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Litho- and chronostratigraphy of holocene sedimentary successions preserved in Lake Illawarra, NSW, Australia

Craig R. Sloss
Queensland University Of Technology, csloss@uow.edu.au

Brian G. Jones
University of Wollongong, briangj@uow.edu.au

Colin V. Murray-Wallace
University of Wollongong, cwallace@uow.edu.au

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Abstract

Using a Holocene barrier estuary, Lake Illawarra, New South Wales, Australia, as an example, a detailed litho- and chrono-stratigraphy of the Holocene estuarine deposits has been investigated. Forty kilometres of seismic surveys, 61 vibracores, supplemented by auger drill holes and trenches, and faunal analysis were used in this study. A detailed chronology of the infilling of the barrier estuary has been established using 121 aspartic acid derived ages and 14 radiocarbon ages. The results provide a detailed chronology for the deposition of marine transgressive deposits between ca. 8 and 5 ka years ago. Barrier growth, initiated with rising sea levels during the post-glacial marine transgression and subsequent Holocene sea level highstand, resulted in the development of a low-energy back-barrier depositional environment from ca. 5 ka years ago, and fluvial progradation into the present Lake Illawarra basin from ca. 2 ka years ago. The results from Lake Illawarra indicate that the generalised evolution of the barrier estuary occurred in five geomorphologically distinct phases associated with rising sea levels following the last glacial maximum and the subsequent Holocene sea level highstand.

Keywords

lake, australia, preserved, sedimentary, holocene, nsw, illawarra, litho, successions, chronostratigraphy, GeoQuest

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LITHO- AND CHRONOSTRATIGRAPHY OF HOLOCENE SEDIMENTARY SUCCESSIONS PRESERVED IN LAKE ILLAWARRA, NSW, AUSTRALIA

Craig R. Sloss, Brian G. Jones, Colin V. Murray-Wallace.

School of Earth and Environmental Sciences, University of Wollongong, NSW 2522, Australia

ABSTRACT

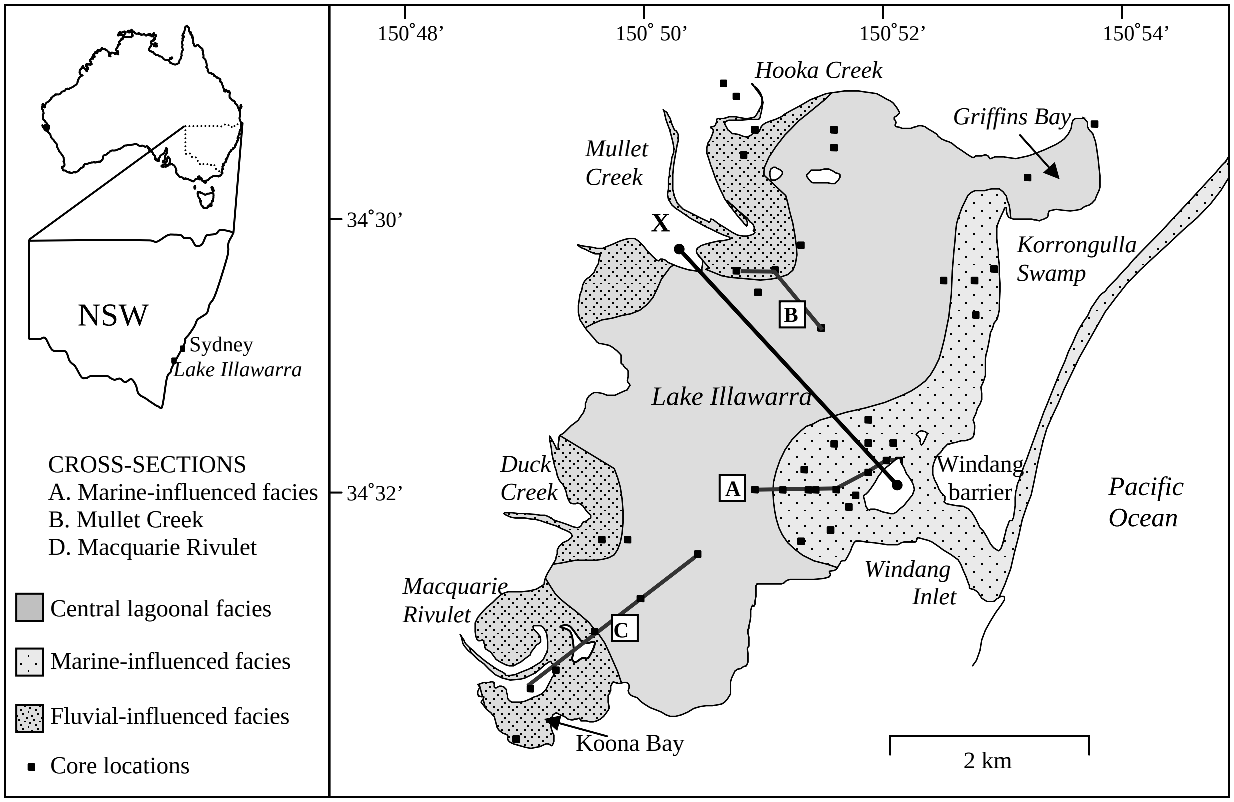
Using a Holocene barrier estuary, Lake Illawarra, New South Wales, Australia, as an example, a detailed litho- and chrono-stratigraphy of the Holocene estuarine deposits has been investigated. Forty kilometres of seismic surveys, 61 vibracores, supplemented by auger drill holes and trenches, and faunal analysis were used in this study. A detailed chronology of the infilling of the barrier estuary has been established using 121 aspartic acid derived ages and 14 radiocarbon ages. The results provide a detailed chronology for the deposition of marine transgressive deposits between *ca.* 8 and 5 ka years ago. Barrier growth, initiated with rising sea levels during the post-glacial marine transgression and subsequent Holocene sea level highstand, resulted in the development of a low-energy back-barrier depositional environment from *ca.* 5 ka years ago, and fluvial progradation into the present Lake Illawarra basin from *ca.* 2 ka years ago. The results from Lake Illawarra indicate that the generalised evolution of the barrier estuary occurred in five geomorphologically distinct phases associated with rising sea levels following the last glacial maximum and the subsequent Holocene sea level highstand.

INTRODUCTION

Lake Illawarra is a coastal lagoon located approximately 80 km south of Sydney, New South Wales (Fig. 1). Lake Illawarra displays the characteristics of a wave-influenced barrier estuary that has developed on a relatively tectonically stable coast (Roy, 1984; Bryant, 1992). It fills a shallow (<20 m) incised valley system scoured into Permian bedrock and Pleistocene sediments by river action during previous sea level low stands. The coastal lagoon displays a characteristic tripartite facies division comprising fluvial-dominated bay-head delta facies, central lagoonal mud facies, and marine-influenced sandy barrier facies (Roy, 1984; Nichol, 1991; Dalrymple, 1992; Fig. 1).

The present day tripartite facies division observed in Lake Illawarra also applies to the ancient facies successions that are linked to sea level changes observed over the last glacial cycle. Studies on the nature of rising sea levels following the last glacial maximum (LGM) and the subsequent development of barrier estuaries on the New South Wales coastline have been extensively investigated (Thom and Roy, 1983, 1985; Roy, 1994; Roy and Boyd, 1996). Results from these studies have shown that culmination of the last postglacial marine transgression (PMT) reached a maximum of +1 m between 6500 and 7500 yr BP (Thom and Roy 1983; 1985). Research in the Illawarra region has narrowed the timing of the culmination of the PMT to between 7500 to 7000 yr BP, with sea level reaching a maximum of + 2 m above present sea level (Jones *et al*., 1976; Bryant *et al*., 1992; Young *et al*., 1993). The culmination of the last PMT was followed by a sea level highstand, slightly higher than present sea level, that lasted to *ca*. 3 ka (Flood and Frankle, 1989; Roy, 1994).

Figure 1: Tripartite facies division, cross-section and core locations for Lake Illawarra, NSW, Australia.



In response to the rising sea level associated with the last PMT, sediment stored on the inner continental shelf migrated shoreward. The stabilisation of the sea surface and subsequent sea level highstand promoted the shoreward prograding sediment to stabilise in the mouth of incised valley systems resulting in barrier development and the deposition of fine estuarine mud in backbarrier lagoons (Chapman *et al*., 1982; Roy, 1994). The response of marginal marine depositional environments to Holocene sea level trends has been the basis for models for barrier estuary evolution on relatively tectonically stable coastlines (Chapman *et al*., 1982; Nichol, 1991; Roy, 1994). Established models of barrier estuary evolution provide the framework for this investigation. In this work a chronology of Holocene deposition within Lake Illawarra is derived based on amino acid racemisation and radiocarbon dating.

PLEISTOCENE DEPOSITS AND PALAEOVALLEYS

In Lake Illawarra, Pleistocene deposits are characteristically composed of reduced mottled clay, typically containing sub-angular to angular, medium- to coarse-grained quartz. Alteration of these Pleistocene successions represents a lowstand weathering profile. Mapping the Pleistocene surface obtained from seismic traces (Fig. 2) and vibracores permitted the nature of the coalescing Pleistocene low-stand channels to be determined (Fig. 3).

The top of the Pleistocene succession is represented by a valley system that was formed by fluvial incision during the last glacial cycle and is generally less than 20 m below present sea level. The Pleistocene surface represents a complex east-ward draining network of palaeochannels that would have operated at various times during

Figure 2: Seismic section showing Pleistocene palaeochannels and palaeochannel infill overlain by the Holocene marine transgressive sand sheet, Holocene estuarine backbarrier lagoonal mud, and the Mullet Creek delta.

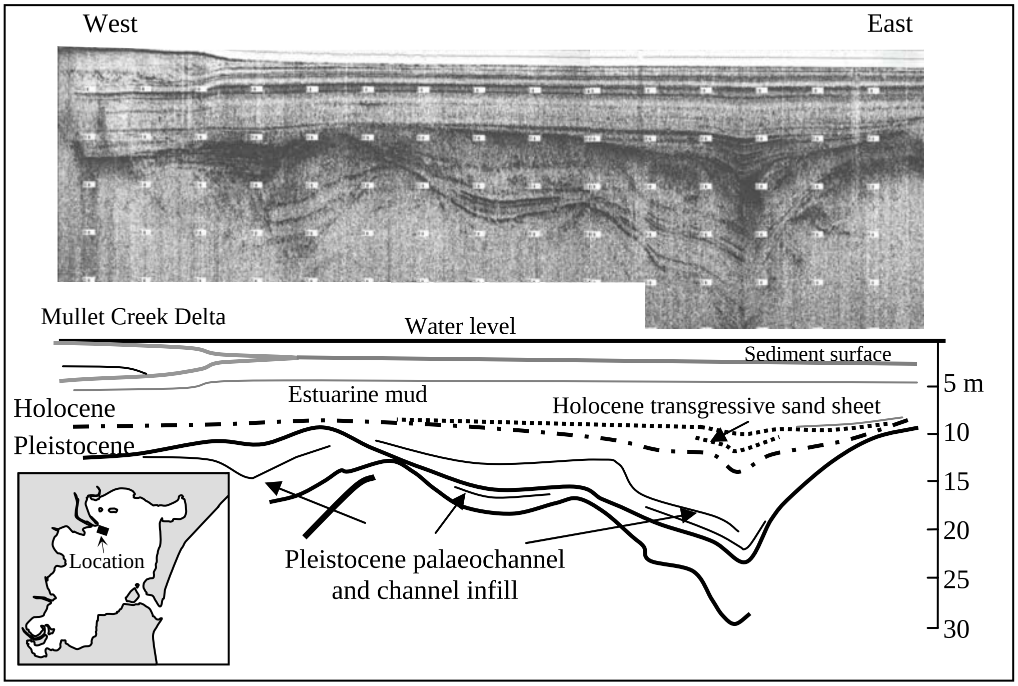
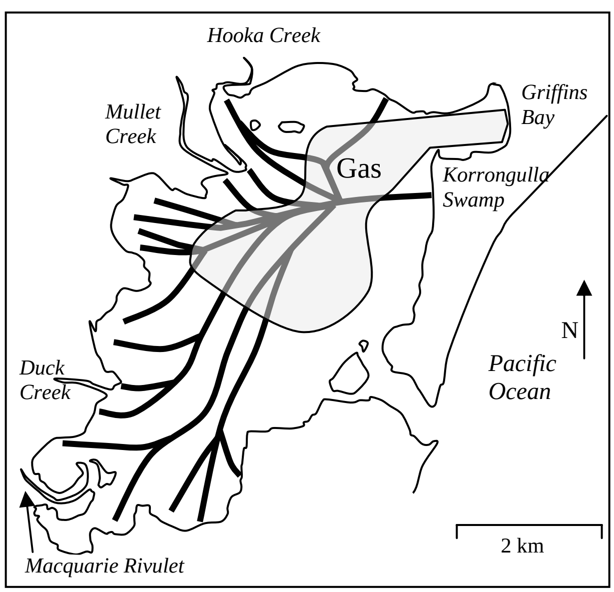


Figure 3: Pleistocene palaeochannels determined from seismic results coalesce into a single channel exiting through the Korrongulla Swamp region.



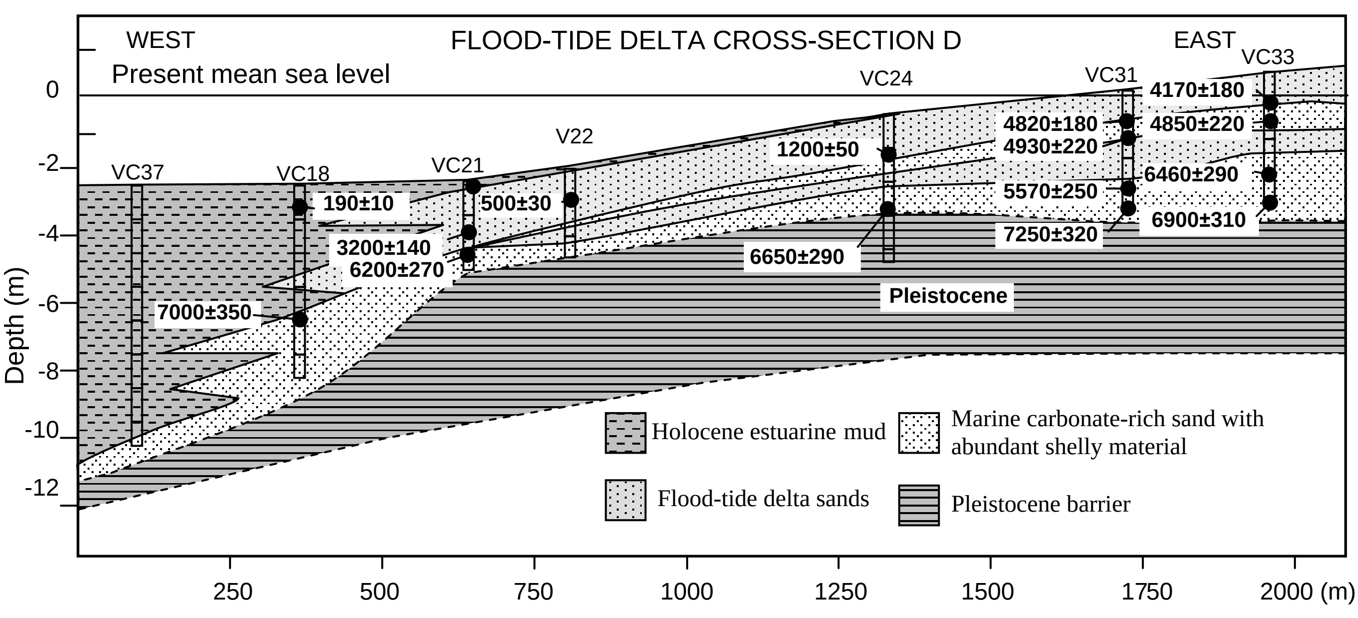
the LGM. At least three main tributary channels coalesced into a single large channel that exited the Pleistocene valley system at the present location of Korrongulla Swamp (Fig. 3).

POSTGLACIAL MARINE TRANSGRESSION

A transgressive sand sheet composed of rounded to well rounded medium- to coarse-grained quartz- and carbonate-rich sand overlies the antecedent Pleistocene land surface. Faunal elements in the transgressive sand sheet are dominated by the estuarine bivalves *Anadara trapezia*, *Ostrea angasi* and *Notospisula trigonella* and the gastropod *Velacumantis australis*. Within the transgressive sand sheet there are also abundant *Austrocochlea constricta*, *Bittium lacertinum* and *Prothalotia comtessei* and minor occurrences of *Dosinia* sp. These molluscs typically inhabit low- to medium-energy estuarine muddy-sand and sand flats that are commonly colonised by sea grass (Ludbrook, 1984; Yassini, 1986; Jensen, 2000). Also occurring within the transgressive sand sheet are numerous whole barnacle shells and barnacle shell fragments which are restricted to the nearshore zone on rocky coasts, fragments of *Katelysia scalarina* which inhabit sandy shores in the lower littoral zone (Ludbrook, 1984) and the marine foraminifera *Elphidium discoidalis multiloculum* (Yassini and Jones, 1995). The presence of the diverse mix of estuarine molluscs and a fauna that typically inhabits medium-energy sand flats and high-energy near shore zones indicate that the transgressive sand sheet most likely represents reworked quartz-dominated tidal sand flats, tidal channel sands and wash-over sands in a depositional environment that was open to direct marine influences.

Deposition of the quartz-dominated transgressive sand sheet indicates that rising sea levels associated with the last PMT inundated the Pleistocene incised valley system some time before *ca.* 7500 years ago and as early as 8000 years ago. An aspartic acid derived age on disarticulated *A. trapezia* recovered from the top of a 19 cm thick basal gravel lag of rounded quartz and lithic

Figure 4: Schematic cross-section of the marine-influenced facies showing progradation of the marine transgressive sand over an older barrier of inferred last-interglacial age (for location see Fig. 1).



sandstone pebbles (up to 6 cm) proximal to experienced a higher energy depositional environment as rising sea levels inundated the incised valley, similar to the modern inlet and beach facies.

The initial inundation of the basin by marine processes is also evident from aspartic acid derived ages from articulated *A. trapezia* close to the present inlet channel, at a current depth of 3-6 m (AHD), having similar ages of 7250 ± 320 yr (VC31), 6900 ± 310 yr (VC33), 7000 ± 350 (VC18) and 6650 ± 290 yr (VC24; Fig. 4). Aspartic acid derived ages on disarticulate *A. trapezia* collected from the transgressive sand sheet on the western side of the lagoon, distal to present marine influence range from 5000 to 6200 yr (Figs 5 & 6). This indicates that the landward progradation of medium- to coarse-grained marine sands associated with the Holocene PMT inundated the incised valley as early as 7300 years ago and more open marine influences dominated until 5000 years ago.

CENTRAL LAGOON

Following the deposition of the transgressive sand sheet, a distinct facies change to a low-energy backbarrier depositional environment, composed of fine cohesive estuarine mud is evident. This change from muddy marine sand to a reduced estuarine mud represents a depositional environment where restricted oceanic water circulation followed the emergence of a developed barrier system. Aspartic acid derived ages on articulated *in situ N. trigonella* from basal muds above the transgressive sand sheet yielded an age of 4900 ± 220 yr (VC5) indicating that the transition from a marine embayment to a low-energy backbarrier environment occurred between 4500 and 5000 years ago (Figs 5 & 6).

FLUVIAL PROGRADATION

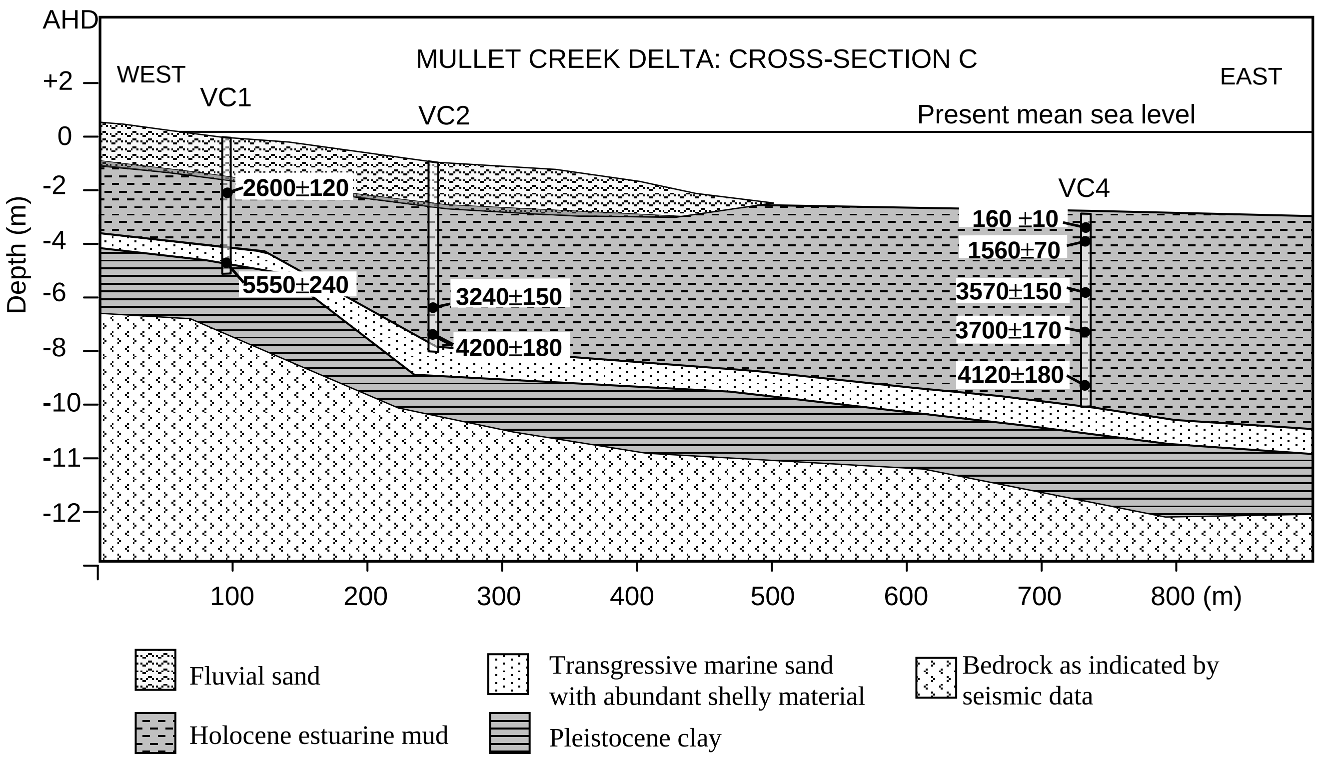
The fluvial-influenced facies associated with the landward margin of the estuarine environment is currently dominated by the progradation of the Hooka Creek, Mullet Creek and Macquarie Rivulet bay-head deltas (Fig. 1). Using a combination of seismic surveys, lithostratigraphic and geochronological data, the reconstruction of the progradation and evolution of the fluvial zone into the estuarine environment has been investigated.

Mullet creek and hooka creek:

Mullet Creek has a subaqueous lobate fluvial delta that extends *ca.* 0.6 km east-southeast from the mouth of Mullet Creek and has a maximum width of *ca.* 1 km. It has a single fluvial channel and a delta that is characteristic of a wave-dominated system, resulting from wind-generated waves associated with the dominant southeasterly storm winds. The main Mullet Creek delta has been relatively inactive since the establishment of the Tank Trap in 1941 that redirected sediment from Mullet Creek into the northern part of Koong Burry Bay and the present location of the rapidly prograding Hooka Creek delta (Sloss *et al*., 2003; Fig. 1).

The initial influence of a more open estuarine system and greater oceanic water circulation within the Lake Illawarra basin is indicated by the deposition of the marine transgressive sand sheet containing a mix of estuarine and shallow marine fauna observed in the Mullet Creek area (Fig. 5). An articulated specimen of *A. trapezia* from the marine sands yielded an aspartic acid derived age of 5550 ± 250 yr (VC1). The presence of these sands and the age of fossil molluscs preserved in the deposit correspond well with the deposition of the transgressive sands closer to the inlet. The transgressive sands are overlain by a strongly reduced, cohesive estuarine mud (Fig. 5). This change in depositional environment to a system of low-energy lagoonal facies can be inferred from the accumulation of estuarine mud from at least *ca.* 4200 years ago (VC2).

Figure 5: Schematic cross-section of Mullet Creek delta showing progradation of the fluvio-deltaic sequence into the muddy estuarine basin that overlies the transgressive marine sand sheet (for location see Fig. 1).

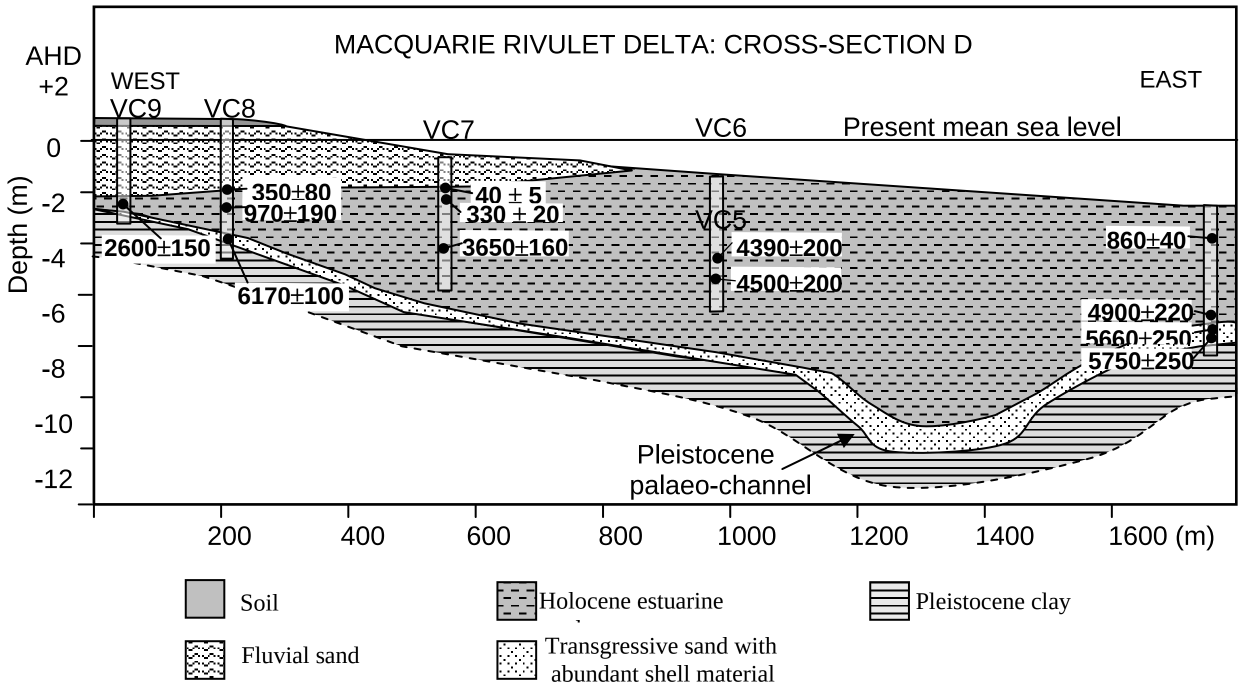


Progradation of the modern fluvial delta overlying the estuarine mud cannot be precisely dated due to the lack of bivalves preserved in life position within this facies. However, a relative age can be established based on an aspartic acid derived age of 2600 ± 120 yr on *N. trigonella* preserved in the underlying estuarine mud (VC1), which suggests that the delta lobe was prograding over the central lagoon facies some 2500 years ago (Fig. 5). These data correspond with evidence collected from the Hooka Creek delta, which indicated that fluvial progradation into the present lagoon was occurring at <2900 years ago.

Macquarie Rivulet:

The river-dominated birdsfoot delta associated with Macquarie Rivulet is located in the southwest of Lake Illawarra extending *ca.* 1.3 km into the lagoon (Sloss *et al.*, 2003; Fig. 1). Litho- and aminostratigraphic results obtained from Macquarie Rivulet delta (Fig. 6) indicate that delta progradation into the central lagoon facies follows a similar depositional history to that observed at Mullet and Hooka Creeks. Muddy marine sand containing *A. constricta, V. australis, N. trigonella, A. trapezia* and barnacle shell unconformably overlie clays of the Pleistocene lowstand land surface. The presence of the transgressive sand suggests that the initial deposition of marine sand also reached the southwestern margin of the estuary (Fig. 6). An aspartic acid derived age 5750 ± 250 yr (VC5), and a radiocarbon age of 6170 ± 100 cal yr BP (VC8) from *A. trapezia* preserved in the transgressive sand sheet provide additional evidence for a more open estuarine system with oceanic water circulation operating between *ca.* 7500 and 5000 years ago (Fig. 6).

Figure 6: Schematic cross-section of Macquarie Rivulet delta showing progradation of a relatively recent fluvio-deltaic sequence into the estuarine basin. It also shows the nature of sedimentation associated with the incised palaeochannel beneath the central lagoonal facies (for location see Fig. 1).



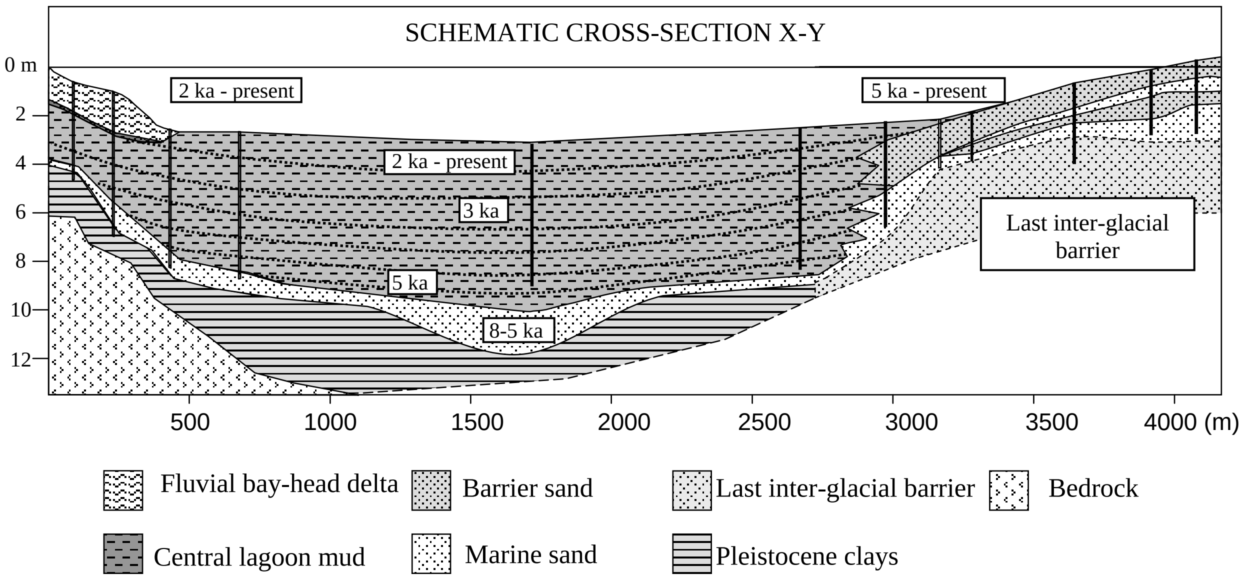
The central lagoonal facies composed of cohesive estuarine mud overlies the transgressive sand sheet. An aspartic acid derived age on *N. trigonella* towards the base of the central lagoon facies in core VC5 yielded an age of 4900 ± 220 yr, indicating that the transition to the central lagoonal facies at *ca.* 5000 years ago was a basin-wide phenomenon (Fig. 6).

Prograding fluvial sands of the modern delta lie directly over cohesive reduced clay. Towards the western margin of the delta a specimen of *A. trapezia* yielded a radiocarbon age of 2600 ± 150 cal yr BP (Wk-7906, VC9), which corresponds well with the ages of fluvial progradation observed for Hooka and Mullet Creek. However, the geochronological results also highlight that the distal portion of the delta is a relatively recent deposit. This relatively recent phase of fluvial progradation is indicated by the radiocarbon age obtained from basal sands of the delta in core VC8 that yielded an age of 350 ± 80 cal yr BP (Wk-7903, VC8) and an aspartic acid derived age derived on *N. trigonella* of 330 ± 150 yr (VC7; Fig. 6). This indicates that the progradation of Macquarie Rivulet delta in this region has occurred over the last 400 years, while older deposits are preserved farther to the west and to the north in the Duck Creek region.

DISCUSSION

The combination of data collected from the fluvially-influenced, central lagoon and marine-influenced depositional environments allows a reconstruction of the sedimentary evolution of Lake Illawarra (Fig. 7).

Figure 7: Schematic cross-section showing the chronology of sedimentary facies deposited in Lake Illawarra



This evolutionary development of Lake Illawarra may be viewed as having occurred through five geomorphologically distinct phases associated with the last PMT, the Holocene sea level highstand and the subsequent fall to present sea level (Fig. 8).

Stage One: During the LGM sea levels on the NSW south coast were estimated to be *ca.* 120 m below present mean sea level (Murray-Wallace *et al*., 1996). During the lowstand in sea level, fluvial activity extended across the continental shelf and resulted in fluvial incision into the Pleistocene landsurface. This fluvial incision resulted in the development of a dendritic drainage network, within the incised valley system, that cut through the Pleistocene barrier at the present location of Korrongulla Swamp (Fig. 8a).

Stage Two: The second stage of the evolution of the Lake Illawarra barrier estuary is represented by the deposition of a transgressive sand sheet over the Late Pleistocene erosion surface. Inundation of the antecedent incised valley system by rising sea levels during the PMT, and the subsequent Holocene sea level highstand, resulted in the deposition of a medium- to coarse-grained transgressive sand sheet between *ca.* 7900 yr and *ca.* 5000 yr (Fig. 8b). This represents a youthful stage in the development of the estuarine succession prior to barrier development, with the system operating as a broad drowned river estuary. The molluscs *Anadara trapezia* and *Ostrea angasi*, both species of bivalve indicative of tidal sand flats in estuarine environments, dominate the faunal assemblages within the transgressive sand sheet. Proximal to the present barrier, the transgressive sand sheet also contains a more diverse mix of low- to medium-energy estuarine molluscs that typically inhabit muddy-sand and sand flats, and a fauna that typically inhabits moderate- to high-energy nearshore environments including *Katalysia sp*. and barnacles. Landward, the transgressive sand sheet becomes muddier with an increase in population of the estuarine bivalve *Notospisula trigonella*. The increase in mud content and a decrease in faunal diversity indicates that an interaction between marine and fluvial processes influenced depositional environments operating in the inner part of the drowned river estuary.

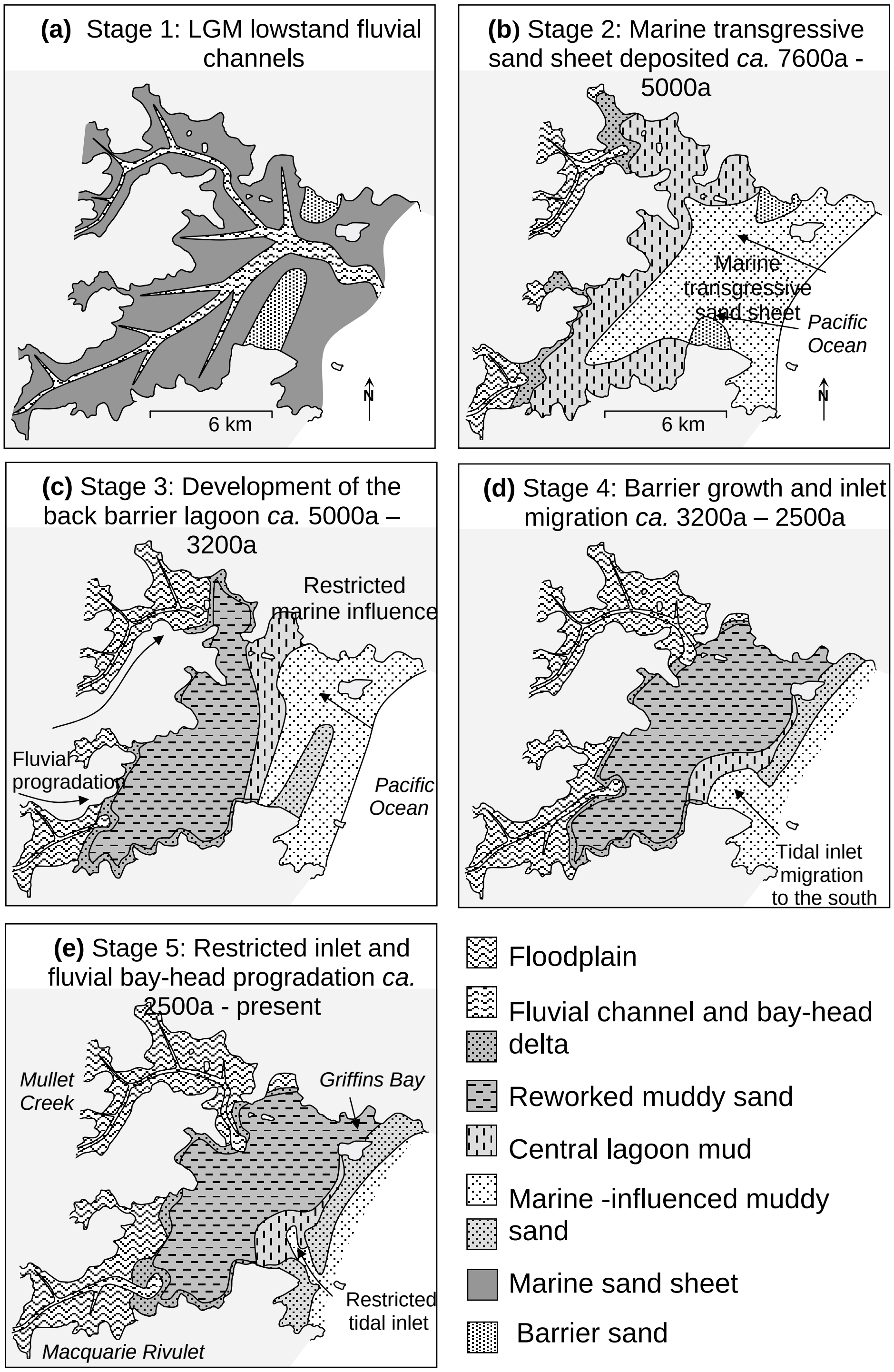
Stage Three: The third stage of the evolution of Lake Illawarra is represented by the emergence of the sand barrier during the Holocene sea level highstand and the subsequent deposition of cohesive estuarine mud in a low-energy backbarrier lagoon (*ca.* 5000 to 3200 years ago). During this stage of evolution, the northern inlet became less efficient at moving marine sediment into the lagoon, and tidal sand flats were spatially restricted proximal to the present barrier system. The restriction of open oceanic influence and the growth of the barrier facilitated the deposition of fine-grained silty estuarine mud in the back-barrier lagoon. Deflation of the southern barrier and closure of the northernmost inlet occurred during the early part of stage three. The locus of the fluvial bay-head deltas would still have been farther inland than the present western lagoon margin (Fig. 8c).

Stage Four: With the further development of the northern part of the Windang Barrier and restriction of the northern inlet near Korrongulla Swamp, the inlet channel migrated south to its present location *ca.* 3200 years ago. The timing of the inlet migration is based on ages obtained from relict flood-tide delta deposits to the north of Windang Barrier that indicate the cessation of marine-influenced deposition at *ca.* 3200 yr, and the initiation of flood-tide deposits at the location of the present inlet at the same time. The migration of the inlet channel to its present location at Windang and the further restriction of oceanic water circulation caused by a 1-2 m drop in sea level resulted in the extension of the central lagoonal facies from the deeper portions of the incised valley system to a more extensive basin wide depositional environment from 3200 years ago (Fig. 8d). It was also during this stage that the main fluvial deltas started prograding over the older estuarine sequence into the present lagoonal basin as sea level fell and the upper reaches of the valleys filled rapidly because of decreasing accommodation space (Fig. 8d).

Stage Five: Stage five represents the infilling of the barrier estuary from *ca.* 2500 years ago to the present and is represented by prograding fluvial bay-head deltas along the western lake margin, and the restriction of the Windang tidal inlet. This stage also represents relatively modern morphological changes and accelerated sedimentation associated with recent fluvial progradation induced by land clearing and urbanisation (Chenhall *et al*., 1995; Sloss *et al*., in press) In contrast to the fluvial-influenced depositional environment, the marine-influenced depositional environment has been relatively inactive over the last 200 years (Fig. 8e).

The five-stage geomorphological evolution the Lake Illawarra barrier estuary is in general agreement with previous models of Holocene barrier estuary evolution (Nichol, 1991; Roy, 1994; Fig 9b). However, results from this study add detail to the early stages of barrier estuary development with the deposition of a basin-wide basal transgressive marine sand containing a diverse assemblage of estuarine and marine mollusc species. The deposition of this transgressive sand sheet occurred between *ca.* 7900 – 5000 years ago when the barrier estuary was more open to oceanic influences, and dominated by the deposition of wash-over sands, transgressive tidal sand flats and tidal channel sands (Fig. 9a). The deposition of this basin wide transgressive sand sheet provides the foundation for an alternative model for the early stage of barrier estuary evolution where marine influenced facies lie unconformably over the antecedent Pleistocene land surface. This differs from previously published models of barrier estuary evolutionary, which were based on research conducted in deeply incised valley systems where marine-influenced facies stabilise in the mouth of the incised valley and back-barrier lagoonal mud lies directly over the Pleistocene land surface (Nichol, 1991; Roy, 1984, 1994; Roy and Boyd, 1996; Fig. 9b).

Figure. 10: The main stages associated with the Holocene evolution of Lake Illawarra
(a) Stage 1: Antecedent Pleistocene landsurface and lowstand fluvial channels
(b) Stage 2: Deposition of a marine transgressive sand sheet associated with rising sea level and Holocene sea level highstand from *ca.* 7900a – 5000a.
(c) Stage 3: Early development of the Holocene barrier and back-barrier lagoon associated with the Holocene sea level highstand *ca.* 5000a – 3200a.
(d) Stage 4: Further barrier growth associated with regressing sea levels. The inlet migrated from its norther location to its present position south of Windang Peninsula *ca.* 3200a – 2500a.
(e) Stage 5: Restricted inlet size and rapid fluvial bay-head delta progradation from *ca.* 2500a – present.



CONCLUSIONS

Results from this study, while in general agreement with previously established models of barrier estuary evolution, provides greater detail in relation to early stages of barrier estuary formation. In particular, this study has revealed evidence for the deposition of a basin-wide transgressive sand sheet deposited in response to rising sea levels associated with the last postglacial marine transgression. The transgressive sand sheet lies unconformably over the Late Pleistocene antecedent land surface and is composed of medium- to coarse-grained sand with a high carbonate content and a diverse mix of estuarine and nearshore marine molluscs. The deposition of the transgressive sand sheet represents tidal sand flats, tidal inlet sands and washover deposits, associated with the initial inundation of ocean water within the incised valley *ca.* 7500 to 7900 years ago (sidereal years). This detailed chronstratigraphy of the Holocene infill of Lake Illawarra provides valuable information on the relationship between Holocene sea level change and transgressive depositional history in shallow incised valley systems for the southeast coast of Australia, and environs with similar Holocene sea level history and geomorphological characteristics.

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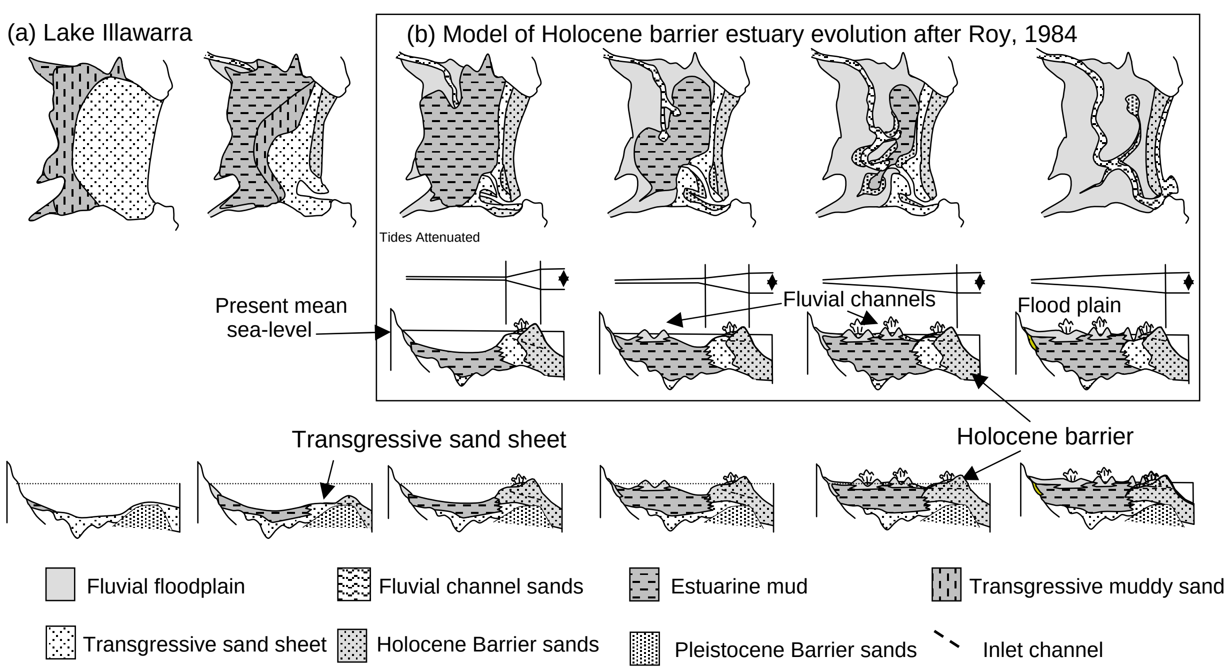
The School of Earth and Environmental Sciences, University of Wollongong; The Research Centre for Landscape Change, University of Wollongong; an Australian Postgraduate Scholarship; and an Australian Institute of Nuclear Science and Engineering (ANSIE) Postgraduate Award provided financial and fieldwork support. We also thank, Charles McClennen and the

Figure 9: Schematic model of the Holocene evolution of barrier estuaries on tectonically stable coastlines. (a) Lake Illawarra showing the initial deposition of a transgressive sand sheet associated with the last PMT and subsequent Holocene sea level highstand. (b) Previous model of barrier estuary evolution (after Roy, 1984).



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