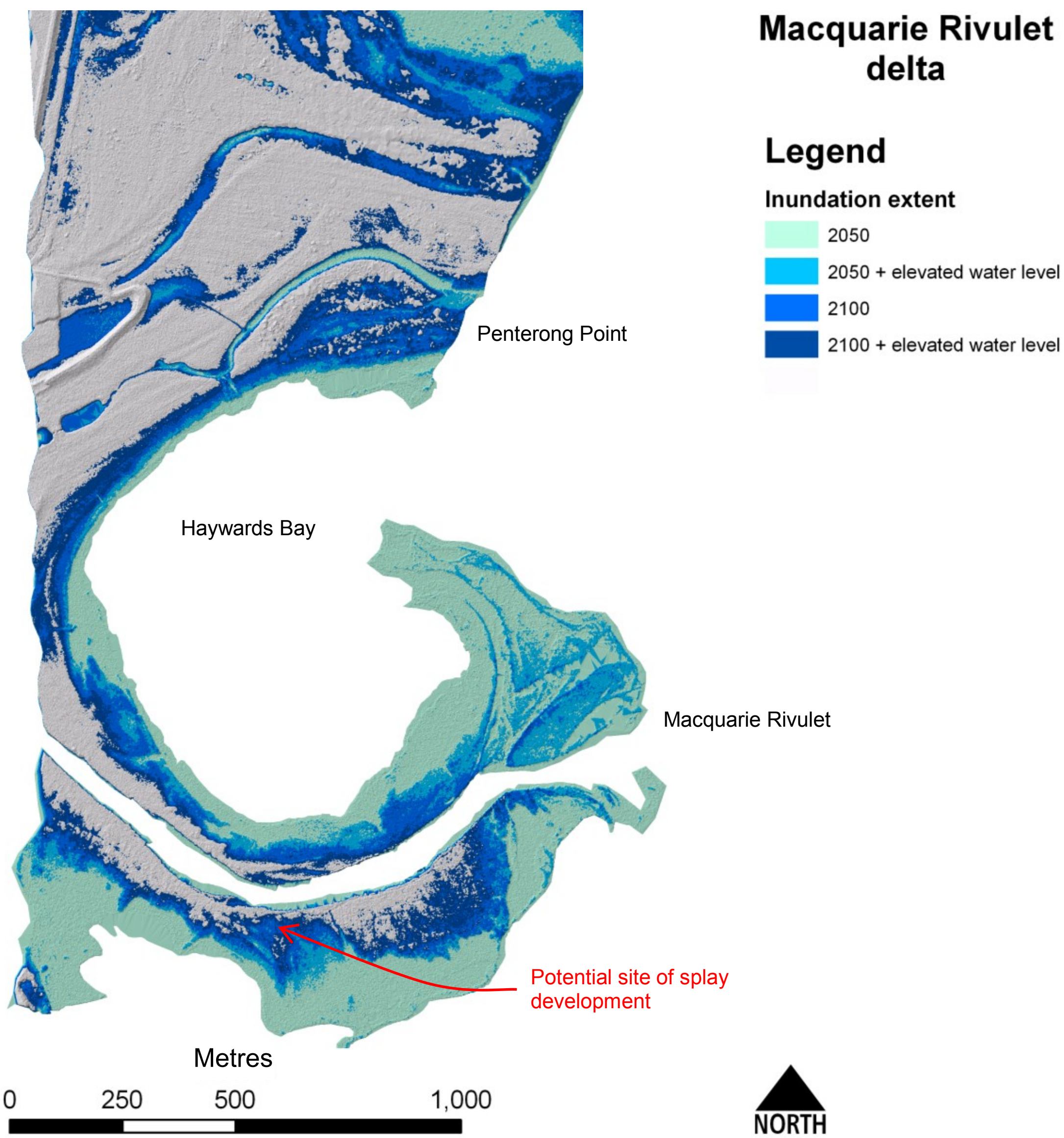

Figure 9.2: *Potential inundation map of Macquarie Rivulet delta. Map shows 2050 and 2100 inundation extents plus the 2050 and 2100 inundation extents with an additional 0.25 m overlain to reflect the current elevated water level within the lagoon. Not the*

thinning of the southern delta lobe which may result in a splay developing and the delta avulsing.

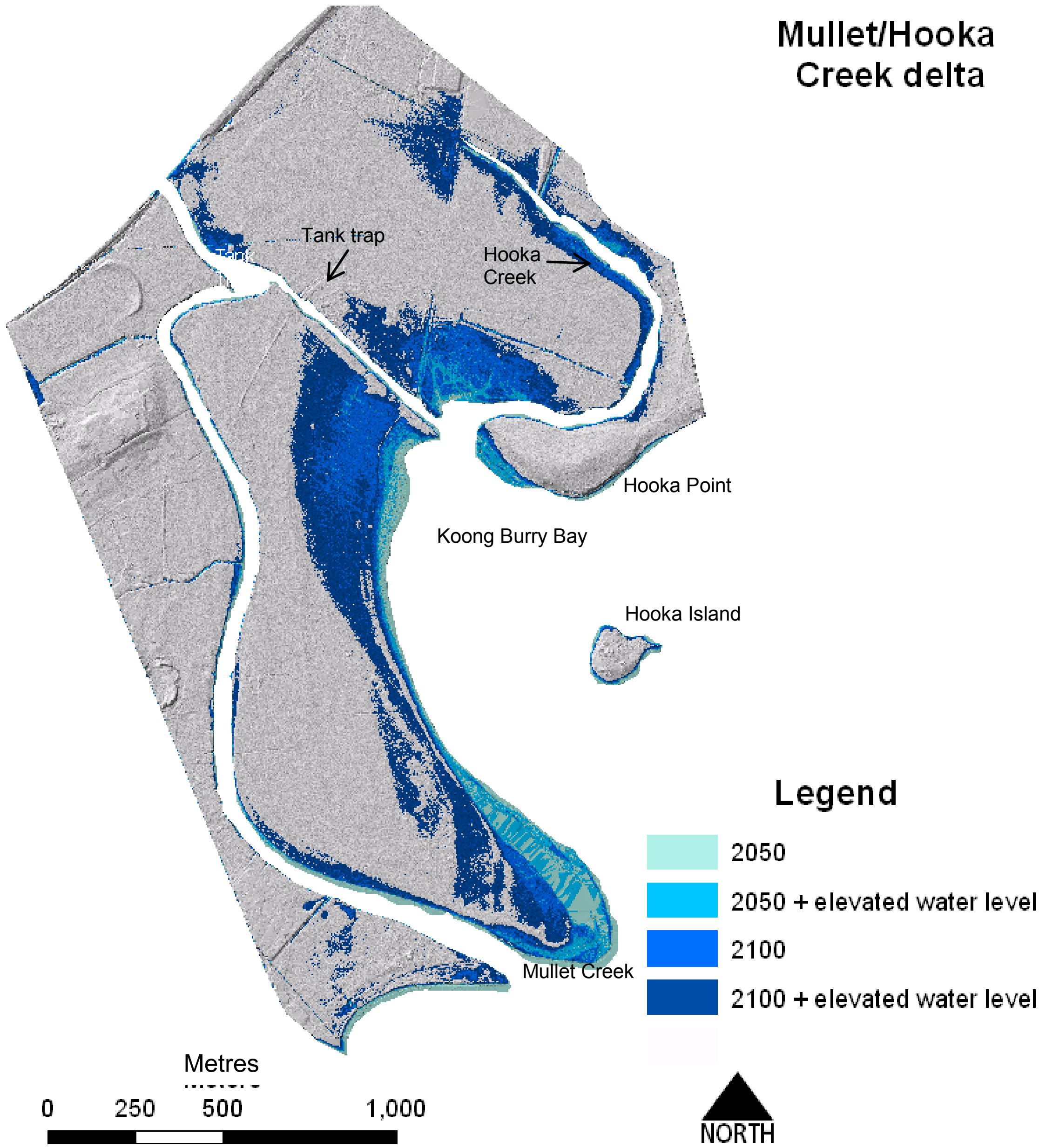

Figure 9.3: *Potential inundation map of Mullet/Hooka Creek delta. Map shows 2050 and 2100 inundation extents plus the 2050 and 2100 inundation extents with an additional 0.25 m overlain to reflect the current elevated water level within the lagoon.*

The presence of the weirs upstream from the two study areas are likely to be acting as sediment sinks capturing the bed load and saltating sediment migrating down stream.

By preventing this sediment reaching the delta fronts it is possible that the measured modern sedimentation rates presented in this thesis may be lower than the potential sedimentation rates if the weirs were not present. The capacity of weirs/dams to prevent downstream sediment migration has also been documented by Day *et al.* (1997) for various deltas, Syvitski *et al.* (2005) for various deltas; Syvitski and Sito (2007) for the Nile Delta, Hopley (2011) for Duck Creek, Hinderer (2012) for the Mississippi delta and Fatoric and Chelleri (2012) for the Ebro delta. For example, Day *et al.* (1997) noted sediment reduction rates exceeding 95% for the Nile, Indus and Ebro deltas, 75% for the Po delta and 50% for the Mississippi delta can be attributed to the construction of dams across the waterways.

Preventing the sediment transported via bed load and/or saltation processes from reaching the delta fronts increases the delta's vulnerability to sea level rise and impacts on the overall environmental sustainability of the deltas. The increase in vulnerability is attributable to the potential rate of vertical accretion being lower than it would be had the structures not been present increasing the rate and extent of inundation under a sea level rise scenario. The overall sustainability of the delta is impacted as the inability for the delta to vertically accrete at the same pace as the sea level rise will result in the loss of wetlands, which are key to the overall health of the deltaic system and the estuary into which they prograde.

Despite the negative impacts the presence of the weirs have on deltas discussed above, these structures could also provide land managers with a potential opportunity to reduce the deltas vulnerability. It may be possible to extract this sediment, assuming sufficient volumes are available, and nourish the topographically lower portions of the floodplain to artificially increase the rate of vertical accretion. This adaptive approach has also been suggested by Fatoric and Chelleri (2012) for the Ebro delta. However, further research is required to establish the net benefits (positive and negative) of such an undertaking to ensure no adverse environmental issues arise. One of the key issues that would need to be established is what impact the additional sediment load would have on the rate of delta subsidence. Specifically, if the subsidence rate is increased

then the delta may be more vulnerable to sea level rise post nourishment as the upper surface elevation may become lower than the present level. This will be particularly important for the Macquarie Rivulet delta where there is already evidence of subsidence occurring at a rate greater than the rate of vertical accretion (Figure 8.8).

One factor often overlooked is the impact of sea level rise on saltwater intrusion. Saltwater intrusion will have several effects at the two study sites. The increased salinity and level of the ground water may render some of the dams used by livestock unsuitable. The increased salinity may also result in areas of land experiencing salt burn/scaring rendering them unable to support the plant life that they currently do. Increased salinity within the receiving basin may also alter the river mouth depositional process by enabling the saline wedge to penetrate farther upstream than at present, reducing the systems capacity to transport solids (Fatoric and Chelleri 2012). This, in turn, may reduce the ability of the Macquarie Rivulet and Mullet/Hooka Creek deltas to prograde. It may instead lead to the deltas regressing. However, the presence of the weirs on the two waterways may limit the extent of intrusion and its impact on ground water and depositional processes.

9.2.2: Altered rainfall intensity and associated flooding

Rainfall intensity is strongly associated with flood frequency and the scale of a given flood. Under current climate change modelling the CSIRO (2007a) suggested rainfall intensities for extreme events (40 year ARI over 24 hours) will increase across NSW by approximately 12%. The DECC (2008) projected changes associated with altered rainfall patterns will see an increase in runoff during the autumn (14%) and summer months (22%). Increases during the spring and winter months are lower at 1% and 3%, respectively. Furthermore, impacts associated with the resultant inundation extents are likely to be exacerbated if the out-flowing water backs up behind a coastal surge (DCC 2009).

The impact of flooding on the evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas is evident in many of the cores collected and analysed while undertaking this

research. Sedimentological evidence derived from the cores includes flood and splay deposits within host facies such as the prodelta/lagoonal mud and floodplain facies (Figure 6.1 and 7.1; Volume 2, Appendix 5). The increased sediment loads transported downstream by flood events is likely to have resulted in subaerial and subaqueous vertical accretion of the delta. However, due to a lack of material suitable for analysis, the rapid deposition of the sediments and the scale variability of the flood events it is not possible to derive the rate of vertical accretion directly attributable to a given event. Hopley *et al.* (2007), Hopley and Jones (2007) and Chapter 8 of this thesis illustrate, using photogrammetric techniques, how flooding, in addition to anthropogenic activities, has shaped the modern subaerial footprint of the delta. The morphological adjustments which are attributed to flooding include the development of crevasse splays resulting in delta bifurcation and the reduction in delta size due to bank erosion.

If rainfall intensities do increase as expected due to climate change, the morphology of both deltas may be altered in both positive and negative ways. Some of the morphological changes which may occur include:

- Change in the dominance of a given process, i.e. fluvial, wave or tide. Note it is unlikely tides will impact on the deltas due to the presence of the barrier.
- More frequent migration or avulsion of the delta mouths due to processes such as the development of crevasse splays through existing levees, the lateral migration of distributary channels and/or the reactivation of palaeochannels.
- Increased rates of bank erosion due to increased downstream water velocities resulting in the loss/damage to land and habitat.
- Increased vertical accretion of the subaerial and subaqueous components of the delta.
- Increased frequency and extent of inundation as modelled by Cardno (2011).

Preventing/managing these morphological changes is very difficult. Implementation of hard engineering on the deltas could be undertaken such as channel lining/stabilisation (e.g. Rhone and Fraser deltas; Syviski and Saito 2007) or the construction of in-channel weirs (e.g. Macquarie Rivulet, Hean and Nanson 1985). However, this sort of activity often results in issues beyond the engineered sections, such as accelerated erosion close

to the engineered sections. As such, these activities should be avoided where possible. The use of flood retarding/detention basins would be most effective upstream. However, these would also pose ongoing infrastructure and environmental management issues. It also requires the allocation of suitable available land, which is limited within the Illawarra (Cardno 2011). Stabilisation of the delta floodplains, levees and channel banks through environmental plantings is likely to enhance the deltas adaptation capacity through the stabilisation of the subaerially exposed floodplains and levees. The increased vegetation density will also increase Manning's N values reducing water velocities across the delta floodplains, lessening the erosive potential of flood events and facilitating the deposition of suspended sediments on the floodplains/levees. The increased deposition will facilitate vertical accretion which may further reduce the deltas vulnerability to the projected sea level increase. This will only be possible through the development, adoption and enforcement of strategic land management/planning policies such as Local Environment Plans (LEP's). These plans/policies will only be effective if they adequately identify and address in a balanced way all of the potential implications of the predicted increase in rainfall intensity and any subsequent management strategies, particularly hard engineering.

9.2.3: Altered wind patterns/strengths and wind-wave generation

As discussed in Chapter two and illustrated in Figure 2.4, northeasterly, southeasterly and southerly winds are common throughout the warmer months with westerly and southwesterly winds common during the winter months. The influence of waves generated by these winds on the morphological evolution of the two deltas studied is most evident in the cuspate morphology associated with the Mullet Creek delta lobe. The cuspate morphology is likely associated with reworking by the southeasterly wind-waves which typically operate all year round. Although a fluvially dominated delta, the curvature of Macquarie Rivulet delta is likely to be associated with the redistribution of sediments by wind-waves associated with the weaker northeasterly winds during summer.

In 2007 the CSIRO and BOM (CSIRO 2007b) completed a study which addressed climate change and included an assessment of potential changes to wind strengths and directions. However, due to complexities associated with wind generation and resultant patterns the study contained large uncertainties. The study predicted wind patterns and strengths across NSW would be altered under a climate change scenario. During the summer months wind speeds are likely to increase with the exception of winds from the northeast. Autumn winds from the east and south are predicted to decrease with winds from the northwest increasing in strength. The increased strength of northwesterly winds during autumn will persist through the winter. Winds during spring are anticipated to increase from all directions.

These altered wind patterns/strengths and associated wind-waves will have implications for the morphological evolution of the two deltas to varying degrees. During summer months the sediment redistribution capacity of wind-waves associated with the northeasterlies is likely to be reduced. The decreased size of the wind-waves, combined with the sheltered nature of the Macquarie Rivulet delta (Figure 2.4) and the limited capacity for wave generation from other directions, may result in the delta prograding in a more easterly direction. The reduced capacity of the northeasterly generated waves to erode or transport sediment may also have a minor impact on the morphology of the Mullet Creek lobe of the Mullet/Hooka Creek delta. However, the primary deposition on the Mullet/Hooka Creek delta is now associated with the tank trap in a very protected part of Lake Illawarra. The predicted changes in winds during the remaining months are likely to have negligible effects on the morphology of the deltas due to the restricted capacity for wind-wave generation, particularly with winds originating from the west.

9.3 Anthropogenic impacts

In recent years, the body of research documenting anthropogenic impacts on delta evolution has increased substantially. Examples of these studies include, but are not limited to, Fatoric and Chelleri (2012) on the Ebro delta, Gu *et al.* (2011) on the Yangtze River delta, El Banna and Frithy (2009) on the Nile delta, Jones *et al.* (2006) on the Macquarie Rivulet delta, Li *et al.* (2006) on the Red River delta, Day *et al* (1997) on the

Mississippi delta and Fanos (1995) on the Nile delta. There are many reasons for this such as urban expansion, infrastructure construction, flood control, irrigation and sediment redistribution. The majority of the studies reviewed while undertaking this research have all demonstrated that anthropogenic modification of the catchments and deltaic plains have altered their evolution. Syvitski *et al.* (2005a, b, c) noted that the Po River delta has been modified since 1150, and modifications continue today to ensure the Venice lagoon does not infill with sediment and to minimise/prevent flooding. The Yellow River delta has been modified since the mid 1800's through to present day. These modifications on the latter delta have included distributary channel diversion and the construction of dikes to protect the reclaimed land. These activities resulted in the delta prograding at a rate of 4 km/year and increased channel gradients resulting in upstream scouring as the channel hydrology rebalanced (Syvitski and Saito 2007).

This study has illustrated that the modern (post-European settlement *ca* 200 years ago) morphologies of Macquarie Rivulet and Mullet/Hooka Creek deltas have been influenced to varied degrees by anthropogenic activities, after European settlement, both within the defined study areas and the broader catchment. The scale and nature of these changes were established using photogrammetric and GIS analytical techniques and are discussed in Chapter 8. One of the best examples of the impact of anthropogenic activates on delta evolution observed in this study occurs within the Mullet/Hooka Creek study area. Construction of the tank trap in the early 1940's diverted sediment away from the Mullet Creek distributary channel mouth and redirected it to Kong Burry Bay close to Hooka Point. The impacts of anthropogenic modification of the catchments are also highlighted by the modern sedimentation rates of up to 31.25 mm/year (MR 33, Table 4.6a).

The current sedimentation rates measured at the mouths of Macquarie Rivulet and Mullet/Hooka Creek are likely to continue as their respective catchment's are further developed in coming years (e.g. West Dapto expansion project), despite the presence of the weirs on both waterways. The largest development currently proposed for the Macquarie Rivulet catchment is the 700 ha Calderwood release which will contain an

estimated 4,800 homes (Figure 9.4; Delfin Lend Lease 2012). However, a review of submitted documentation,, such as the flood study by Rienco Consulting (2010), would indicate the anthropogenic impacts, in addition to the climate change impacts, associated with the development have not been fully considered or based on recently published work. For example, the report refers to morphological assessments conducted by Young (1976), noting the growth of the delta has stabilised in recent years. The higher resolution research presented by Hopley *et al.* (2007) and discussed in Chapter 8 illustrates the subaerial portion of the delta has continued to grow, with much of the growth coinciding with changes in land use patterns. The report also indicated sedimentation rates have diminished due to channel stabilisation, however, sedimentation rates presented in this thesis and published by Sloss *et al.* (2004, 2011) do not support this claim. The lack of consideration of the geomorphic implications of anthropogenic modification of the catchment is also evident in adjacent developments as discussed by Hopley (2011). This is significant as the utilisation of incorrect information restricts the capacity of decision makers to make fully informed decisions.

Developments abutting waterways often involve some degree of channel modification such as channel realignment, construction of weirs and channel armouring. These modifications are typically undertaken to reduce flood risk, increase the area of land deemed to be suitable for development and improve water quality. Despite, these modifications occurring within the area being developed, the implications of these changes are often observed above and below the engineering works, e.g. Macquarie Rivulet (Hean and Nanson 1985). Some of the impacts associated with engineering works include increased channel bed scouring (Syvitski and Saito 2007), increased bank erosion (Hean and Nanson 1985, NOW 1997), increased delta progradation (Syvitski and Saito 2007), reduced flood handling capacity (Gu 2011, Hopley 2011), biodiversity impacts (i.e. reduced fish passage: NOW 1997) and altered channel hydrodynamics/flood behaviour (Fatoric and Chelleri, 2012). Based on the above examples, proposed modification of waterways must be carefully considered and include particularly the up- and down-stream implications of the proposed works.

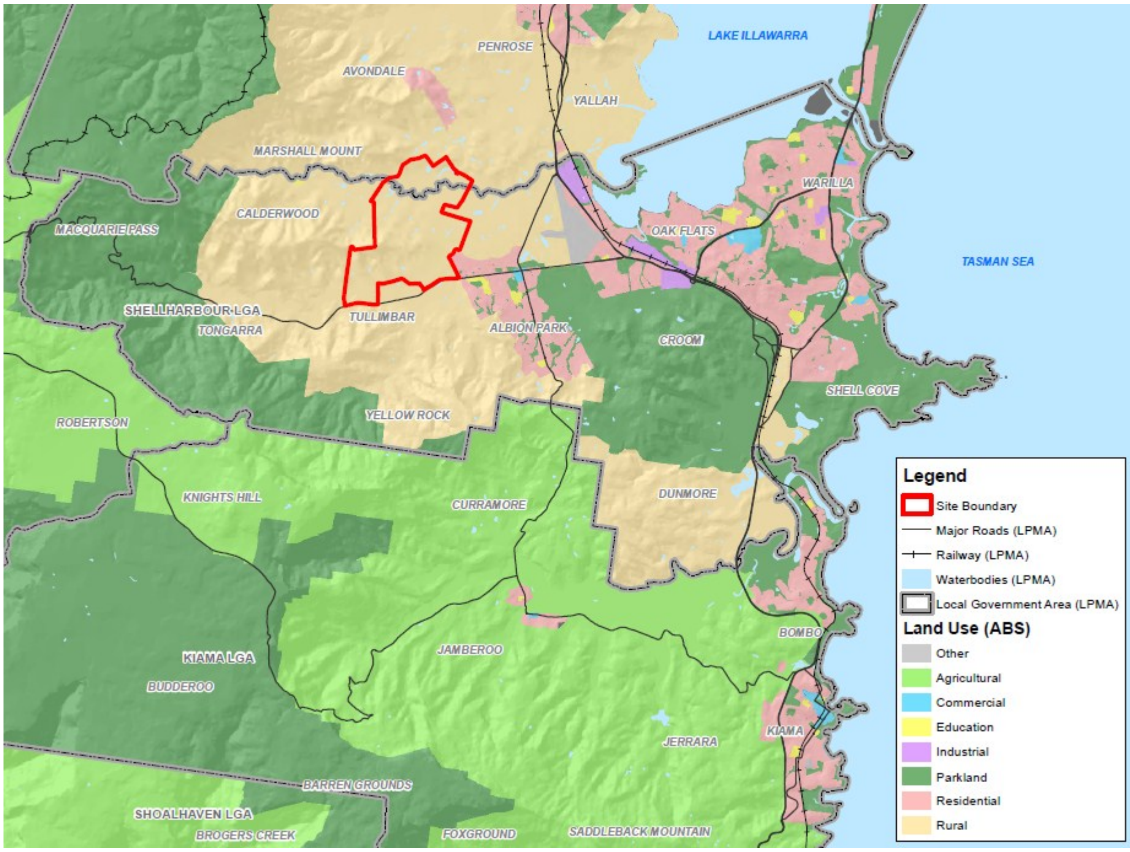

Figure 9.4: *Map illustrating the location of the proposed Calderwood development within the Macquarie Rivulet catchment (Delfin Lend Lease 2012).*

Previous research undertaken by Wollongong City Council (unpublished) has demonstrated that coal-wash emplacements can generate nitrogen-based species such as ammonia. As Lake Illawarra is nitrogen limited (WBM 2003), increased nitrogen levels entering the lagoon can result in environmental pollution and associated algal blooms. This is significant as current and proposed developments within the two studied catchments, and neighbouring catchments, intend to or have used coal-wash to fill lows and elevate flood vulnerable areas above the 1 in 100 year and PMF flood lines.

With respect to the Macquarie Rivulet study area an estimated 2,100,000 tonnes of coal-wash have been emplaced at the Haywards Bay residential development for either geotechnical preloading or as engineered fill (Ecoengineers 2012). In an effort to minimise the impact of the coal-wash on Lake Illawarra, Wollongong City Council specified the developers instigate a ground and surface water monitoring program.

Based on these conditions a network of piezometers was installed along several transects. Analysis of the Haywards Bay Water Quality Monitoring Program reports show a reduction in nitrogen species concentrations between the piezometers located near the emplacement and the lagoon's foreshore. However, data from piezometer OB5C-N (Figure 9.5) near the Haywards Bay foreshore may be compromised due to the presence of the Pleistocene high intersected in MR 15 and evident in Figure 6.1, section G-H. As the Pleistocene sediment is very fine-grained, compacted and impermeable it is likely to impede the movement of ground water along transect 5. As such the reduced ammonia levels detected in the piezometer may not be attributable to the nitrogen transformations as suggested by Ecoengineers (2012). Instead the values reflect nitrogen levels within the ground water table which is potentially influenced by Lake Illawarra waters due to the presence of permeable sediments between the shoreline and piezometer OB5C-N. This example demonstrates that a detailed understanding of the subsurface geology can assist in the development of effective environmental monitoring programs in deltaic environments or associated catchments.

9.4: Chapter summary

Predicting climate change implications is difficult due to the degree of uncertainty about how the climate will change/respond. However, based on the available information and an understanding of how the deltas have responded in the past to sea level change is likely to have the greatest influence on our predictions about the deltas' future evolution from a natural perspective. Despite the high modern sedimentation rates associated with both Macquarie Rivulet and Mullet/Hooka Creek deltas it is likely they will be inundated as the projected sea level increases. However, the presence of weirs up-stream of both deltas may be masking the potential sedimentation rate. If the weirs were removed or the sediment harvested and used to nourish the delta front or floodplains the deltas capacity to adapt to sea level rise may increase. Current predictions suggest rainfall intensities and wind patterns may be altered under a climate change scenario. Increased rainfall intensity and flooding may result in significant changes to the delta's morphology and sedimentation patterns. Altered wind patterns, as predicted, are likely to have minimal effect on the deltas' evolution.

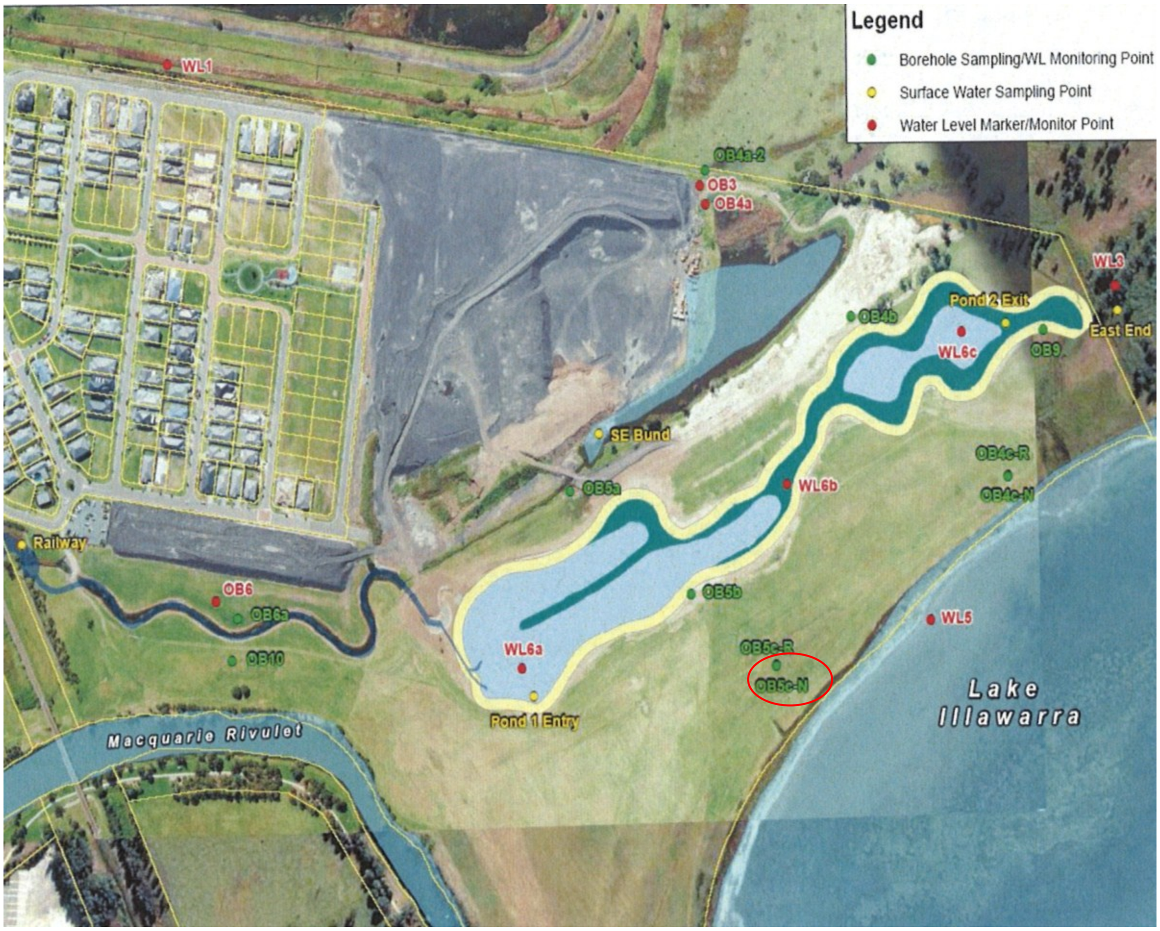

Figure 9.5: *Location of ground water monitoring transects at the Haywards Bay development site. The position of OB5C-N is circled in red (Ecoengineers 2012).*

Anthropogenic modifications within the catchments have contributed to and have directly caused significant morphological changes at the two deltas as demonstrated in Chapter 8. The impacts are also supported by modern sedimentation rates of up to 31.25 mm/year (MR 33, Table 4.6a). Future development proposed for the Macquarie Rivulet and Mullet/Hooka Creek deltas' catchments will inevitably have downstream impacts on the two deltas. A review of the planning documents associated with one of the proposed developments indicated that out-dated information was included in the report and factors such as climate change have not been considered. By excluding up-to-date information and not adequately addressing climate change implications, the capacity for decision makers to make fully informed decisions is restricted. This chapter has also illustrated that a greater understanding of the subsurface geology is required

when designing groundwater quality monitoring programs in deltaic environments to ensure the data collected are representative of what is occurring within the whole system.

Chapter 10

Thesis Synthesis and Conclusions

10.1: Introduction

The data presented in this thesis has addressed the five hypotheses outlined in Chapter 1 and reiterated below.

1. That the key evolutionary processes controlling the evolution of small scale bay-head deltas prograding into wave dominated barrier estuaries differs from the 14 key delta evolutionary processes as identified by Coleman and Wright (1975), Coleman (1976) and Coleman (1980). These difference are likely to reflect that the previously described processes were developed based on the analysis of mega/continental scale deltas typically prograding into open marine environments.

2. That the spatial resolution of deltaic studies impacts on the ability to identify and establish the sedimentological and morphological response to autocyclic, allocyclic and anthropogenic processes. Specifically, higher resolution studies are better placed to more accurately establish delta evolution during the Late Pleistocene and into the Holocene due to the complex interaction of key evolutionary processes.

3. That facies relationships in river dominated deltas is independent of scale.

4. That existing barrier estuary evolutionary models (i.e. Roy 1984, Dalrymple 1992 Roy *et al.*(2001 and Sloss *et al.*(2005, 2006a) are based on limited data from the fluvial/bay-head deltas (Zone C) and thus they do not adequately represent the evolution of bay-head deltas.

5. The rate of delta growth and morphological change has accelerated during the Anthropocene (post 1800s) in response to modification of the waterway and catchment, and that future growth will continue to be influenced by these modifications.

Specifically, this thesis has presented the findings of a detailed sedimentological and morphological investigation into the evolution of the Macquarie Rivulet and Mullet/Hooka Creek deltas, Lake Illawarra. These investigations have included a detailed subsurface coring program, photogrammetric assessments and interpretation of LiDAR data. Establishing the depositional timeframes of the various facies intersected was problematic. The key issues are summarised and discussed. This chapter also compares the evolution of the two deltas to each other. Based on the subsurface data a schematic facies model representing the Holocene evolution of the two deltas has been developed. The capacity for delta plan morphology to transition in response to process changes is also discussed. The final sections of the chapter provide a broad overview of the thesis discussing how the original research aims have been addressed.

10.2: Facies geochronology

This study has highlighted the difficulties in establishing the depositional timeframe for individual facies within deltaic environments. These difficulties arise for a range of complex reasons. This section discusses the key issues associated with the establishment of depositional timeframes identified within the study. The issues include the limited number of suitable dating techniques, a lack of specimens/samples suitable for dating within the various facies and the occurrence of age inversions/discrepancies. This section also synthetises and discusses the validity of ages which exceed previously published data.

A limited number of techniques were identified as suitable for the establishment of the deltas' geochronology. After assessing the various dating methodologies it was determined AAR would be the primary technique with ^{14}C utilised for comparative purposes and where AAR was deemed not to be suitable. The use of these two methods, particularly AAR restricted the variety of specimens which were suitable for analysis. Despite the capacity to obtain ages from floral and faunal samples the ^{14}C technique was also restrictive particularly in carbon depleted facies such as the fluvial sand facies. Furthermore, where ^{14}C was used as a comparative technique the study has shown that significant variances between the two ages can arise (Table 4.7). Where the

discrepancies were identified, it is likely they are indicative of an analytical/process error. The use of ^{210}Pb techniques was also restrictive as it could only be applied to recent sediments.

While establishing the methodology to be used, thermo luminescence and optically stimulated luminescence techniques were excluded as advice sought from proponents of these techniques suggested the resultant ages may be erroneous. Specifically, the proponents suggested the likely erroneous results would be attributable to uncertainties around bleaching of the quartz grains in these muddy environments. Despite the inability to utilise these techniques in this study, it presents an opportunity to investigate, in the future, these methodologies with a view to establishing a technique which would yield consistent and valid results. If this was to occur, the capacity to establish the geochronology of deltas would be enhanced, particularly in the facies which lack floral and faunal specimens.

One of the major barriers to establishing facies depositional timeframes was the limited number of specimens present and identified as suitable for geochronological analysis. Where cores contained specimens, a large number were disregarded due to their, often poor, physical condition. Typically, the disregarded specimens were disarticulated and/or abraded and/or showed signs of alteration. The disarticulated and abraded nature of the specimens suggested it was unlikely they were in situ and, therefore, any resultant ages would be questionable. Similarly, specimens displaying signs of alteration were disregarded as it was likely they too would have yielded erroneous ages if analysed. Further complicating the issue was that facies intersections in a large number of the cores contained no specimens at all. This was particularly evident in the distal delta and fluvial sand facies. The lack of specimens within these two facies is attributable to increased energy levels and reduced salinity levels limiting faunal diversity and populations. Furthermore, the high energy environments associated with these two facies often resulted in the specimens within the facies being fragmented as they were reworked during delta progradation.

Age inversions within individual cores can impede the establishment of an accurate geochronological record for the core and at a broader scale the facies. In this study age inversions were minimal when compared to the overlying age from the same core. The low number of inversions is likely to reflect the degree of care taken when selecting specimens to undergo analysis. Where inversions occurred it was at times possible to resolve the inversion if multiple ages were obtained from the same core. For example, in the case of MC 4, it was determined the age established for the articulate *Notospisula trigonella* at -3.24 m AHD was erroneous. This determination was based on the ages of the overlying and underlying specimens. However, where it is not possible to identify the erroneous age, care is required in the interpretation of the data and the provision for data exclusion when required.

A strong correlation typically existed between specimen derived ages utilising AAR and ^{14}C techniques (Table 4.7). However, analysis of a specimen in MC63 highlighted that variations between ages derived from the same specimen can differ when analysed using two different techniques. In this example the ^{14}C technique yielded an age of 6460±200 years BP whereas the AAR technique yielded an age of 8,010±60 years BP (Table 4.7). Comparative analysis of the derived ages (Figure 7.11) and ages derived from specimens in the same facies from other cores (MC 27, 29, 30, 45, 67 and 68) supported the AAR derived age. The discrepancy between the two ages may be due to an analytical processing error.

Age inversions/discrepancies identified in this study may have occurred due to one or a combination of:

- post-mortem specimen reworking;
- environmental factors affecting diagenesis; and
- errors within the analytical process.

By recognising the above factors it is possible to reduce the likelihood of age inversions occurring. Detailed visual analysis was the key strategy implemented in this study to minimise the risk of erroneous ages associated with post-mortem reworking. Typically,

the selected specimens were articulated bivalves with minimal signs of reworking such as abraded/damaged or discoloured valves. The use of this technique can also aid in the identification of specimens which may have been adversely affected by environmental factors, such as acidic ground water movements. Implications associated with diagenetic environmental factors were further reduced by implementing rigorous treatment strategies to ensure only fresh unaltered material was assessed. The use of highly regarded geochronology laboratories with tightly controlled processes would have significantly reduced the chance of the erroneous ages being attributable to errors within the analytical process. However, as the analytical processes require human intervention there still remains a chance of process error such as cross-contamination.

Several of the derived ages presented in Chapters 6 and 7 exceeded previously reported ages (Sloss *et al.* 2005, 2006a and 2007) from equivalent facies within the study area. For example, several of the derived ages for the prodelta/lagoonal mud facies from both Macquarie Rivulet and Mullet/Hooka Creek delta exceeded 7 ka (Table 4.6 a and b). Despite these ages exceeding the previously assumed age ranges, the articulate nature of the specimens analysed would suggest the specimens had undergone minimal reworking and, therefore, were likely to be in situ. These ages are further validated by ages derived from specimens in stratigraphically higher or lower positions within the same core (e.g. MC 20) or in other cores (e.g. MC 27, 29, 30, 45, 67 and 68). The increased facies age ranges, suggested in this study, are likely attributable to the higher spatial resolution when compared to previous studies such as Sloss (2005) and Sloss *et al.* (2005, 2006a and 2007). These ages also illustrate the dynamic nature of deltaic environments which can result in multiple depositional environments occurring simultaneously within close proximity to each other.

10.3: Evolutionary summary: Macquarie Rivulet and Mullet/Hooka Creek deltas

The high spatial resolution used in this study has enabled the Holocene evolution of the two deltas to be reconstructed and described with a high degree of certainty (Chapters 6, 7 and 8). The following section compares and contrasts the evolution of the two

deltas. It also discusses their evolution with regards to the estuarine evolution model propose by Sloss *et al.* (2005, 2006a).

During the late Pleistocene both study areas, including the future receiving basins, were subaerially exposed with the palaeo-Macquarie Rivulet and Mullet/Hooka Creek channels incising into the land surface as they flowed to the late Pleistocene shoreline (Figures 6.2, 7.2, 10.1 and 10.2). The resultant late Pleistocene morphology has played a significant role in the morphological evolution of both deltas. This was particularly evident during the initial infilling of the palaeoreceiving basin.

During the initial inundation phase the sedimentary record from both sites has preserved the near-shore muddy sand facies. This facies has been interpreted to represent palaeoshoreline deposits as described in Section 5.4. Derived facies ages from both sites range from the early to mid Holocene, suggesting an extended depositional timeframe with deposition initiated *ca 7.5 to 8 ka* across the basin. Despite the increased prevalence of the facies within the Macquarie Rivulet study area, the facies appears to thin in a westerly direction and displays a north-south orientation at both sites.

During this inundation phase preservation of the fining upwards regressive delta facies suggests the rate of sedimentation and vertical accretion was less than, or similar to, the rate of sea level rise. The preservation of the finer layers within the facies also suggests that energy levels near the western margin of the basin would have been relatively calm However, the occurrence of a calm environment is contrary to the higher energy levels which would be associated with open marine conditions that were suggested to occur during this timeframe in the evolutionary model of Sloss *et al.* (2005, 2006a). It is possible that the shallow depth to the antecedent Pleistocene barrier and overlying sediments, as discussed by Sloss (2001, 2005) and Sloss *et al.* (2005; Figure 1.4), and the accumulating Holocene barrier may have acted as a buffer limiting the influence of marine processes such as wave and tidal reworking. Hopley and Jones (2006) have also noted the presence of a presumed barrier/Pleistocene high can limit the extent of

marine influence on delta evolution. The presence of an antecedent Pleistocene barrier at shallow elevations has also been noted by Boyle (2004) for the Minnamurra estuary.

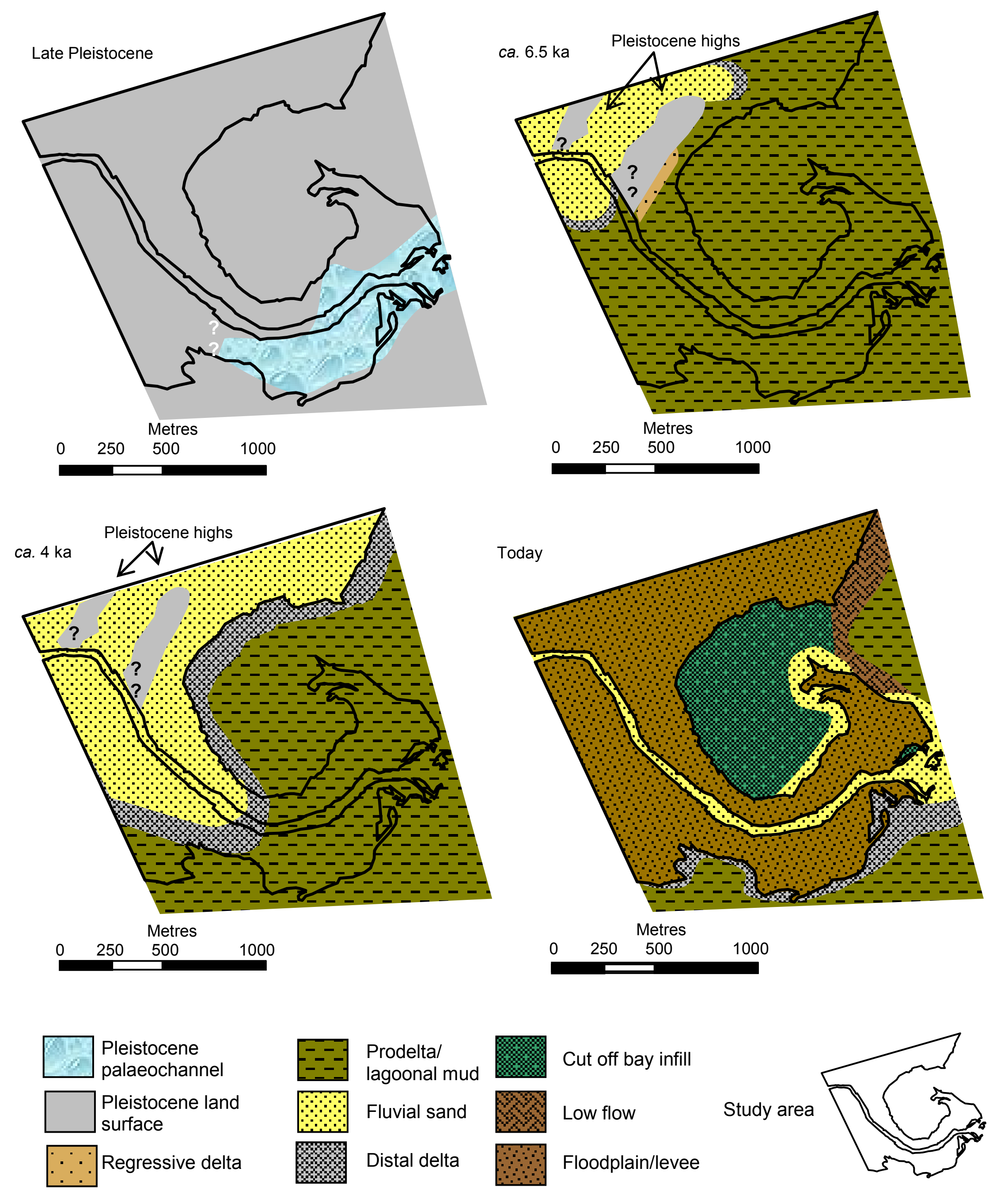

Figure 10.1: *Evolution summary model of the Macquarie Rivulet delta. Note the extent of the Pleistocene highs is indicative based on the available core data.*

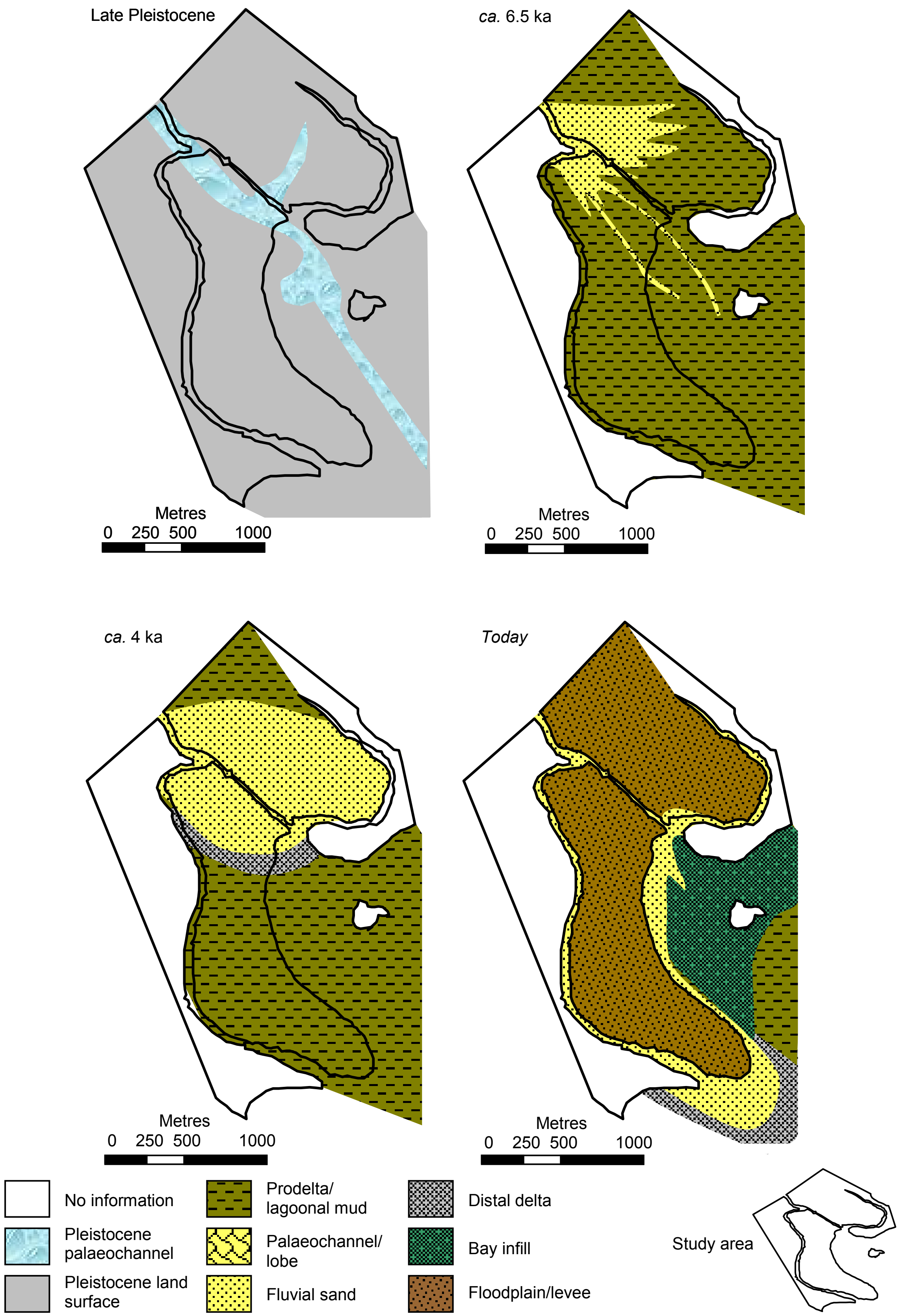

Figure 10.2: *Evolution summary model of the Mullet/Hooka Creek delta.*

Increased water levels within the receiving basin facilitated the deposition of the transgressive bay fill/back swamp facies in the northern section of the Mullet/Hooka Creek study area. The presence of the swamp facies in this locality reflects the protection afforded by Hooka Point which created a sheltered back embayment. The lack of material suitable for dating has prevented this study from defining a depositional timeframe based on geochronological data. Instead, super-positioning, relative to sea level and geochronological data from adjacent facies, suggests the facies was also deposited at *ca.* 7.5 to 8 ka. Sloss *et al.* (2007) suggested that water level within the basin at this time would have been at or close to its present elevation with the basin exposed to open marine conditions. However, as discussed above, the antecedent Pleistocene barrier and overlying sediments may have limited the influence of marine processes during this early evolutionary phase.

As sea level inundated deeper portions of the palaeoreceiving basin, deposition of the prodelta/lagoonal mud facies commenced (Figure 10.1 and 10.2). The frequency and thickness of the facies intersections declined in a westerly direction, unless the intersection was associated with the infilling of a low such as a Pleistocene palaeochannel. This pattern is to be expected as the minimum depth to the Pleistocene land surface, relative to AHD, decreases towards the west. Geochronological data presented in this thesis suggests deposition of the facies commenced *ca.* 7.5-8 ka. As discussed in Section 10.2 this depositional age is older than previously thought. However, the physical attributes of the specimens yielding these older ages and the relative sea level proposed by Sloss *et al.* (2007) also supports the potential for these ages to be accurate. These earlier ages also mean the estuarine evolutionary model proposed by Sloss *et al.* (2005, 2006a) needs to be modified to reflect these earlier than expected ages.

The limited number of palaeochannel intersections within the Macquarie Rivulet cores/drill holes (MR 21 and 22) suggest this delta's progradation was relatively stable with minimal avulsions occurring. This is contrary to the current morphology of the delta. In contrast several of the Mullet/Hooka Creek cores/drill holes intersected the

palaeochannel/lobe facies. The increased number of intersections within the Mullet/Hooka Creek study area has been interpreted to represent an actively avulsing delta, consistent with fluvial dominance (Figure 10.1). Furthermore, the basal facies intersections suggest the rate of sea level rise had slowed, enabling the delta to prograde (Section 7.2.3; Mullet/Hooka Creek sections C-D, G-H and K-L to Q-R, Figure 7.1). The capacity for the two deltas' morphologies to change with respect to process dominance is discussed in Section 10.6 and illustrated in Figures 10.1 and 10.2. The absence of specimens suitable for geochronological assessment within the Macquarie Rivulet channel intersections and the limited number within the Mullet/Hooka Creek channel intersections restricted the ability of this study to determine a definitive age for the commencement of channel deposition.

At both study sites the main fluvial phase of the deltas' evolution is marked by the distal delta facies which is, in turn, overlain by the fluvial facies (Figures 10.1 and 10.2). Geochronological data from the distal delta facies indicates fluvial activity within the delta may have commenced *ca.* 6 ka. Significantly, these ages are approximately 2,000 years older than the oldest age previously published by Sloss (2005) and Sloss *et al.* (2005) for the equivalent facies. These ages are also older than those reported by Hopley and Jones (2007) for the Wandandian Creek delta. The discrepancy between the previously published ages and the ages established in this study is likely to reflect the increased westerly extent of this study area, the increased spatial resolution of core/drill holes and the increased number of samples analysed from the facies.

The sea level regression, which commenced *ca.* 2, ka would have reduced the receiving basin's accommodation space. This reduction would have enabled the progradation rate of the two deltas to increase. Furthermore, the current plan morphology of the deltas, such as the Mullet Creek channel directional change discussed in Chapter 7, was also influenced and controlled by the sea level regression.

As discussed in Chapters 6 to 8 the influence of anthropogenic catchment modifications has accelerated the rate of delta progradation and, as such, altered the deltas'

morphological evolution. These alterations include, but are not limited to, the increased sedimentation rates changing the dominance of morphological processes and the diversion of sediments through the construction of channels through the floodplain (tank trap). These anthropogenic related changes seem to have had a greater influence on the deltas' evolution over the last 200 years than autocyclic processes.

Furthermore, during this later evolutionary phase the overall influence of the inherited morphology of the palaeoreceiving basin appears to have been negated. This reduced capacity is attributable to most of the palaeoreceiving basin's lows being infilled and flattened. Due to this reduced influence, the current morphology of the deltas reflects the relative dominance of physical processes, as expressed in Galloway's (1975) tripartite classification model (Section 2.4.1). In the case of Macquarie Rivulet, the delta is fluvially dominated as evidenced by its birdsfoot morphology which contrasts with the cuspate morphology of the wave-dominated Mullet Creek delta lobe. However, the predominantly subaqueous Hooka Creek lobe is likely to be fluvially dominated due to its sheltered location and the diversion of sediment from Mullet Creek, via the tank trap.

Typically the levee and floodplains attain higher elevations, relative to AHD, in the western portions of the study area decreasing towards the east (Figures 6.1, 7.1, 10.1 and 10.2). This resultant topography probably reflects the higher and more stable water levels during the mid Holocene enabling the deposition of thicker basal units facilitated by the increased depositional timeframes when compared to the more easterly deposits. The increased topographic elevation is also a likely reflection of the increased frequency of inundation attributable to flood events.

At both sites the floodplain morphology has been modified by both natural and anthropogenic processes. The shallow depressions evident in the high resolution LiDAR data typically relate to old creek channels which are typically active only during periods of high rain or flood (Figures 4.5, 4.7). Within the Macquarie Rivulet study area some of the natural channels have been altered to facilitate development and the management of leachate from fill emplacements (Figure 9.5). Furthermore, extensive portions of the

floodplain have been covered with fill to facilitate the Haywards Bay development. The largest floodplain modification within the Mullet/Hooka Creek study area was the construction of the tank trap. However, as with Macquarie Rivulet, portions of the floodplain have been filled to produce level surfaces. Filling of the delta's floodplain in this instance is predominantly associated with Fred Finch Park.

Predicting the future evolution of the deltas is complex and fraught with a large number of unknowns. Despite this, Figures 9.1 and 9.2 illustrate that significant portions of the deltas will be inundated if the sea level rise scenarios, as suggested by the NSW State Government, are realised. Furthermore, the information presented in this thesis has illustrated that the deltas' depositional environments have the capacity to respond quite rapidly to change, be they natural or anthropogenic. This rapid morphological response provides land managers with both an opportunity and a problem. If inappropriate management strategies are developed and implemented then the environmental health of the deltas will rapidly deteriorate and their vulnerability to climate change may increase. However, if appropriate land management strategies are developed and implemented based on a sound holistic understanding of these environments then the health of the deltas will be maintained and their capacity to adapt to climate change scenarios may be enhanced.

10.4: Holocene bay-head deltas: Evolutionary parameters

This study hypothesised that the key processes controlling the evolution of small scale bay-head deltas prograding into wave dominated barrier estuaries differs from the key delta evolutionary processes as identified by Coleman and Wright (1975), Coleman (1976) and Coleman (1980) for the large continental/mega deltas such as the Mississippi delta. The following section argues that some but not all of the parameters identified by Coleman and Wright (1975), Coleman (1976) and Coleman (1980) are applicable to the evolution of deltas such as the Macquarie Rivulet and Mullet/Hooka Creek deltas.

As discussed and illustrated in section 2.4, Coleman and Wright (1975) identified 400 parameters which they found to impacted on the evolution of deltas. However, the

research showed that of these only a small number of autocyclic and allocyclic processes/factors were significant. This previous research was based primarily on the evolution of larger scale deltas than those found prograding into ICOLS, such as Lake Illawarra. This section evaluates the applicability of the identified processes/factors as applied to the evolution of the small deltas studied here.

Colman and Wright (1975) and Coleman (1976) noted that climatic conditions within the catchment are probably the most significant natural factors affecting delta evolution. The climate influences factors such as wind and rain patterns and intensity, vegetation type and distribution along with the rate of erosion. Many of the associated climatic conditions described above are also influenced by the catchment relief, which in the case of the studied deltas is relatively steep as discussed in Chapter 3. In turn these factors combine to influence the discharge characteristics of the waterways supplying the deltas.

The influence of climate, catchment relief and river discharge as described by Coleman and Wright (1975) and Coleman (1976) is evident to various degrees within the studied deltas. The combination of catchment relief, rainfall patterns and the high erodability potential soils within the catchment has combined to influence the sedimentological characteristics of the deltas through the deposition of the flood deposit facies as evident in cores such as MC 34-36 (Appendix 5).

As discussed in Chapter 3 climatic conditions, particularly rainfall, within the study area are relatively stable throughout the year. This climatic stability has enabled the deltas to become hydrologically stable which has reduced the number of avulsions observed in the deltas. This finding is consistent with those of Coleman and Wright (1975) and Coleman (1976) who noted less frequent channel avulsion is likely to occur in rivers and deltas which are exposed to regular discharge patterns.

The research supports the notion that wind plays a significant role in the evolution of delta’s such as those studied. Both Macquarie Rivulet and the Mullet/Hooka Creek delta

have been shaped by wind generated waves to varied extents. This is particularly evident by the cuspate morphology of the Mullet/Hooka Creek delta (Figure 10.4). Additionally, early maps of Macquarie Rivulet (Figure 8.4) suggest its morphology at the time of initial European settlement was also consistent with that of a wave dominated delta. Despite the current fluvial dominated morphology associated with the modern Macquarie Rivulet delta it has also been influenced by wind waves, specifically, the hooked morphology associated with the present inactive northern distributary channel.

Coleman and Wright (1975) noted the significant role that receiving basin geometry and tectonic stability play in the evolution of deltas. However, none of the five types identified (Section 3.4.3.9) accurately reflect the geometry and tectonic setting of ICOLs/ barrier estuaries, such as Lake Illawarra, situated along the southeast coast of NSW. This omission from their findings most likely reflects the continental scale of the deltas they studied.

In the case of the Lake Illawarra, the receiving basin geometry has transitioned in response to the estuary's development through the Holocene. It is also important to note that the lake has formed in a tectonically stable area. As discussed in Chapter 1 the Lake Illawarra palaeoreceiving basin evolved during previous sea level lowstands and is characterised by a relatively flat bottom dissected by palaeochannels (Roy and Peat 1974, 1975; Sloss *et al.* 2005). During this phase of the estuary's development it is likely oceanic processes would have had an influence on the deltas' evolution. However, the presence of the remnant Pleistocene barrier at shallow depths overlain by a developing Holocene barrier (Sloss 2004, 2005) would have limited the impact of marine processes, particularly wave action. Furthermore, the influence of marine processes would have decreased still further as the Holocene barrier rapidly developed enclosing the lake and altering the basin's geometry.

Based on the above, a new receiving basin geometry is proposed. This new geometry is defined as a transitional geometry and reflects the capacity for the receiving basin geometry to evolve from an open ended geometry to an enclosed geometry in response

to the development of a barrier or similar topographic feature. The morphological implications of the transitional receiving basin geometry on the evolution of the Macquarie Rivulet and Mullet/Hooka Creek deltas have been discussed in Chapters 6 and 7. These morphological factors are likely to be applicable to other ICOLs, barrier estuaries or coastal lagoons evolving in a tectonically stable environments in Australia or internationally.

The combined effect of processes/factors identified by Coleman and Wright (1975) which operate at the point of interaction between the inflowing water and the receiving basin significantly influenced the evolution of the deltas studied. At both study sites hypopycnal flow conditions appear to operate due to the deposition of coarse material proximal to the shoreline with the finer fraction being transported in suspension and deposited in the lagoon's central basin. These flow conditions are also supported by the sedimentary and morphological characteristics of the mouth bars developing at the current mouth of the Macquarie Rivulet delta.

Coleman and Wright (1975) noted three main channel morphologies exist within deltaic environments as discussed in Chapter 2 and illustrated in Figure 3.15. The Macquarie Rivulet delta displays a bifurcating channel morphology typically associated with fluvial dominated systems. Coleman and Wright (1975) noted bifurcated channels develop in areas associated with high rates of subsidence, low wave energy, small tidal range, low offshore slope and finer grained sediment. The results of this study generally agree with the above factors, however, it has been shown these channel morphologies can occur where the sediment load contains a significant coarse fraction and subsidence is not occurring. In contrast, the Mullet/Hooka Creek delta displays a morphology consistent with a single channel delta.

Coleman and Wright (1975) and Reading and Collinson (1996) both noted that marine processes influence significant control over the evolution of deltas. However, as discussed in Chapters 6 and 7 the overall influence of these processes on the evolution of the deltas is likely to have been limited when compared to deltas such as the

Mississippi, one of the deltas used to identify the processes. In the case of Lake Illawarra the remnant Pleistocene barrier and developing Holocene barrier during the early Holocene would have acted to provide a buffer limiting the ingress of waves and tides. As the barrier continued to develop the marine influences would have further decreased. The lack of marine influence on the evolution of the studied deltas is supported by the absence of any tidal related sedimentary structures within the 147 cores.

Coleman and Wright (1975) and Coleman (1976) did not identify the potential for anthropogenic modification of the deltas and their catchments to affect their evolution. However, Fanos (1995) on the Nile delta, Day *et al* (1997) on the Mississippi delta, Li *et al.* (2006) on the Red River delta, El Banna and Frithy (2009) on the Nile delta, Gu *et al.* (2011) on the Yangtze River delta and Fatoric and Chelleri (2012) on the Ebro delta have demonstrated the morphological implications of anthropogenic modification on deltas. As with these studies the research presented in this thesis demonstrates that anthropogenic related changes do indeed have the capacity to significantly alter the evolutionary trajectory of smaller bay-head deltas in the same way as it has on the larger scale deltas. In the case of Macquarie Rivulet the delta has increased by approximately 15 ha between 1892 and 2006 (Table 8.1) resulting in the deltas morphology transitioning from a wave dominated delta to a fluvial dominated delta. Much of this growth has been linked to anthropogenic modifications within the catchment such as land clearing, agriculture and urban development. It is also important to note the deltas growth may have been greater if it was not for the presence of a weir upstream from the study area. The presence of the weir is likely to be limiting the amount of coarser material being transported as bed or saltating load from reaching the delta front. The research has also illustrated that construction of the tank trap in the 1940’s significantly altered the morphology of the Mullet/Hooka Creek delta. This anthropogenic modification has resulted in the main Mullet Creek channel being essentially bypassed with the majority of sediment now being transported through the tank trap and deposited in Koong Burry Bay. This diversion of sediment reflects the increased hydraulic gradient afforded by the shortening of Mullet Creek. These

examples highlight the need to incorporate anthropogenic related factors when evaluating bay-head delta evolution, particularly in areas where the catchments or the deltas have experienced anthropogenic modification.

10.5: Holocene bay-head deltas: Models of evolution

Bay-head deltas are dynamic, rapidly evolving features forming at the fluvial aquatic interface. Due to this, deltas are exposed to both fluvial and aquatic processes that may include floods, wind-waves, tides, sea level fluctuations and anthropogenic modifications. These complex interactions lead to the development of a significant number of depositional environments characterised by distinct facies architecture and stratigraphic position/succession. Typically these relationships are represented through the development of stylised stratigraphic columns, sections and evolutionary models. This thesis tested the hypothesis that the existing estuary evolutionary models do not adequately represent the evolution of bay-head deltas. Examples of wave-dominated barrier estuary evolutionary models include those developed by Roy (1984), Dalrymple *et al*. (1992, Figure 3.7), Roy *et al.* (2001, Figure 3.6) and Sloss *et al.* (2005, 2006a, Figure 3.7). Despite the existence of these columns, sections and models the research presented in this thesis has demonstrated these models are focussed on the broader evolution of the estuary, not specific to the evolution of bay-head deltas and therefore lack the detail to adequately represent the complex evolution of the deltaic features. As such a revised estuarine evolution model and a new delta evolutionary model are proposed.

With respect to deltas, authors such as Coleman and Gagliano (1965), Coleman and Wright (1975), Galloway (1975), Coleman (1980), Coleman (1984), Bhattacharya and Walker (1992), Nichol *et al.* (1997), Correggiari *et al.* (2005), Gani and Bhattacharya (2005), Kulp *et al.* (2005) among others have produced numerous section diagrams, detailed stratigraphic logs and proposed deltaic evolutionary models. These models have been based on studies into the evolution of larger deltas such as the Hawkesbury, Klang, Mississippi, Sao Francisco, Po and Senigal deltas, which have been and continue to be directly influenced by marine processes such as tides and/or ocean waves.

Broadly, the facies relationships within these large scale deltas are similar to that of the smaller bay-head deltas studied. Specifically, these smaller deltas display the broad facies distributions associated with Gilbert/fluvial style deltas as illustrated in Figure 3.10. However, internal facies architecture differs between the larger and smaller deltas. This variability reflects the differing evolutionary parameters as discussed in Section 10.4. As such the existing models do not adequately represent the morphological and stratigraphic evolution of smaller bay-head deltas prograding into shallow calm environments such as Lake Illawarra.

As mentioned in Chapter 3, Dalrymple *et al.* (1992) noted these deltaic and estuarine models suggest that the spatial distribution of facies is predictable. However, this study does not agree with this statement and suggests that previously proposed models do not adequately represent the evolutionary complexities associated with bay-head delta evolution. An increased understanding of these facies and their stratigraphic relationships can aid in palaeoenvironmental reconstructions. Furthermore, this information can assist with the development of knowledge about how these systems will respond to future autocyclic/allocyclic processes and anthropogenic impacts. The following sections present revised models based on the findings presented in this thesis.

10.5.1: A stratigraphic facies model

Previously published delta stratigraphic columns, sections and evolutionary models have mainly been derived from studies analysing larger deltas which are influenced by marine processes. One of the key features within all of these models is the presence of sedimentary structures attributable to tidal movements, e.g. Coleman and Gagliano (1965; Mississippi River delta) and Nichol (1997; Hawkesbury River delta). The resultant tidal current activity within these systems facilitates the formation and preservation of sedimentary structures such as ripples and plane lamination as a feature of the sediment instability. Significantly, Dalrymple *et al.* (1992) also suggested the presence or absence of tidal structures distinguished bay-head delta sediments from fluvial sediment. However, the depositional conditions with a calm wave-dominated barrier estuary differ greatly to those of the deltas mentioned above. In the case of a wave-

dominated barrier estuary the tidal influences are greatly reduced if not negated. For example, in Lake Illawarra the tidal range at the bay-head deltas is less than 50 mm when the entrance is open, reducing to zero when the entrance is closed. Typically, the only time these deltas will be exposed to current activity would be as the result of high rainfall flood events. The calmer environment means deposited sediments are more stable, which is not conducive for the formation of current/tidal based sedimentary structures. Furthermore, the increased sediment stability provides a greater opportunity for faunal colonisation (Figure 5.10) and subsequent bioturbation (Figure 5.8). This increased rate of bioturbation destroys most laminations and/or sedimentary structures which may have formed. As such there is a need to develop a stratigraphic facies model which reflects these environmental conditions.

In Lake Illawarra high resolution analysis of 147 cores from the bay-head deltas (Volume 2, Appendix 4, 5) has resulted in the identification of ten main facies/facies associations, three minor facies and two imported units (Sections 5.3 to 5.13). It is noteworthy that no single core analysed contained all, or even most, of the facies/facies associations identified. The lack of a representative core is directly attributable to the large number of depositional settings associated with fluvio-deltaic environments.

Figure 10.3 is a stratigraphic model developed based on the facies intersected in the Macquarie Rivulet and Mullet/Hooka Creek study sites. The figure illustrates relative grain size and the stratigraphic relationships of individual facies. Vertical thicknesses represented in Figure 10.3 are indicative only as the observed in-core thicknesses of the facies are highly variable. Due to the number of facies/facies associations identified, several with overlapping stratigraphic relationships, it was necessary to illustrate the stratigraphic relationships on two separate logs. The most frequently encountered facies/facies associations are illustrated in the left hand log; whereas facies/units illustrated in the right hand log can be substituted for, or added to, those in the left hand log.

Sea level variations throughout the Quaternary at a local and global level are well documented and discussed in Chapter 2 of this thesis. During sea level low stands, deltas prograde towards the newly established shoreline, whereas when sea level increases deltas are drowned and regress, with delta progradation resuming during periods of stable sea level (Sutter 1994). Architecture and stratigraphic relationships of the basal facies, illustrated in Figure 10.3 are consistent with those previously described by Sloss *et al.* (2004, 2005, 2006a) and those in the basal facies of the Wandandian Creek delta (located approximately 100 km south of the study sites) described by Hopley and Jones (2007).

The basal facies is overlain by either the near shore muddy sand facies or the regressive delta facies (Figure 10.3). However, in MC 10 the reworked transgressive (near-shore muddy sand) facies is overlain by the regressive delta facies. These two deposits mark the transition from a subaerially exposed land surface to a subaqueous fluvio-deltaic/estuarine environment associated with Holocene sedimentation. Sutter (1994) noted the presence of similar regressive delta deposits at the base of the Mississippi delta. The Cretaceous Dunvegan Formation in Alberta (Bhattacharya and Walker 1991) and Ferron Sandstone Member in Utah (Ryer 1981) contain examples of regressive deposits formed due to previous sea level rises and or subsidence of the delta lobes. Equivalent transitional facies have been identified by Nichol *et al.* (1997) within cores taken from the upper reaches of the Hawkesbury River. In their study the transition was marked by aggraded fluvial deposits underlying a transgressive bay-head delta and mud facies, which is equivalent to the overlying prodelta/lagoonal mud facies in this study.

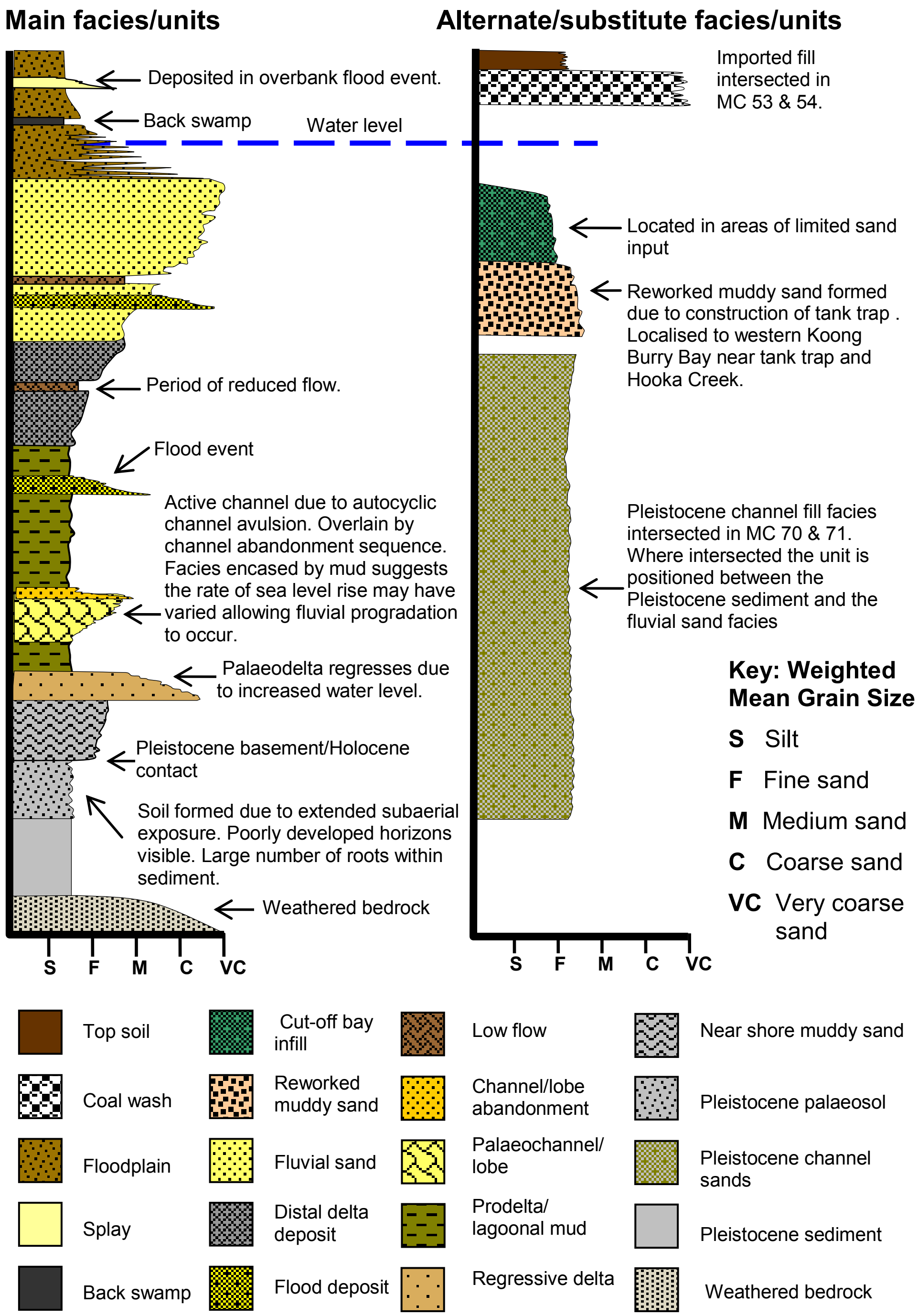

Figure 10.3: *Stylised stratigraphic log showing the stratigraphic relationship between sedimentary facies/units based on analysis of 147 cores from Macquarie Rivulet and Mullet/Hooka Creek deltas. Alternate facies/units can be inserted in place of main facies/units at equivalent vertical elevations on scale. No vertical scale is indicated due to variable facies/unis thicknesses in individual cores.*

Significantly, previous studies into the evolution of Lake Illawarra and its deltas (Sloss *et al.* 2005, 2006a) failed to identify this facies. This is attributable to the broader focus of their studies which decreased the resolution of their assessment of the deltaic environments. For example, the previous studies derived Mullet/Hooka Creek delta's facies architecture and stratigraphic relationships based on the analysis of seven cores as compared to the 73 cores in this study.

The overlying prodelta/lagoonal mud facies (Figure 10.3) is characterised by a marked decrease in grain size. The observed decrease in grain size is attributable to an increased water level within the receiving basin. Facies with similar sedimentological/stratigraphic characteristics have been observed and described both locally (Shoalhaven River: *Umitsu et al.* 2001; and Minnamurra estuary: Panayotou *et al.* 2007) and globally (Mackenzie delta: Hill *et al.* 2001; and Volga delta: Overeem *et al.* 2003). Within the basal portion of this facies, palaeochannel and channel abandonment facies were intersected (e.g. Mullet/Hooka Creek sections C-D, G-H and K-L to Q-R, Figure 7.1). The presence of the palaeochannel/lobe facies suggests the rate of sea level rise may have slowed/paused enabling the delta to briefly prograde prior to the rate increasing again resulting in the delta being drowned and continue to regressing. The presence of this initial fluvial phase encased in prodelta/lagoonal mud within the Mullet/Hooka Creek study area was also identified by Sloss *et al.* (2005).

Deltaic facies models often oversimplify the transition from estuarine to fluvial-dominated environments representing the facies as a continuous coarsening upwards sequence referred to as the delta slope facies. However, this research has increased the resolution by subdividing the fluvial delta slope facies into distal (distal delta Section 5.9) and proximal facies (fluvial Section 5.10). Additional units identified in this study included finer grained low flow and flood deposits which are characterised by a coarse base which then fines upwards. Although the overall facies coarsens upwards the presence of the low flow and flood deposits results in the facies being characterised by a saw-tooth like grain size distribution as evidenced in Figure 5.14.

As previously noted, Dalrymple *et al.* (1992) indicated that bay-head delta facies are distinguished from true fluvial sediments based on the presence of tidal structures and/or brackish-water fauna, such as those identified by Coleman and Gagliano (1965) for the Mississippi delta and Nichol *et al.* (1997) for the Hawkesbury River estuary. However, analysis of the 147 cores, which informed this study, does not support this. Specifically, the two main fluvial influenced facies, the distal delta and fluvial facies, identified in this study lack tidal structures. Furthermore, previous studies which have established the evolution of bay-head deltas within wave-dominated barrier estuaries, such as Hopley and Jones (2006), Sloss *et al.* (2005, 2006a, 2006b) and Panayotou *et al.* (2007), did not note the presence of tidal structures within any of the fluvial influenced facies. The lack of tidal structures within these wave-dominated barrier estuaries is attributable to the presence of a barrier and a restricted or closed entrance channel limiting tidal reworking of deposited sediments. As such the definition proposed by Dalrymple *et al.* (1992) cannot be universally applied when identifying facies associated with the progradation of bay-head deltas.

The overlying floodplain/levee facies illustrated in Figure 10.3 is characterised by an overall fining upwards trend consistent with comparable facies successions proposed by authors including Coleman and Wright (1975) and Hill *et al.* (2001). The basal sedimentological profile of the facies is highly irregular, taking on a saw-tooth like appearance. The irregularities are attributable to the subaqueous to subaerial transitional nature of the facies base. Once subaerial exposure has occurred the facies sedimentary profile is more stable/consistent up section as floodplain depositional processes, such as overbank vertical accretion replace in-channel processes. However, some overbank events can result in the deposition of splay deposits. Proximal splays are readily distinguished by their sharp erosional base, coarser grain size and fining-up profile. The more distal splays are harder to distinguish due to energy dissipation across the floodplain and reduced grain size.

10.5.2: Holocene barrier estuary and delta evolutionary models

The results of this study indicate that the existing conceptual models of barrier estuary evolution, as proposed by Roy (1984), Dalrymple *et al*. (1992, Figure 3.7), Roy *et al.* (2001, Figure 3.6) and Sloss *et al.* (2005, 2006a, Figure 3.7) and discussed in Chapter 3, do not adequately represent the complex facies relationships associated with the evolution of bay-head deltas. The two key issues identified while completing this study include the lack of current-generated sedimentary structures within the fluvial zone and the timing of delta progradation. These observed gaps within the existing models are likely to reflect the broad nature of previous studies into estuarine evolution, such as Roy (1984), Dalrymple *et al*. (1992), Roy *et al.* (2001), Sloss (2005) and Sloss *et al.* (2005, 2006a), which have been used to construct the models. Furthermore, as discussed in Chapter 3 Section 3.5 there are a limited number of studies which have addressed the evolution of bay-head deltas prograding into the wave-dominated barrier estuaries along the southeastern coast of Australia. It is important to note that these studies have all addressed the evolution to various degrees but have been focused on the spatial distribution of delta facies rather than the internal structure of the delta system. By adopting such a broad approach it is not possible to accurately capture and represent the complexities of bay-head delta evolution. However, the high spatial resolution of this study (Chapters 5-7) has enabled development of a revised estuary evolutionary model. The revised model provides additional detail within the fluvial zone. The additional detail, regarding bay-head delta evolution, presented in this study, enabled the development of a specific model representing the evolution of bay-head deltas prograding into a broad and shallow wave-dominated barrier estuary such as Lake Illawarra.

The following discussion compares the proposed model to the model published by Sloss *et al.* (2005, 2006a) as this latter model incorporates the Roy (1984) and Roy *et al.* (2001) models. Stage 1a of the Sloss *et al.* (2005, 2006a) model indicates that the antecedent Pleistocene land surface is overlain by a continuous muddy marine transgressive sand sheet in the western portion of the study area. However, this study suggests this transgressive marine sand sheet is not as extensive as previously

suggested. Stage 1 of the revised model (Figure 10.4) includes the presence of an underlying Pleistocene high/barrier across the mouth of the estuary. The Pleistocene barrier is included as it would have reduced the influence of marine processes, such as waves, within the estuary. The presence of underlying highs/barriers has been documented or inferred for Minnamurra (Boyle 2004, Panayotou 2007), Lake Illawarra (Sloss 2005), Burrill Lake (Sloss *et al.* 2006b) and St Georges Basin (Hopley and Jones 2006). Furthermore, such a barrier is included in the tripartite zonation model proposed by Dalrymple et al. (1992, Figure 3.7). The revised model (Figure 10.4) indicates the western margin of the estuary is characterised by a discontinuous near-shore muddy sand unit overlying the Pleistocene land surface. This revision to the model is also supported by the results published by Hopley and Jones (2006) and Sloss *et al.* (2010) which failed to intersect the transgressive marine sand sheet, as proposed by Sloss *et al.* (2005, 2006a), in the inner part of the embayment. Additionally, the revised stage 1 includes the presence of a regressive delta facies which was found to occupy the topographic lows created by Pleistocene palaeochannels during previous sea level low stands.

Ages derived from the prodelta/lagoonal mud facies indicates deposition commenced earlier than previously published (Table 4.6, 4.7). This combined with the calm environment required for the deposition of the facies tends to indicate that the influence of marine process was further restricted by *ca.* 6.5 ka, approximately 1,500 years earlier than previously published (Sloss *et al.* 2005). This earlier age is also in agreement with the data presented by Nichol (1991a) who indicated basin sedimentation commenced within Wapengo Lagoon 6,500 years ago. Based on this the accompanying text of the model has been amended to reflect the increased influence of the barrier with respect to restricting marine influences (Figure 10.4). The inclusion of bay-head delta progradation during stage 2 (Figure 10.4) is one of the most significant revisions made. This revision is based on the geochronological data presented in this thesis (Table 4.6, 4.7 and discussed in Chapters 6 and 7) which indicates fluvial progradation commenced *ca.* 6.5 ka during the Holocene high stand.

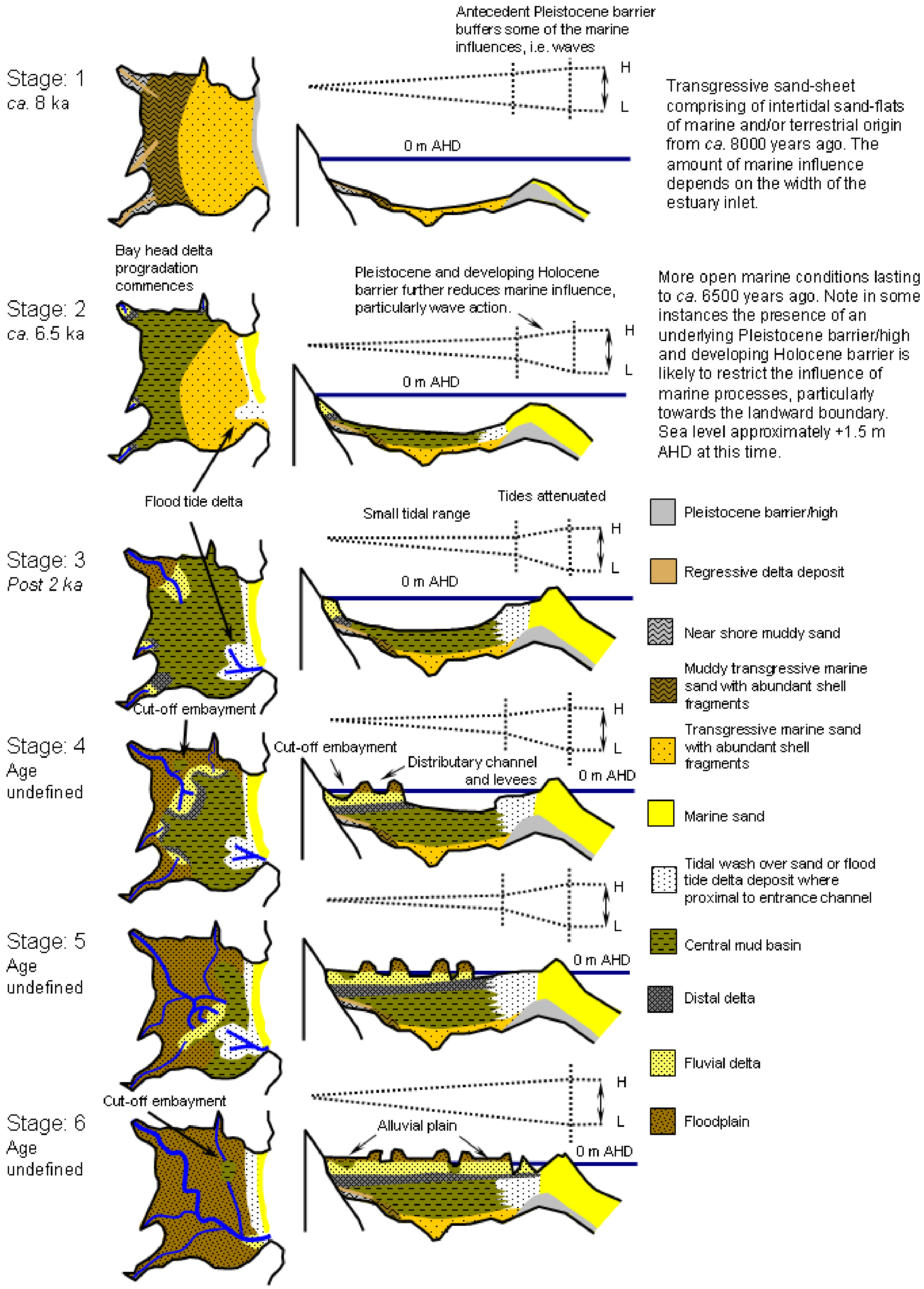

Figure 10.4: *Revised barrier estuary evolutionary model. Dashed line represents tidal range. Stages 1 and 2 based on Sloss* et al. *(2005, 2006a) where as stages 3-6 based on Roy (1984) and Roy* et al. *(2001).*

Stages 3-6 of the revised model (Figure 10.4) are relatively unchanged from that proposed by Sloss *et al.* (2005, 2006a). The revisions, other than those discussed for stages 1 and 2, include the development of cut-off embayments at a more youthful stage of infill, as previously discussed by Hopley and Jones (2006), and the inclusion of multiple deltas infilling the receiving basin simultaneously. Unlike the earlier evolutionary stages it is not possible to assign fixed age ranges to stages 3 to 6. This inability reflects the high variability in the rate of delta progradation and associated estuarine infill. For example, the Minnamurra and Shoalhaven River deltas have completely in filled their respective receiving basins, whereas it will be a considerable amount of time (about 1000-1500 years), based on the geochronological results from this study, before the Macquarie Rivulet and Mullet/Hooka Creek deltas will infill Lake Illawarra. Note this does not include climate change and anthropogenic implications which may or may not increase the rate of infill. Furthermore, the time it will take for the deltas to infill the lake may be extended under a sea level rise scenario as the accommodation space within the receiving basin will increase.

Despite the revisions made to the wave-dominated barrier estuary evolution and zonation model, described and illustrated above, it still lacks the resolution required to illustrate the complexities of Holocene bay-head delta evolution. As such, a new bay-head delta evolutionary model (Figure 10.5) is proposed which addresses the Holocene evolution of bay-head deltas. Note this model only represents the landward margin of the estuaries. And thus should be viewed in conjunction with the revised barrier estuary evolutionary model (Figure 10.4). The proposed bay head delta model is based on the high resolution data set presented in this thesis while incorporating the results from the previous studies addressing bay-head delta evolution including Bradshaw (1987), Nichol (1991a), Umitsu (2001), Boyle (2004), Hopley (2004), Hopley and Jones (2006), Sloss *et al.* (2005, 2006a, 2006b) and Panayotou (2007).

During the Late Pleistocene low stand waterways flowing across the antecedent land surface resulted in the formation incised channels (Stage 1, Figure 10.5). As with modern fluvial systems these channels appear to have migrated across the floodplains and are

infilled with fluvial sediments of varied grain size, angularity and composition. In some instances the presence of bedrock highs would have influenced the degree and direction of channel migration during the low stand period. Furthermore, the presence of extensive root traces and rudimentary soils suggests the channel margins would have been vegetated. The resultant Late Pleistocene topography represents the basement over which the estuarine and deltaic facies have subsequently been deposited.

During the second stage of the evolutionary phase the inherited morphology of the receiving basin would have influenced facies distributions. In some instances deltas were able to regress in response to the Late Pleistocene Early Holocene transgressive event (Figure 10.5). These deposits typically fine upward and are characterised by subrounded relatively clean very coarse-grained sand to clean fine- to medium-grained sand at the base of the facies grading upwards into muddy fine-grained sand to very muddy very fine-grained sand. Where intersected the facies typically occupied topographic lows. However, these deposits will only occur where sedimentation rates are able to keep pace with the rate of sea level rise.

As sea level increased the discontinuous near-shore muddy sand facies was laid down. This facies represents the interaction between inflowing fluvial waters transporting terrestrially derived sediments and organic matter combining and depositing them in an estuarine environment. Although the research has not shown this it is assumed this near-shore facies would grade into the transgressive marine sand sheet away from the shoreline.

The transgressive bay-fill facies can be found directly overlying the Pleistocene land surface. These deposits are likely to be found in sheltered areas such as behind bed rock highs where the finer sediments could settle out of suspension. Furthermore, the remnant Pleistocene barrier and developing Holocene barrier would have limited the extent of marine influence, further decreasing energy levels across the basin.

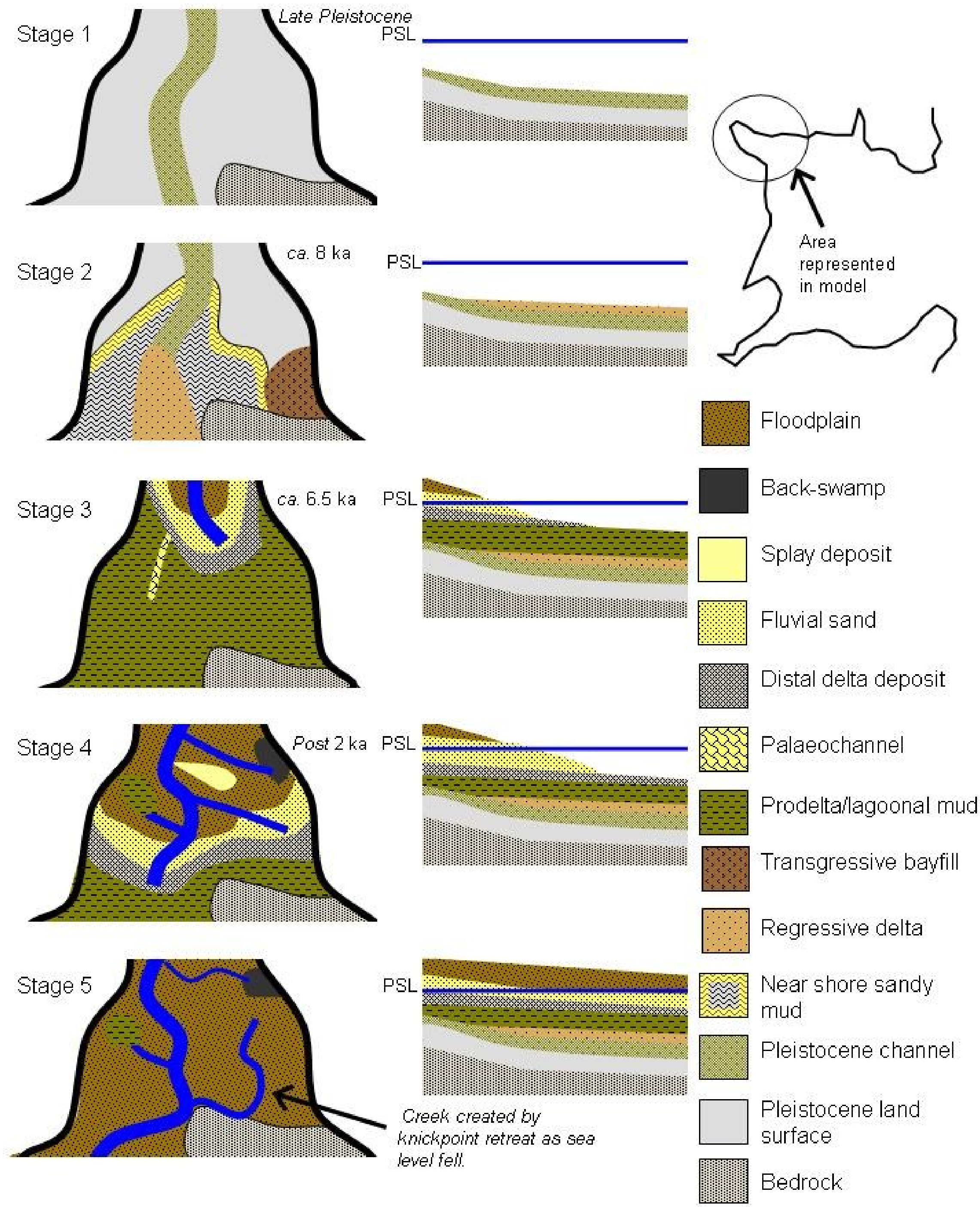

Figure 10.5: *A five stage conceptual model the evolution of bay-head deltas from the Late Pleistocene through to the present. Note the model is intended to be viewed together with the revised barrier estuary evolution model illustrated in Figure 10.4.*

By approximately 6,500 years ago sea level had stabilised around 1.5 m AHD (Lewis *et al.* (2012). The increased water depth within the receiving basin combined with continued development of the Holocene barrier further restricted the influence of marine related processes. The resultant calm environment enabled the deposition of the prodelta/lagoonal mud in the deeper portions of the basin (Stage 3, Figure 10.5). Sediment accretion within the basin during this evolutionary phase would have reduced the influence of the inherited basin morphology on the deltas evolution. Furthermore, stabilisation of water levels within the basin enabled the deposition of the coarsening upwards distal delta and fluvial sand facies, both of which are associated with delta progradation. These facies are in turn overlain by the floodplain/levee sequence. Due to the elevated water levels during the mid-late Holocene these facies can be intersected at elevations greater than present sea level.

Since 2 ka, as sea level gradually fell to its current position (Lewis *et al.* 2012), the rate of delta progradation is likely to have increased due to a reduction in accommodation space within the receiving basin. Stage 4-5 of the model (Figure 10.5) represents how the bay-head deltas have responded to this fall in relative sea level. However, as with Stage 3 to 6 of the estuary evolution model (Figure 10.4) the rate of progression from Stage 4 to 5 of the bay-head delta evolution model cannot be accurately defined as some bay-head deltas have infilled their respective receiving basin (e.g. Shoalhaven River) and it will be a considerable amount of time before others reach the same degree of maturity (e.g. Macquarie Rivulet, Mullet/Hooka Creek and Wandandian Creek deltas).

As evident in both the plan and sectional diagrams, the facies relationships during Stages 4 and 5 are consistent with Stage 3 of the model in that the basic sequence consists of prodelta/lagoonal mud at the base which is then subsequently overlain by distal delta, fluvial sand and floodplain/levee deposits. As a result of the falling sea level the facies tend to dip slight seaward slightly. During these stages, particularly Stage 4 of the model the rate of channel avulsion and meandering was likely to have increased as the channels adjusted their hydraulic geometry and gradients in response to the

reducing sea level. These continual channel adjustments resulted in the formation of cut-off embayments and backswamps. The decreasing sea level during these later evolutionary stages also contributed to the development of knickpoints which cut in an upstream direction to form small channels such as Hooka Creek, Lake Illawarra.

As presented in previous Chapters the morphology of bay-head deltas reflects the ratio between fluvial, tidal and wave dominance. Due to the large number of end member morphologies, combined with the capacity for bay-head delta morphology to transition from one type to another, it was not practical to incorporate this into the proposed bay-head delta evolutionary model. Despite this omission from the model it still provides a robust overview of the general evolutionary path that bay-head deltas have followed throughout the Holocene.

10.6: Transitional deltas

Deltas are typically classified based on their planform morphology which is attributable to the relative prevalence of tide, wave or fluvial processes. As such deltas are broadly classified into tidal, wave or fluvial deltas. However, this morphological classification typically only describes the deltas current morphology and does not recognise the capacity for deltas to transition from one type to another. This section discusses the concept of transitional deltas based on the results from this study.

The modern Macquarie Rivulet delta is classified as a fluvially dominated birdsfoot delta, similar to the Mississippi (Galloway 1975; Coleman and Wright 1975; Bhattacharya and Walker 1992), Volga (Overeem 2003) and Po (Syvitski and Saito 2007) deltas. These highly constructive deltas form where there is a relatively large sediment supply and calm depositional environment. However, the high resolution sedimentological and photometric analysis of the Macquarie Rivulet site, discussed in Chapters six and eight, indicates the processes controlling the deltas morphology have changed during this latest (Holocene) progradation phase.

As discussed in Section 6.2.1 and illustrated in Figure 6.4 initial delta progradation would have been influenced by the inherited morphology of the receiving basin. The presence of a single main channel dissecting the Pleistocene land surface would have impeded the delta's capacity to avulse and develop the birdsfoot morphology associated with the modern delta. This limited capacity to avulse is also evidenced by the limited number of palaeochannel/lobe facies intersections. As such it is likely the delta's morphology was initially influenced by wind-waves rather than fluvial processes. This is also supported by the cuspate morphology illustrated in Figure 8.4a, a sketch map from 1834.

Since 1834 catchment modifications such as land clearing and development have increased the amount of sediment transported by Macquarie Rivulet to the delta front. Increased sedimentation at the delta front has resulted in the morphological evolution process transitioning from wave to fluvial dominance as evidenced by Figures 8.4 to 8.7. The transition was also aided by the delta's progradation into a deeper portion of the palaeoreceiving basin (Figure 6.4). However, despite the fluvial dominance of the modern delta, wind-waves play an important role in the redistribution of the sediments delivered to the delta front.

As with Macquarie Rivulet the dominant process influencing the morphology of the Mullet/Hooka Creek delta has transitioned. The sedimentological analysis detailed in Chapter 7 suggests the Mullet/Hooka Creek delta's initial morphology was likely to be comparable to that of a fluvially dominated delta, despite the natural state of the catchment, which would have limited sediment supply. The fluvial dominance during the initial evolutionary stages is likely attributable to the protection afforded by Hooka and Kanahooka Points, Hooka Island and to a lesser extent Gooseberry Island limiting the reworking capacity of southeasterly generated wind-waves. As the delta continued to prograded infilling the area behind Hooka Point and extending beyond the shelter of Kanahooka Point the influence of wind-waves in the deltas evolution would have increased. The increased influence of the wind-waves is evident by the cuspate nature of the Mullet Creek floodplain topography and the delta mouth (Figure 10.6).

Since the construction of the tank trap progradation of the Mullet Creek delta has slowed due to sediment deprivation. Instead the rate of progradation of the Hooka Creek delta at the mouth of the tank trap has increased. The subaqueous nature of the delta elements makes it difficult to identify the dominant process. However, it is likely to be a fluvial-dominated depositional system. The lack of subaerially exposed floodplains associated with the Hooka Creek delta is likely attributable to the higher velocity waters of the Tank Trap transporting sediment as a plume into Koong Burry Bay. These characteristics are consistent with hypopycnal flows (Figure 3.13). As Koong Burry Bay continues to infill and the delta progrades beyond Hooka Island the dominant process is likely to revert to a wave-dominated system as seen in the Mullet Creek delta.

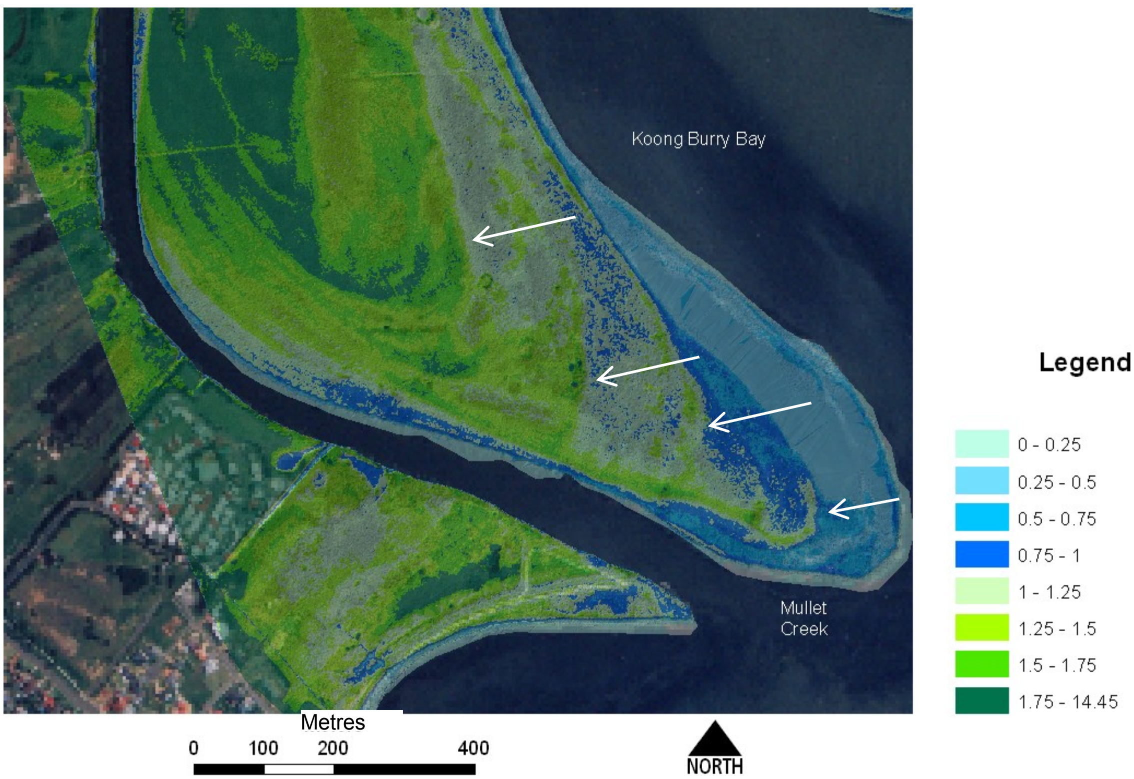

Figure 10.6: *LiDAR image of the Mullet Creek delta with elevations given in metres. Note the cuspate morphology of the delta mouth and the cuspate nature of the topographic changes evident on the floodplain (indicated by white arrows).*

Larger continental/mega deltas such as the Mississippi delta are likely to have a reduced capacity to transition from one type to another. For example, it would take a significant

increase in wave and or tidal forces to transition the delta from displaying the characteristics of a fluvial dominated delta to that of a wave or a tide dominated delta. However, as described above these transitional thresholds are significantly reduced within smaller deltas. This is attributable to the smaller scale of the studied deltas and that they are prograding into a shallow calm receiving basin enabling them to respond more rapidly to smaller changes within the system than the larger continental/mega-scale deltas. This reduced transitional threshold means they are more vulnerable to autocyclic, allocyclic and anthropogenic change which can pose both challenges and advantages when developing management strategies for these smaller deltas under continued environmental and anthropogenic pressure.

The information presented above illustrates the dynamic nature of deltas and their adaptive capacity to respond to variations in prevalence of predominant processes. Both Macquarie Rivulet and Mullet/Hooka Creek deltas' plan morphologies have altered during their current evolutionary phase. This research has shown the combined use of sedimentological data obtained from the extensive coring program, photometric analysis of historical air photographs/maps and the high resolution LiDAR topographic data enhances the capacity to identify the changes in these two deltas and similar features would be expected in other comparable deltas.

10.7: Thesis conclusions

The stratigraphic and morphological evolution of deltas is a function of autocyclic and allocyclic processes combined with anthropogenic factors. The late Pleistocene to present evolution of Macquarie Rivulet and Mullet/Hooka Creek deltas has been established through the sedimentological and geochronological analysis of 147 cores/drill holes from the two sites. The core data are also supported by photometric analysis of historical maps and aerial photographs within a GIS framework.

Previous studies which have assessed the evolution of these smaller deltas have lacked the spatial representation to capture the large number of facies described in this thesis. The high resolution of this study has resulted in the identification of ten main

facies/facies associations, three minor facies and two anthropogenic units, each with a distinct depositional environment. However, establishing the depositional time frame for the facies was problematic for several reasons such as a lack of specimens, age inversions and the limited number of applicable techniques. Despite this possibly being perceived as a negative, it in fact provides an opportunity for further research with a view to enhancing or developing new techniques to address this limitation.

The high resolution analysis of the deltas' evolution is significantly different to the previous published evolutionary models for the deltas. Specifically, the study has shown the deltas' evolution, particularly the fluvial phase, commenced approximately 2,500 years earlier than recorded in previous studies. The study has also highlighted the capacity of deltas to have multiple depositional environments occurring simultaneously and within close proximity to each other. The simultaneous occurrence of differing depositional environments has further added to the complexity of establishing the evolution of the two deltas.

The proximity of cores within each of the study areas facilitated the development of 3D TIN models and subsequent contour maps of the intersected facies at each of the sites within a GIS framework. The use of these techniques significantly aided in addressing the complexities of the deltas' evolution. The use of the TIN models aided in demonstrating the strong relationship between the inherited morphology of the palaeorecieving basin and the basal facies. The models also illustrate the diminishing influence of the inherited morphology of the palaeoreceiving basin as it infilled and flattened throughout the Holocene. This is particularly evident in the Koong Burry Bay area where the Hooka Creek delta lobe morphology is unrelated to the underlying Pleistocene palaeochannel.

This study has shown the use of photogrammetric techniques combined with GIS analysis is a powerful technique which can be used to assess the modern evolution of the deltas. The rapid expansion of the Macquarie Rivulet and Mullet/Hooka Creek deltas showed a strong correlation to catchment modifications following European settlement.

The increase in area observed utilising the photogrammetric techniques is further supported by the high post-European sedimentation rates established for both study sites. Overall, the use of these techniques is valid and can be applied to studies of other rapidly evolving deltas.

The plan morphology of both deltas appears to have evolved and transitioned as the deltas prograded into the basin. In the case of Macquarie Rivulet the delta appears to have evolved from a cuspate wave-dominated delta into a fluvial-dominated birdsfoot delta. This transition in process dominance is attributable to the cumulative impacts of post-European catchment modification. Conversely, the Mullet Creek delta lobe appears to have evolved from a fluvial-dominated delta into a wave-dominated delta. The transition in this instance is instead attributable the delta prograding into more open waters beyond the shelter afforded by Hooka and Kanahooka Points. Morphology of the modern Hooka Creek delta lobe, an anthropogenic construct due to the tank trap's construction in the early 1940's, is non-descript due to limited subaerial exposure of the delta plain. Despite the subaqueous nature of the lobe it is probably fluvial-dominated due to the high sediment discharge.

The spatial resolution of this study combined with the significant number of cores/drill holes undertaken as part of this research provided an opportunity to develop a stratigraphic model for small-scale deltas prograding into a wave-dominated barrier estuary. The resultant stratigraphic model is typically consistent with previously published models. However, identification of previously undescribed facies such as the transgressive bay-fill, distal delta and regressive delta facies along with the reinterpretation of the near shore muddy sand facies has enhanced these models. The facies model again highlighted the complex nature of these environments whereby several depositional environments can occur simultaneously.

The data presented in this thesis enable refinements to be made to previously published barrier estuary evolutionary models. These revisions have focussed on the inclusion of additional detail within the bay-head delta area and also some revisions with respect to

the previously suggested timing of stages. Furthermore, the wealth of data enabled the development of a specific evolutionary model for bay-head deltas.

The future evolution of the two deltas is uncertain. This is primarily attributable to the uncertainty surrounding the combined impacts of climate change and forecasted urban land releases within the deltas' catchments. However, under the sea level rise scenarios published by the NSW Government significant portions of the deltas, particularly Macquarie Rivulet, will be inundated. This inundation will probably result in the deltas regressing until such time as sea level rise slows and/or stabilises, which will then enable progradation to recommence. This likely evolutionary response is supported by the sedimentary data presented in this study.

The study has illustrated that current planning practices/policies and plans do not adequately address the downstream implications of development proposals. The research has shown the documentation supporting these practices/policies and plans often contain outdated information and do not adequately reflect and/or assess the system as a whole. This lack of a holistic approach has detrimental effects on the deltas. Instead, planning authorities will need to take greater care in the development and implementation of appropriate whole of catchment plans and policies to ensure the cumulative downstream impacts are adequately considered and addressed.

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