2006

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Recommended Citation
Jones, Brian G.; Sloss, Craig R.; Price, David M.; McClennen, C.E.; and de Carli, John: The geomorphological evolution of a wave-dominated barrier estuary: Burrill Lake, New South Wales, Australia 2006, 229-249.
https://ro.uow.edu.au/scipapers/4172

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The geomorphological evolution of the Holocene wave-dominated barrier estuary at Burrill Lake on the New South Wales coast, Australia, has been delineated using a combination of seismic stratigraphy and the lithostratigraphic analysis of vibracores collected from the back-barrier estuarine environment. A combination of radiocarbon and aspartic acid racemisation-derived ages obtained on Holocene fossil molluscs, and the thermoluminescent signal in remnant Last Interglacial barrier sediments provides the chronological framework for this investigation. Results from this paper show that the barrier estuary occupies a relatively narrow (<1.5 km wide) and shallow (<40 m deep) incised bedrock valley formed during sea-level lowstands. Late Pleistocene sedimentary successions and remnants of the Last Interglacial barrier have been preserved within the incised valley axis and the mouth of the incised valley. These sediments, deposited during the Last Interglacial sea-level highstand, have subsequently been partially removed during the last glacial maximum. Overlying the antecedent late Pleistocene landsurface is a near basin-wide basal marine sand deposited in response to rising sea level associated with the most recent post-glacial marine transgression, which inundated the shallow incised valley ca.7800 years ago. More open marine conditions, with a diverse assemblage of estuarine and marine mollusc species, persisted until ca. 4500 years ago when the stabilizing Holocene barrier resulted in the development of a lowenergy back-barrier lagoonal environment. A late Holocene 1-2 m regression of sea level ca. 3000 years ago further restricted oceanic circulation, increased the rate of fluvial bay-head delta progradation and the extension of the backbarrier central basin mud facies. This evolutionary model of barrier estuary evolution developed for Burrill Lake is consistent with recent research conducted in Lake Illawarra and St Georges Basin and can be applied to other estuaries that have formed in relatively shallow and narrow incised bedrock valleys on tectonically stable, wave-dominated coastlines.

Keywords

geomorphological, evolution, wave, dominated, barrier, estuary, Burrill, Lake, South, Wales, Australia, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

Sloss, C. R., Jones, B. G., McClennen, C., de Carli, J. & Price, D. M. (2006). The geomorphological evolution of a wave-dominated barrier estuary: Burrill Lake, New South Wales, Australia. Sedimentary Geology, 187 (3-4), 229-249.

The geomorphological evolution of a wave-dominated barrier estuary: Burrill Lake, New South Wales, Australia

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Abstract

The geomorphological evolution of the Holocene wave-dominated barrier estuary at Burrill Lake on the New South Wales coast, Australia, has been delineated using a combination of seismic stratigraphy and the lithostratigraphic analysis of vibracores collected from the back-barrier estuarine environment. A combination of radiocarbon and aspartic acid racemisation-derived ages obtained on Holocene fossil molluscs, and the thermoluminescent signal in remnant Last Interglacial barrier sediments provides the chronological framework for this investigation. Results from this paper show that the barrier estuary occupies a relatively narrow (<1.5 km wide) and shallow (<40 m deep) incised bedrock valley formed during sea-level lowstands. Late Pleistocene sedimentary successions and remnants of the Last Interglacial barrier have been preserved within the incised valley axis and the mouth of the incised valley. These sediments, deposited during the Last Interglacial sea-level highstand, have subsequently been partially removed during the last glacial maximum. Overlying the antecedent late Pleistocene landsurface is a near basin-wide basal marine sand deposited in response to rising sea level associated with the most recent post-glacial marine transgression, which inundated the shallow incised valley ca.7800 years ago. More open marine conditions, with a diverse assemblage of estuarine and marine mollusc species, persisted until ca. 4500 years ago when the stabilizing Holocene barrier resulted in the development of a low-energy back-barrier lagoonal environment. A late Holocene 1-2 m regression of sea level ca. 3000 years ago further restricted oceanic circulation, increased the rate of fluvial bay-head delta progradation and the extension of the back-barrier central basin mud facies. This evolutionary model of barrier estuary evolution developed for Burrill Lake is consistent with recent research conducted in Lake Illawarra and St Georges Basin and can be applied to other estuaries that have formed in relatively shallow and narrow incised bedrock valleys on tectonically stable, wave-dominated coastlines.

Keywords: Aminostratigraphy; Holocene geochronology; estuarine sedimentation; seismic stratigraphy.

1. Introduction

Following the last glacial maximum (LGM) sea-level rose rapidly from ca. -120 m at 20,000 cal yr BP (Ferland et al., 1995; Murray-Wallace et al., 1996, 2005) reaching and stabilizing within +1.5 m of present sea-level between 7,500 and 7,000 years ago (Jones et al., 1979; Thom and Roy, 1983, 1985; Young et al., 1993; Sloss et al., 2005a, b). The stabilization of the sea surface during the culmination of the most recent post-glacial marine transgression (PMT) and subsequent Holocene sea-level highstand allowed shoreward prograding sediment to stabilize within the mouths of incised valley systems from ca. 6,500 years ago. This resulted in the growth and stabilization of Holocene barriers and the deposition of fine-grained estuarine mud in back-barrier estuarine lakes (Roy et al., 1980, 1994, 2001; Chapman et al., 1982; Thom and Roy, 1983; Roy, 1984a, b, 1994). Previous stratigraphic studies into the geomorphological evolution of wave-dominated barrier estuaries on the southeast coast of Australia suggested that the initial stages of sedimentary infill display a tripartite facies division (Chapman et al., 1982; Roy, 1984a, b, 1994; Roy et al., 1980; Heap et al., 2004). Landwards, lowstand fluvial deposits directly overlie the antecedent Pleistocene landsurface and are, in turn, overlain by mid to late Holocene estuarine mud. In the central basin fine-grained estuarine mud disconformably overlies the antecedent Pleistocene substrate. Seaward, a basal sequence comprising transgressive sands containing estuarine and nearshore molluscan fauna directly overlies the Pleistocene substrate and inter-fingers landward with mid to late Holocene central basin estuarine mud. Directly overlying the PMT sandsheet are flood-tide delta, back-barrier sand-flats and barrier sands associated with the early stages of barrier development (Roy et al., 1980; Thom and Roy, 1983; Roy, 1984a, b, 1994). Following the early deposition of the basal estuarine sedimentary successions, marine sediments continued to accumulate in the mouth of the incised valleys promoting the further development of the Holocene barrier and resulting in a low-energy back-barrier depositional environment and the early stages of fluvial progradation (Roy et al., 1980; Chapman et al., 1982; Roy, 1984a, b, 1994).

Recent research conducted in Lake Illawarra and St Georges Basin, two wave-dominated barrier estuaries formed within broad (ca. 10 km wide) and relatively shallow (<30 m deep) incised valley systems, indicated that the early stage of barrier estuary evolution is different to the established conceptual models (Sloss et al., 2005b). The differences from the previous models of barrier estuary evolution reflects a greater emphasis on the palaeo-morphology of the lowstand incised valley and antecedent Late Pleistocene landsurface, and the deposition of a near basin-wide basal transgressive sandsheet during the most recent PMT. The transgressive sandsheet, comprising marine quartzose sand and containing a mix of estuarine and nearshore shallow marine fossil molluscs, was deposited as rising post-glacial sea levels breached remnant Last Interglacial barrier systems and inundated the incised valleys from ca. 8,000 years ago (Sloss et al., 2004b, 2005a, b, in submission). During this stage of Holocene sedimentary infill, the drowned incised valley system operated as a sheltered ocean embayment or broad drowned river estuary open to direct oceanic influences. This contrasts with established models for barrier estuary evolution on the southeast coast of Australia, where transgressive sandsheets are restricted to the mouths of incised valleys and back-barrier central basin muds lie directly over the antecedent Pleistocene landsurface.

While the incised bedrock valley associated with Burrill Lake is relatively shallow (ca. <40 m deep) the narrow nature of the bedrock valley (<2 km wide) has resulted in a morphology that is significantly different to the Lake Illawarra and St Georges Basin barrier estuaries (Fig. 1). As a result, the investigation of the Burrill Lake barrier estuary provides the opportunity to assess the geomorphological evolution of barrier estuaries that have experienced the same climatic conditions and sea-level fluctuations throughout the Holocene to those recently investigated on the New South Wales southern coast (Sloss et al., 2004b, 2005a, b) and to those used to construct previous estuarine evolutionary models (Roy et al., 1980; Chapman et al., 1982; Roy, 1984a, b, 1994), but have formed in incised valley systems with a significantly different palaeo-morphology.

2. Geological setting

Burrill Lake located ca. 230 km south of Sydney is a wave-dominated barrier estuary with a bilobate morphology that formed in a relatively shallow (ca. <40 m) and narrow (<2 km wide) valley that was incised into bedrock basement during previous lowstands of sea-level (Fig. 1). The southern limb of the bilobate system is underlain by Permian quartz sandstone (Snapper Point Formation), while the northern limb has scoured into the Mesozoic Milton Monzonite (Carr, 1984; Jones et al., 2003). Around the margin of the estuary the sandstones of the Snapper Point Formation crop out as low sub-horizontal rock benches or small cliffs. At its narrowest point, close to where the two limbs merge, the bedrock bound estuarine lake is only ca. 400 m across. At its widest position in the northern limb the impounding bedrock embankments are ca. 1.2 km apart (Fig. 2).

The estuarine water body at present covers an area of 4.2 km^2, draining a total catchment area of ca. 80 km^2 that is bounded to the west by the Budawang Range with elevations in excess of 270 m. Stony Creek is the major tributary that enters Burrill Lake in the northern limb of the estuary producing a bayhead delta extending ca. 1.4 km into the lagoon (Fig. 2; Jones et al., 2003). Water depths in the estuarine lake reach a maximum of ca. 10 m and the estuary is connected to the Pacific Ocean by a narrow and extensively shoaled (<2 m deep) sinuous channel ca. 2.4 km long (Fig. 2). The tidal channel is sufficiently long to reduce the tidal range within the estuary to a few centimeters, although periodically the lagoon is cut off from the sea by a sand barrier and shows no tidal variation. Sand has largely filled the tidal channel area and produced a flood-tide delta extending as a prominent feature into the central part of the estuarine lake (Fig. 2). The flood-tide delta has a sharp delta-front building out into the deepest part of the estuary (ca. 10 m deep). It also extends across the narrow channel between the northern and southern limbs of the estuary and lines the southeastern embayment near Bungalow Park (Fig. 2; Jones et al., 2003). The impounding barrier and extensively shoaled inlet channel have resulted in a mean elevated back-barrier estuarine water level of 23 cm above PMSL.

3. Methods

In this paper the geophysical evolution of the Burrill Lake wave-dominated barrier estuary has been delineated within the framework of ca. 40 km of seismic surveys (Figs 2 and 3) and the facies association and faunal analysis of 14 vibracores collected from the back-barrier environment (Fig. 2; Table 1). The chronostratigraphy of the sedimentary successions preserved in the Burrill Lake barrier estuary has been delineated based on thermoluminescence dating of remnant Late Pleistocene barrier sands, and radiocarbon analysis and the extent of amino acid racemisation of fossil specimens of *Anadara trapezia*, *Notospisula trigonella* and *Katelysia scalarina* preserved in Holocene sedimentary successions (Tables 1 and 2). The combination of geophysical, lithological and geochronological data has permitted the location of lowstand channel incision (Fig. 4) and the geomorphological evolution of Burrill Lake to be determined.

3.1 Seismic profiles

The seismic stratigraphy of Burrill Lake has been delineated based on recurring seismic sequences observed around the margins of the estuarine lake, in southern limb and the central basin and at the seaward margin of the lagoon (Figs 2 and 3). The seismic traces were obtained using a SB-

424 Towfish sonar and X-star interface software system. This Edgetech acoustic sub-bottom system has a single transmitter and duel receivers operating over a frequency of 2-24 kHz. This method of seismic investigation provided high resolution of up to 20 m in cohesive estuarine muds but had the disadvantage of low penetration in sandy substrates (ca. 2 m).

Additional seismic data was obtained using a ¼ second 200 joule, Geo-acoustics boomer with EG&G power supply operating over a frequency of 500 kHz, with a Benthos 20 element streamer (Fig. 3). The Geo-acoustic boomer had the advantage of greater penetration in sandy substrates (>25 m), but the resolution was not as good as the Towfish. Nevertheless, the second series of seismic traces (Fig. 3) gained more data from the Pleistocene/Holocene boundary and determined the location of incised river channels and prior inlet channels at the marine margin of the estuarine lake (Fig. 4).

3.2 Vibracores

Fourteen semi-undisturbed cores of unconsolidated sediment were extracted from the estuarine lake using a petrol-operated vibracorer (Fig. 2; Table 2). The cores were obtained from the marine-influenced facies and the fluvial bay-head delta. The retrieved cores were opened and visually logged documenting color, sediment texture, lithological composition, and significant facies changes. The cores were adjusted for compaction (measured depth vs. recovered depth) and compiled data were plotted into the graphic logging program WinLoG 3.12 (GAEA Technologies; see Fig. 9).

3.3 Faunal assemblages

Faunal assemblages from the major sedimentary units were described to determine their palaeo-ecological significance and to determine depositional environments of sedimentary successions preserved in Burrill Lake. A visual assessment of the nature of preservation and relative abundance of macrofossil populations was made on the vibracores collected. The macrofossils were collected by dividing the cores into obvious divisions related to shell density. The collected samples were then washed and the macrofossils present were identified. The relative abundance of individual molluscan species in relation to specific facies divisions was determined (Table 1). As Roy (1981) noted, this qualitative analytical method provided a quick faunal population assessment, as counting individual tests would be time consuming and impractical. Nevertheless, the use of the visual population assessment provided a good estimate of the faunal assemblages in each sedimentary facies preserved within incised valley succession.

4. Geochronology

4.1 Thermoluminescence age determination

One sample of bleached unconsolidated medium-grained sand was submitted for thermoluminescence (TL) analysis at the University of Wollongong. The sample was obtained from a vibracore that penetrated the antecedent Pleistocene landsurface in the back-barrier environment (core BUR8; Figs 2, 8 and 9). Sediment submitted for this analysis was collected from the relatively homogenous "A" horizon of the remnant barrier sands ensuring an even radiation flux, and the sample would not have undergone significant water-content variation, accumulation of clay minerals or organic detritus, or experienced significant diagenetic changes during Holocene burial (core BUR8; Fig. 9). The sample comprises medium-grained, moderately to well-sorted bleached quartzose sand dominated by rounded to well-rounded frosted quartz grains suggesting aeolian reworking and it is interpreted as remnant barrier sands. The sample was sealed to prevent light exposure and preserve prevailing moisture. TL-sensitive mineral fractions were prepared for dating following techniques employed at the University of Wollongong (Shepherd and Price, 1990; Nanson et al., 1991; Price et al., 2001). A TL delineated age of >84.4±4.1 ka BP was obtained from these sediments. As this deposit displays characteristics of aeolian reworking and minor post-emplacement diagenetic alteration it is suggested that the sample was originally deposited in a marginal marine back-barrier environment during the Last Interglacial sea-level highstand. The sediment may have been subsequently reworked and bleached (reset) by aeolian processes during a period of lower sea-level following the Last Interglacial.

4.2 Amino acid racemisation

Amino acid racemisation is a bio-chemical dating method that measures the relative abundance of amino acid isomers preserved within organic materials. The application of amino acid dating method has traditionally been used for the study of Quaternary coastal successions (Miller and Brigham-Grette, 1989; Wehmiller, 1993; Murray-Wallace, 1995, 2000; Wehmiller and Miller, 2000). However, Goodfriend (1991, 1992) and Goodfriend et al., (1992) highlighted the potential of aspartic acid (Asp), one of the fastest racemising amino acids, for the dating of early Holocene to recent sediments (10,000 cal yr BP to ca. 50 years). More resent research by Sloss et al. (2004a, b, 2005a, b, in submission) has shown that the extent of Asp racemisation observed in fossil molluscs preserved in Holocene back-barrier sedimentary successions can provide numeric ages between ca. 8000 yr and <100 yr ago.

Sample preparation and analytical techniques undertaken during this study follow the procedures outlined in Murray-Wallace and Kimber (1987), Murray-Wallace (1993) and Sloss et al. (2004a). Average amino acid D/L ratios for each sample analyzed were based on at least three replicate injections on a Hewlett-Packard model 5890A series II Gas Chromatograph at the Amino Acid Dating Laboratory, University of Wollongong, NSW, Australia. Asp racemisation-derived ages were obtained with reference to the radiocarbon dated shells and the degree of Asp racemisation using an apparent parabolic kinetic model. This permitted a direct comparison between the degree of Asp acid racemisation and fossil age (Sloss et al., 2004a, b, 2005a, in submission). Numeric ages for subsequent Asp D/L ratios obtained from fossil molluscs collected from Burrill Lake were calculated following the protocol proposed by Mitterer and Kriausakul (1989) and Sloss et al. (2004a, 2005b) and using the following formula (Table 1);

$$t = [(D/Ls - D/Lm) / Mc]^2$$

where:

- t is the calculated age;
- D/Ls is the average D/L ratio of multiple analyses on a specimen of unknown age;
- D/Lm is the D/L ratio for a modern sample of the same species as D/Ls; and
- Mc is the slope of the regression line, defined as $[D/L_{cal}/t^{1/2}]$ where D/L_{cal} is the extent of racemisation in a fossil of known age and $t^{1/2}$ is the square root of fossil age.

4.3 Radiocarbon age determinations

Radiocarbon ages obtained for this paper utilized both conventional and accelerator mass spectrometry (AMS) dating methods for fossil molluscs collected from sedimentary successions preserved in incised valley fill successions (Table 2). The conventional radiocarbon age was obtained from the Waikato University, New Zealand, and AMS radiocarbon ages were obtained from the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, New South Wales. Radiocarbon ages used in this thesis have been calibrated to sidereal years (calendar age) using the radiocarbon calibration program CALIB^{TM} REV4.4.2 (Stuiver et al., 1986, 1998a, b). The calibration was made using the marine model calibration curve with a Δr value of -1±70 yr to correct for the marine reservoir effect for the southern Australian coastal and estuarine waters (-450 ± 35 a;

Gillespie and Polach, 1979). We present the calibrated radiocarbon ages (cal yr BP) using a 2-sigma uncertainty term (95% degree of confidence; Table 2).

5. Results

5.1 Seismic profiles

Throughout the basin the seismic profiles obtained using the Towfish sonar are generally similar, starting with a strong acoustic reflector representing the bedrock basement (Figs 5 and 6). The valley axis material resting over the strong acoustic reflector starts with up to 3 m of seismically homogeneous material forming a massive fill in the base of channels, most likely representing antecedent Pleistocene or LGM fluvial sedimentary fill. Overlying the seismically homogeneous material is a ca. 2 m thick sequence of strong multi-layered reflectors forming a prominent lower marker throughout the estuarine lake. The seismically well-laminated succession at the base of the Holocene fill may represent deposition during variable energy levels within the embayment during the most recent PMT prior to the development of the coastal sand barrier. Overlying the seismically well-laminated succession is 1-2 m of massive fill then another prominent upper single reflector. The massive (seismically homogenous) sequence is probably related to the slow and relatively uniform accumulation of estuarine mud in sheltered areas and deeper portions of the incised valley behind the initial coastal barrier following the culmination of the most recent PMT. The prominant internal acoustic reflector is probably related to compaction and dewatering of the estuarine muds and/or laterally extensive shell beds. This seismic unit grades upwards into a 4-6 m thick unit of acoustically transparent material. This almost seismically transparent sequence equated to the uniform accumulation of estuarine mud deposited as a near basin-wide sequence following the stabilization and growth of the Holocene barrier. A very faint reflector at about half height within this seismic unit and is also probably related to compaction and dewatering of the estuarine muds and/or laterally extensive shell beds.

At the marine margin the seismic profile obtained using the Geo-acoustic boomer starts with a strong prominent reflector between -5 m and extending to ca. -30 m and represent the surface of the antecedent Late Pleistocene substrate (Figs 7 and 8). Overlying the strong basal reflector is a sequence of seismically massive fill that ranges between 2 m to ca. 20 m thick in the Bungalow Park area (Figs 7 and 8). Discontinuous sub-parallel internal laminae showing on-lap and top-lap occur within this unit, suggesting that this unit was deposited in a higher-energy regime most likely associated with the most recent PMT when shoreward prograding sediments breached the Last Interglacial remnant barrier and filled the LGM incised channel in the Bungalow Park area. Overlying the PMT deposits is a laterally extensive single prominent reflector representing the top of the Late Pleistocene substrate and the base of the mid to late Holocene sedimentary succession. The overlying seismic unit is up to 6 m thick and contains relatively continuous and laterally extensive internal reflectors. It represents flood-tide delta and back-barrier sedimentary successions deposited after the culmination of the most recent PMT and during the Holocene sea-level highstand. At the westward margin of the marine influenced facies the flood-tide delta deposits drop off sharply to depths of ca. 9 m and interfinger with the central basin mud facies represented by strongly laminated horizontal reflectors (Figs 7 and 8).

5.2 Low-stand incised bedrock valley

The actual position of the lowstand palaeo-channels and the extent of the preservation of Pleistocene sediments cannot be accurately defined in the northern part of the estuary due to entrapped gas produced from the thick sequences of organic-rich Holocene estuarine mud, and extensive sea-grass beds in the shallow margins. Both attenuate the seismic penetration and thus the profile imaging of the underlying strata. Similarly, delineation of the depth to bedrock basement around the tidal entrance channel and flood-tide delta have been complicated due to the thick deposits of marine sand in this locality. However, the most-likely location of the incised bedrock channels is based on the seismic sections obtained from the central basin and southern limb, as well as the location of the bounding bedrock margin of the estuarine lake (Fig. 4). In the deeper portions of the central basin and the southern limb of the estuarine lake seismic profiles indicated the presence of a duel cut-and-fill phase that is relatively sharply incised into the bedrock valley and Late Pleistocene valley fill successions (Figs 5 and 6).

Results from the seismic stratigraphy in the central basin to the north of Kings Point indicated that the depth of the incised bedrock valley extends to ca. 14 m (Fig. 5a). In the deeper portions of the central basin and the southern limb the incised bedrock valley extends to a depth of between 20 and 22 m (Figs 5b and 6). At the seaward margin of the estuarine lake the depth to the incised bedrock valley is difficult to ascertain due to the thick sequences of marine sand within the mouth of the incised valley. However, seismic profiles indicate that up to 30 m of sand has accumulated within the lowstand incised channel in the Bungalow Park area (Figs 7 and 8). Taking into account that the incised bedrock valley in the central basin extends to ca. -20 m where the two limbs converge and that the valley-fill succession at the marine margin extend to depths of ca. -30 m, the bedrock valley must be >30 m in this region and would extend to ca. 40 m at the mouth of the incised bedrock valley (Fig. 4).

5.3 Pleistocene sedimentary successions

The seismic stratigraphy of Burrill Lake indicates that the incised valley contains a second phase of cut-and-fill represented by a lowstand valley incised into remnant Late Pleistocene sediments most likely during the LGM. In the central basin and deeper portions of the southern arm Late Pleistocene deposits have been partially removed during the lowstand of sea-level and only occur in the deeper portions of the incised valley (Figs 5 and 6). This is clearly evident along much of the margin of the estuarine lake where Permian sandstone outcrops form benches or low cliffs, which are overlain by the Holocene muddy-sand facies that rims the estuarine lake in water depths <2 m and by laminated estuarine mud to depths of ca. 7 m in the deeper portions of the lagoon (Figs 5 and 6).

Based on seismic stratigraphy, preservation of Pleistocene successions is evident in both the northern limb near Kings Point and in the southern limb (Fig. 5a) where these earlier deposits have been partially eroded by a steep-sided small channel incised down to -10 m, presumably during the LGM. Further evidence of Pleistocene deposits can be seen in the central basin where up to 5 m of probable Pleistocene material lies between the bedrock and the Holocene fill (Fig. 5b). The second phase of fluvial incision into remnant Pleistocene deposits follows the same axial trend as the incised bedrock valley and extends to depths of ca. 15 m in the deeper portions of the central basin and the southern limb (Fig. 6). However, these conclusions are based on seismic data, and it is difficult to ascertain the nature of the sediments preserved in the valley axis due to problems associated with obtaining samples from greater water depths. These sediments may represent older estuarine clays or remnant Last Interglacial transgressive deposits similar to those observed in St Georges Basin and Lake Illawarra (Sloss et al., 2004a, b, 2005b, in submission).

At the seaward margin of the estuarine lake Late Pleistocene barrier deposits have been partially preserved and underlie much of the Holocene flood-tide delta and barrier sediments (Figs 7 and 8). Seismic profiles indicate that the second phase of fluvial incision reached a maximum depth of 30 m in the Bungalow Park region (Fig. 7a). However, Pleistocene deposits in the present inlet channel and along the seaward margin of the southern limb occur within 3 m of the water/sediment interface (Figs 7b and 9). The Pleistocene deposits comprise fine- to medium-grained bleached quartzose sand that is moderately to well-sorted. These sands are typically white, yellow or light grey with minor mottling. This facies has very few lithic constituents, very little carbonate content and is dominated by rounded to well-rounded frosted quartz grains suggesting aeolian reworking. It is interpreted as remnant barrier sands. A TL age determination obtained from the remnant barrier sediments yielded a minimum age of >84.4±4.1 ka BP (Fig. 9a). The characteristics of the sediment and age of this facies suggest that the sand represents a remnant Last Interglacial barrier system that has undergone minor post-emplacement aeolian reworking and diagenetic alteration.

From the seismic data and the position of the bedrock embankments around the margin of the estuarine lake, the position of the lowstand valleys has been delineated (Fig. 4). In Burrill Lake the bedrock incised valley and the LGM lowstand valley follow the same valley axis, merging into a single channel just south of Kings Point. The valley cuts through the Last Interglacial remnant barrier system in the Bungalow Park area and exits the incised valley system to the north of Dolphin Point (Fig. 4).

5.4 Holocene marine influenced facies

Thick deposits of marine sand have been transported into the mouth of the incised valley in the Bungalow Park area during the most recent PMT forming a coastal barrier and an exposed low-lying sandy bar extending ca. 2.5 km into the estuarine lake (Fig. 2). This accumulation of marine sand represents the landward progradation of sediment from the continental shelf during the most recent PMT and subsequent sea-level highstand and is represented by two distinct facies:

- a basal quartzose carbonate-rich sand with a mix of nearshore and estuarine molluscan fauna; and
- an overlying medium-grained quartzose sand with a impoverished faunal assemblage grading up core to an organic-rich quartzose sand with sea-grass colonization.

The basal Holocene sand facies lies unconformably over the antecedent Last Interglacial remnant barrier system and comprises unconsolidated medium- to coarse-grained, rounded to sub-rounded quartz and carbonate-rich marine sand that has only minor lithic constituents. This suggests the sand was sourced from sediment stored on the continental shelf and it prograded landward with rising sea levels during the most recent PMT rather than being sourced from the surrounding catchment, which is composed of lithic sandstone and monzonite. Faunal elements within the transgressive sandsheet show a dominance of the gastropod *Astele subcarinata* and minor occurrence of *Bankivia fasciata* and *Zeacumantus diemenensis*, as well as common to abundant specimens of the bivalves *Brachidontes rostratus* and *Katelysia scalarina*, and rare *Dosinia crocea* and *Fulvia tenuicostata*. All these molluscs typically inhabit low- to high-energy sandy shores and rock reefs in the lower littoral zone in nearshore environments (Ludbrook, 1984; Yassini, 1984; Jensen, 1995, 2000; Fig. 9; Table 1). Also occurring within the transgressive sand are rare to common specimens of the bivalves *A. trapezia*, *N. trigonella* and the gastropods *Batillaria australis*, *Zeacumantus diemenensis* and *Nassarius jonasii*, molluscs that typically inhabit estuarine sand-flats (Ludbrook, 1984; Yassini, 1984; Jensen, 1995, 2000; Fig. 9; Table 1). The transgressive deposit also contains rounded clasts of indurated quartz-rich sediment showing similar characteristics to the underlying Last Interglacial remnant barrier succession.

Asp racemisation-derived ages obtained on specimens of *A. trapezia* and *K. scalarina* collected from the base of the transgressive deposit range between ca. 7,500 – 7,000 years (7,220±380 yr, UWGA-1358; 6,910±320 yr, UWGA-1356; Fig. 9b; Table 1). Similarly radiocarbon ages of 7,770±160 cal yr BP (OZH-285, BUR8) and 7,290±160 cal yr BP (OZG-749, BUR9) were obtained on specimens of *A. trapezia* and *K. scalarina* (Fig. 9; Table 2). The age determinations on fossil molluscs from the base of the transgressive deposit indicate that the initial deposition of this facies occurred between ca. 7,800 and 7,000 years ago. Asp racemisation-derived ages of 4,420±200 yr (UWGA-1354, BUR9) and 4,670±210 yr (UWGA-1357, BUR9) obtained on specimens of *A. trapezia* and a radiocarbon derived age of 4,790±240 cal yr BP (OZH-293, BUR9; Fig. 9b) towards the top of the transgressive sand deposit indicate that more open marine conditions lasted until ca. 4,500 years ago.

At the seaward margin of the estuarine lake the shell-rich transgressive deposit is overlain by olive/brown moderate to very poorly sorted medium-grained sand. This facies forms broad sub-horizontal back-barrier sand-flats colonized by *Posidonia* and *Zostrea* sea-grass beds. This facies also contains random individuals and isolated shell beds dominated by the estuarine molluscs *A. trapezia* and *N. trigonella* along with *B. australis* (Table 1). Asp racemisation-derived ages of 1,160±60 yr (UWGA-1095) and 1,080±50 yr (UWGA-1424) obtained *A. trapezia* towards the top of this facies indicates that active sedimentation in the back-barrier sand-flats continued from ca. 4,500 years ago until ca. 1,000 years ago. The upper 0.5 to 1 m of this facies has a significant increase in organic matter associated with sea-grass beds, and in places contains common to abundant disarticulated, fragmented and weathered *A. trapezia*, *N. trigonella* and *B. australis*. The presence of the organic-rich facies and the fossil death assemblage suggests that active sedimentation had ceased allowing colonization by sea-grass and the reworking of this facies by internally generated wind-waves and currents. Landwards, the back-barrier sand-flat facies grades to muddy sand and inter-fingers with the central basin muds facies (Figs 7b and 8).

5.5 Holocene central basin facies

Unconformably overlying the antecedent Pleistocene landsurface is 1-2 m of strong multi-layered reflectors (Figs 5 and 6). This seismically well-laminated succession near the base of the Holocene fill occurs throughout the lagoon and possibly represents deposition in variable energy levels within the embayment during the most recent PMT and prior to the development of the coastal sand barrier. These well-laminated successions are presumed to be synchronous with the deposition of the transgressive deposits at the seaward margin of the estuarine lake as both form basal Holocene sequences. Overlying the well-laminated succession is a seismically homogeneous unit with a prominent internal acoustic reflector that may relate to a dewatering surface due to sediment compaction or to laterally extensive shell beds. This sequence probably represents slow and relatively uniform accumulation of estuarine mud in sheltered areas and deeper portions of the incised valley following the stabilizing of sea-level and the early development of the Holocene barrier in its present location, i.e. onset of the low-energy back-barrier environment (Figs 5 and 6).

The upper parts of the seismic profiles are generally acoustically transparent or contain a very faint reflector (Figs 5 and 6). This seismic facies is interpreted as the deposition of the central basin mud facies comprising fine-grained terrigenous detritus supplied from the freshwater streams entering the low energy back-barrier depositional environment. This facies is composed of very fine-grained grey/black estuarine silty clay, with considerable organic detritus characteristic of an anoxic environment (Jones et al., 2003). This silty clay represents the full development of the low-energy estuarine environment, facilitated by emergent Holocene barrier systems and the further restriction of open marine oceanic water circulation.

The timing of this change to the near basin-wide low-energy central basin mud facies occurred ca. 4,500 years ago. The timing of this transition can only be regarded as an estimate based on the cessation of the more open marine conditions observed at the marine margin of the incised valley that last until ca. 4,500 years ago. However, these conclusions are consistent with the timing of the transition to low-energy back-barrier environments observed in Lake Illawarra and St Georges Basin (Sloss et al., 2004a, 2005b, in submission).

5.6 Fluvial dominated facies: Stony Creek

The fluvial-influenced facies associated with the landward margin of Burrill Lake is dominated by the progradation of the Stony Creek delta in the northern arm of the estuary (Fig. 2). This very shallow sandy bay-head delta extends ca. 1 km into the estuary. Due to a limited catchment, the equivalent bay-head delta in the southern arm is small and fluvial sediments are restricted to organic-rich sandy mud pro-delta deposits that are extensively colonized by sea-grass.

Shallow vibracores collected from the Stony Creek region permit the stratigraphic sequence to be determined (Fig. 10). The results of the facies analysis show that the delta consists of ca. 2-3 m thick muddy sand. Faunal elements within earlier bay-head delta sands are preserved in shell beds in the river banks and redistributed onto the delta top. This faunal assemblage is composed predominantly of disarticulated, fragmented and bleached fossil molluscs. However, isolated individuals and relatively small shell beds of articulated and well preserved fossil molluscs randomly occur within this facies suggesting a mix between fossil life and death assemblages. A radiocarbon age of 0-310 cal yr BP (OZG-229, BUR3) and an Asp racemisation-derived age of ca. 50 yr obtained on articulated specimens of *N. trigonella* collected from the in situ life assemblage preserved within this facies point to a recent phase of deposition.

The death assemblage preserved in the fluvial bay-head delta contains a mix of purely estuarine molluscs and molluscs that are more characteristic of an estuarine environment open to direct oceanic influences. The latter include *Saccostrea glomerata*, *Barbatia pistachia*, *D*osinia *crocea*, *A*ustrocochlea *constricta*, *A*stele *subcarinata*, *Z*eacumantus *diemenensis* and *B*edava *paivae*. An aspartic acid derived age of 4,570±70 yr (UWGA-890) obtained on a specimen of *A. trapezia* from this facies is consistent with the timing of the deposition of the transgressive deposit at the seaward margin of the estuary (ca. 7,800 – 4,500 cal yr BP). The occurrence of the more marine specimens of fossil molluscs and the mid Holocene age suggests that the fossil assemblage preserved in the modern bay-head delta was eroded from older transgressive deposits that accumulated when the incised valley was more open to direct marine influence.

Landward, the bay-head delta sands are underlain by coarse- to very coarse-grained fluvial channel sands that grade in a westerly direction to a thick sequence of peaty mud associated with pro-delta deposits, and eventually into cohesive estuarine muds with isolated peat lenses. Faunal elements preserved in the pro-delta deposits are dominated by the estuarine molluscs *A. trapezia*, *N. trigonella and T*ellina *deltoidalis*. Asp derived-ages obtained from fossil molluscs preserved in the fluvial pro-delta deposits indicate that delta progradation into the present lagoon occurred over the last 300 years (Fig. 10; 320±20 yr, UWGA-1089; 310±20 yr, UWGA-1094).

Underlying the fluvial channel sands and the peaty pro-delta muds is shell-rich muddy sand. Faunal elements within this facies are dominant by articulated and disarticulated specimens of *A. trapezia* and *N. trigonella* that are interpreted as a back-barrier sand-flat deposited ca. 2,500 – 2,000 years ago (Fig. 12; 2,500±120 yr, UWGA-1087, BUR1; 1,940±90 yr, UWGA-1092, BUR4). This facies is, in turn, underlain by cohesive estuarine mud that presumably extends down to the antecedent Pleistocene substrate or bedrock extending southwards beneath the estuarine lake.

6. Discussion: The geomorphological evolution of the Burrill Lake wave-dominated barrier estuary

Based on seismic stratigraphy, facies associations, fossil faunal assemblages and geochronological data, the geomorphological evolution of Burrill Lake has been determined. This geomorphological evolution can be divided into distinct phases associated with sea-level fluctuations including fluvial incision during the LGM and deposition during the PMT.

6.1 Lowstand incised valley system (Fig. 11a)

Based on seismic data and the position of Permian sandstone benches and small cliffs that rim the margin of the lagoon, the location of the lowstand incised valley channels has been determined (Figs 4 and 11a). Results indicate that the incised bedrock valley extends to depths of 15 m at the landward margin of the northern limb of estuarine lake. In the central basin the incised bedrock valley extends to a depth of ca. 20 m. Results from the seismic profiles and vibracores that penetrated the Holocene sedimentary successions indicate that the initial bedrock valley has subsequently been partially filled with Late Pleistocene sediments and that a second phase of valley during the LGM incision removed much of the Pleistocene sediments from the northern limb and central basin and where it is now confined to the valley axis. These sedimentary successions are presumed to comprise unconsolidated alluvium that was deposited during the LGM and/or older estuarine clays deposited during the Last Interglacial sea-level highstand.

In both the northern and southern limb the LGM lowstand valley reached depths of ca. 10 m. Where the two limbs converge the palaeo-channels coalesced into a single channel that incised into the Late Pleistocene substrate to depths of ca. -15 m. At the seaward margin a combination of seismic data and vibracores that penetrated the Holocene sedimentary successions identified the presence of a remnant Last Interglacial barrier system that has undergone aeolian reworking and minor post-emplacement diagenetic alteration. The Last Interglacial barrier still partly fills the mouth of the incised bedrock valley and provides a core on which the Holocene barrier system has stabilized (Figs 8 and 11a). In this region the LGM lowstand channel cut through the Last Interglacial remnant barrier in the location of Bungalow Park to a depth of ca. -30 m and exited the lowstand valley just to the north of Dolphin Point (Figs 8 and 11a).

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6.2 Most recent PMT (Fig. 11b)

Rising sea levels during the most recent PMT inundated the lowstand river channel and breached the Last Interglacial remnant barrier resulting in the development of a drowned river estuary or sheltered ocean embayment from ca. 7,800 – 4,500 years ago. It resulted in the deposition of relict flood-tide delta and transgressive deposits within the incised valley channel as a near basin-wide deposit (Fig. 11b). The deposition of a shell-rich transgressive deposit with a diverse mix of marine species, which typically inhabit medium- to high-energy nearshore zones, and estuarine molluscs represents reworked intertidal sand-flats, tidal channel sands and flood-tide delta indicates that Burrill Lake was more open to direct ocean influences as rising sea-levels inundated the incised valley, breaching and reworking the Last Interglacial remnant barrier system during the most recent PMT.

The presence of the estuarine fossil assemblage suggests that this early stage of Holocene sedimentation occurred in a mixed energy environment comprising intertidal sand-flats in a sheltered coastal embayment or drowned river estuary.

Supporting evidence for a near-basin wide transgressive deposit is the presence of reworked fossil molluscs that inhabit shallow-marine nearshore environments preserved in the prograding fluvial bay-head delta associated with Stony Creek ca. 5 km from the present coastline.

6.3 Holocene sea-level highstand (Fig. 11c)

Following the deposition of the transgressive deposits, marine sand continued to build up within the mouth of the incised valley resulting in the accumulation of a thick sand succession overlying the Last Interglacial remnant barrier. This probably formed a series of barrier beaches, flood-tide delta deposits and an embryonic Holocene barrier overlying the Last Interglacial remnant barrier system within the mouth of the incised valley. Nevertheless, more open marine conditions persisted until ca. 4,500 years ago when the infilling of the palaeo-inlet channel and the stabilizing of the Holocene barrier system in its present position restricted open ocean influences (Fig. 11c). During this time fine-grained estuarine mud accumulated in the deeper portions of the incised valley and in sheltered areas following the stabilizing of sea-level and the early development of the Holocene barrier in its present location. The infilling and eventual closure of the palaeo-inlet in the Bungalow Park area and the further growth and stabilization of the Holocene barrier resulted in greater restriction of open ocean influences. This resulted in the extension of a low-energy back-barrier environment and the central basin mud facies from ca. 4,500 years ago.

6.4 Fluvial progradation ca. 2,000 yr – present (Fig. 11d).

The final stage of geomorphological evolution in Burrill Lake is represented by the infilling of the barrier estuary from ca. 2,500 years ago to the present (Fig. 11d). At the landward margin this period of geomorphological evolution is dominated by progradation of the Stony Creek fluvial bay-head delta into the present estuarine lake (Fig. 11d). The initial sedimentation associated with Stony Creek post-dates the development of back-barrier sand-flats at the landward margin of the estuarine lake (ca. 2,500 – 2,000 years ago). Fluvial channel sands overlie the back-barrier sand-flats and indicate that initial fluvial progradation occurred sometime after 2,000 years ago as falling sea level following the Holocene sea-level highstand resulted in a decrease in accommodation space. Fluvial progradation is ongoing with extensive delta progradation occurring over the last 300 years.

At the seaward margin of the estuarine lake the final stage of geomorphological evolution represents the cessation of active accretion on back-barrier sand-flats (ca. <1,000 years ago) and the reworking of these sand-flats by internally generated wind-waves and currents. With the infilling of the early to mid-Holocene palaeo-inlet and the further growth and stabilization of the Holocene barrier the marine influenced facies were restricted to extensive shoaling of the inlet channel in its present location and the continued development of a small flood-tide delta at the mouth of the inlet channel (Figs 2 and 11d).

6.5 Barrier estuary evolution on the New South Wales southern coast

Research presented in this paper is consistent with results obtained from Lake Illawarra and St Georges Basin (Fig. 12a; Sloss et al., 2004a, 2005a, b, in submission). While all three estuarine systems are relatively shallow (<40 m) Burrill Lake is significantly smaller and the incised bedrock valley is much narrower than the previously described examples. Nevertheless, the stratigraphic evolution of the Burrill Lake estuary is similar to that observed in the larger and boarder estuaries on the southeast coast of Australia (Fig. 12a). This indicates that wave-dominated barrier estuaries on the New South Wales southern coast follow a similar evolutionary pathway that is significantly influenced by Holocene sea-level fluctuations, the palaeo-morphology of the incised valley and the amount of preserved Last Interglacial remnant barrier. The early stage of sedimentary infill in both broad and narrow incised valley systems was initiated when rising sea levels during the most recent PMT breached the antecedent Last Interglacial remnant barrier ca. 8,000 years ago (Fig. 12). This resulted in the deposition of a near basin-wide shell-rich transgressive deposit unconformably over the antecedent late Pleistocene land surface with the estuarine systems operating as sheltered ocean embayments or drowned river estuaries open to direct oceanic influences. More open marine conditions lasted to some time between 5,000 and 4,000 years ago when growth and stabilization of the Holocene barrier systems restricted open ocean influences and resulted in the development of extensive back-barrier sand-flats, mud basins and the eventual progradation of fluvial bay-head deltas (Fig. 12).

7. Conclusions

The geomorphological evolution of barrier estuaries that formed in narrow and relatively shallow incised valleys has been shown to be different to previously established models of Holocene barrier estuary evolution. In particular, the early stage of sedimentary infill is characterized by deposition of a near basin-wide transgressive sandsheet extending up to near present sea-level. The transgressive sandsheet disconformably overlies the antecedent Pleistocene land surface and was deposited as rising post-glacial sea-level breached the remnant Last Interglacial barrier and inundated the incised valleys from ca. 8,000 years ago. This stratigraphy contrasts with previous established models for barrier estuary evolution on the southeast coast of Australia, where transgressive sandsheets were said to be restricted to the mouths of incised valleys and back-barrier central basin muds lie directly over the antecedent Pleistocene land surface. However, results from this paper are consistent with recent research conducted in Lake Illawarra and St Georges Basin and adds to the growing evidence that more extensive marine-influenced transgressive deposits form the basal Holocene successions in coastal lagoons as a result of rising sea levels during the most recent PMT.

Acknowledgements

We wish to thank the following for financial support; the School of Earth and Environmental Sciences, University of Wollongong; GeoQuEST, University of Wollongong; an Australian Postgraduate Scholarship; and an Australian Institute of Nuclear Science and Engineering (AINSE) Postgraduate Award. AMS radiocarbon ages were obtained from the Australian Nuclear Science and Technology Organization under the AINSE grant numbers PGR5/02 and 02/069P. Thermoluminescence analysis was undertaken by David Price at the University of Wollongong. We also thank the Research Council of Colgate University, Hamilton, New York, for funding assistance in obtaining seismic data.

Table 1: Relative abundance of fossil molluscs preserved in Holocene facies in Burrill Lake.

Species	Habitat	MTS	BBSF	CBM	FPD/FBS	FBD
Anadara trapezia	Estuarine mud and sand-flats	A^{AD}	$A*^{AD}$	R^{AD}	A^{AD}	A^{D}
Astele subcarinata	Shallow marine nearshore	A	-	-	-	-
Austrocochlea constricta	Shallow marine nearshore	A*	R	-	-	-
Barbatia pistachia	Shallow marine nearshore	R-C	-	-	-	-
Bankivia fasciata	Shallow marine nearshore	R-C	-	-	-	-
Batillaria australis	Estuarine mud and sand-flats	A	A	R	C	VC
Bedava paivae	Intertidal in sheltered bays	C	R	R	R	-
Brachidontes rostratus	Shallow marine rocky reefs	$C\text{-}A^{DF}$	-	-	-	-
Dosinia crocea	Shallow marine nearshore	R^{AD}	-	-	-	-
Epitonium helicornum	Shallow marine nearshore	VR	-	R	-	-
Eumarcia fumigate	Intertidal in sheltered bays	R^{D}	-	-	-	-
Fulvia tenuicostata	Shallow marine nearshore	R^{D}	-	-	-	-
Katelysia scalarina	Shallow marine nearshore	$C\text{-}A^{F}$	R	-	-	-
Nassarius jonasii	Estuarine mud and sand-flats	C	C	C	C	C
Notospisula trigonella	Estuarine mud and sand-flats	C^{AD}	VC^{AD}	$A*^{AD}$	$A*^{D}$	$A*^{D}$
Ostrea angasi	Intertidal in sheltered bays	C^{D}	-	-	-	-
Polinices conicus	Shallow marine nearshore	C	C	-	-	-
Polinices sordidum	Intertidal in sheltered bays	C	C	R	-	-
Pyrazus ebeninus	Estuarine sand-flats	R	-	-	-	-
Tellina deltoidalis	Estuarine mud and sand-flats	R^{D}	C^{AD}	C^{AD}	VC^{AD}	A^{D}
Saccostrea glomerata	Intertidal in sheltered bays	C	-	-	-	-
Zeacumantus diemenensis	Estuarine mud and sand-flats	C	-	R	-	-

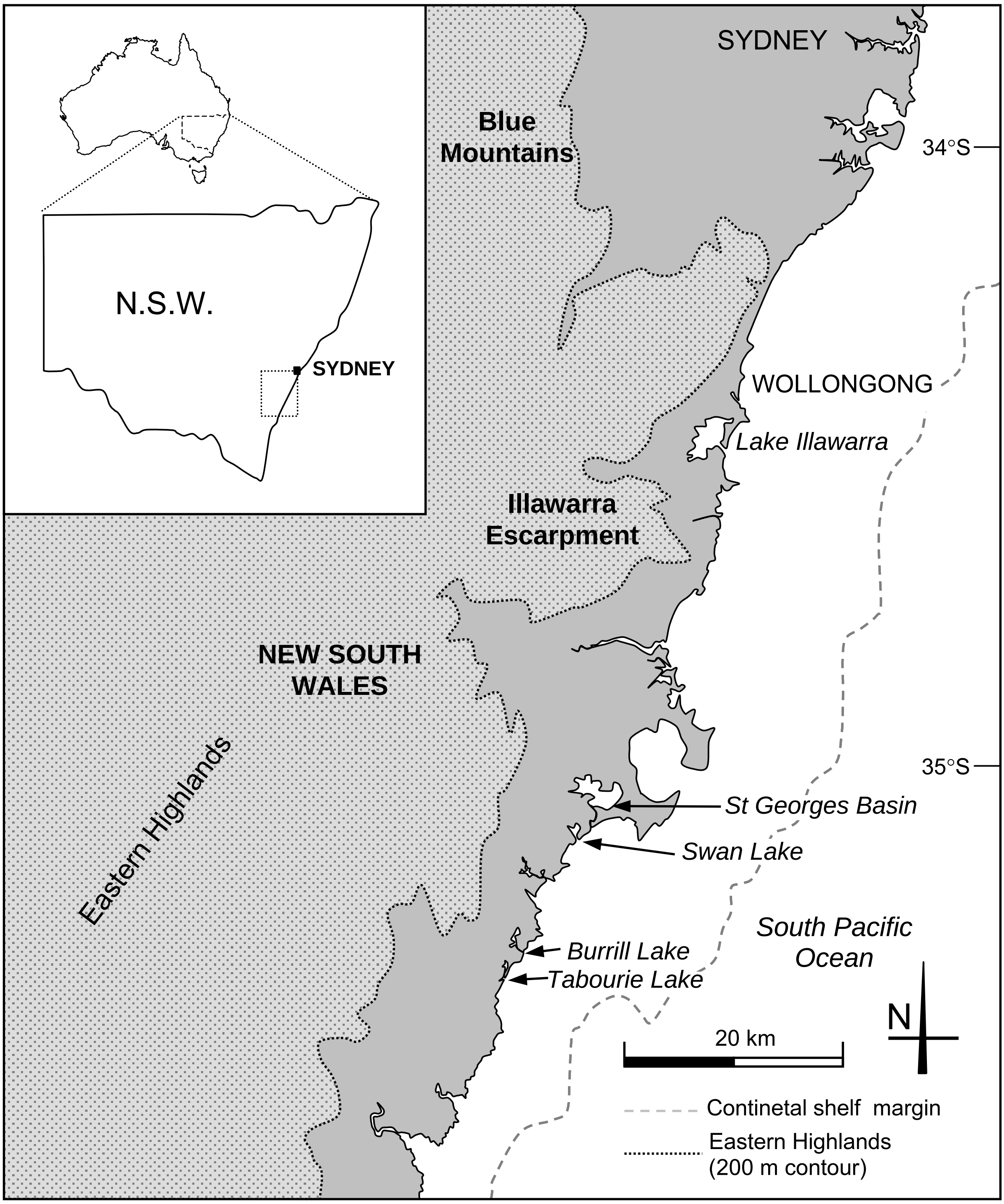
MTS: Marine transgressive sandsheet
BBSF: Back-barrier sand-flat
CBM: Central basin mud facies
FPD/FBS: Fluvial pro-delta/baskswamp
FBD: Fluvial bay-head delta

VR= very rare
R= rare
C= common
VC= very common
A= abundant

* = dominant species
^{D} = mainly disarticulated
^{A} = mainly articulated
^{F} = mainly fragments

FIGURES

Figure 1 (double column)



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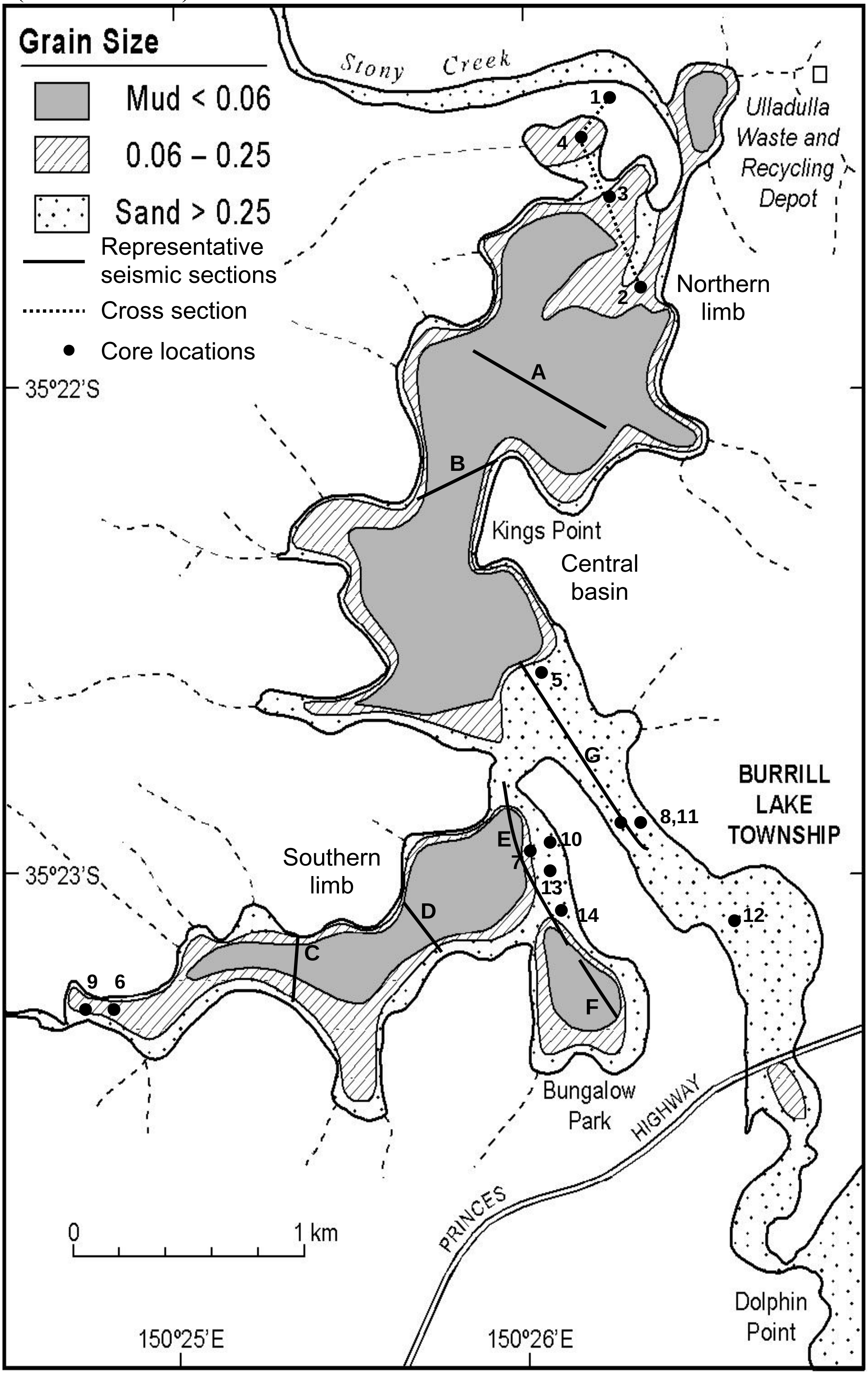

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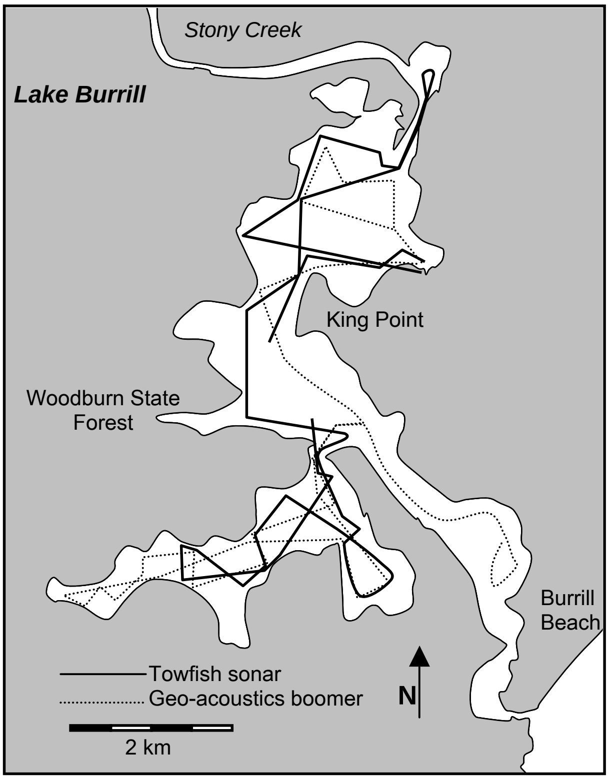

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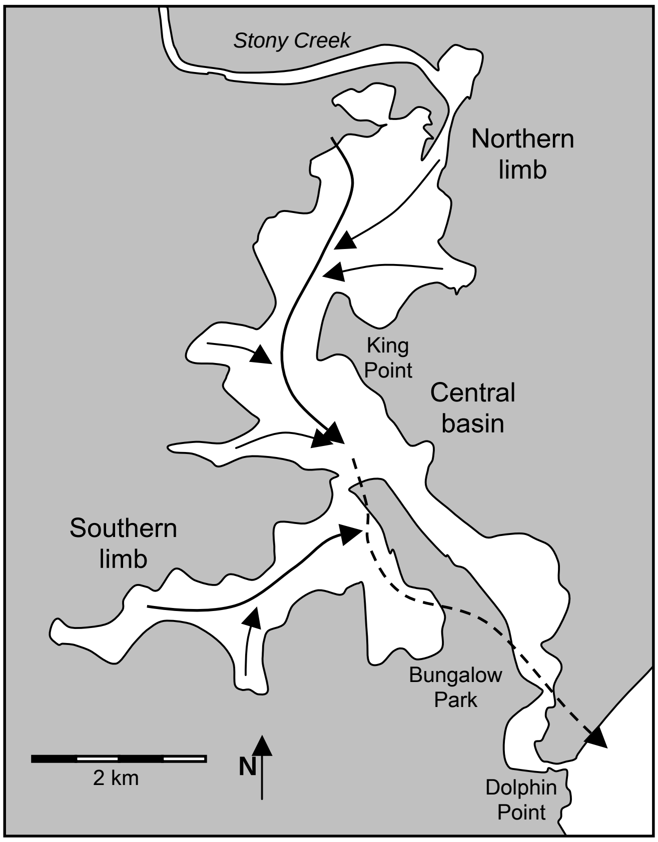

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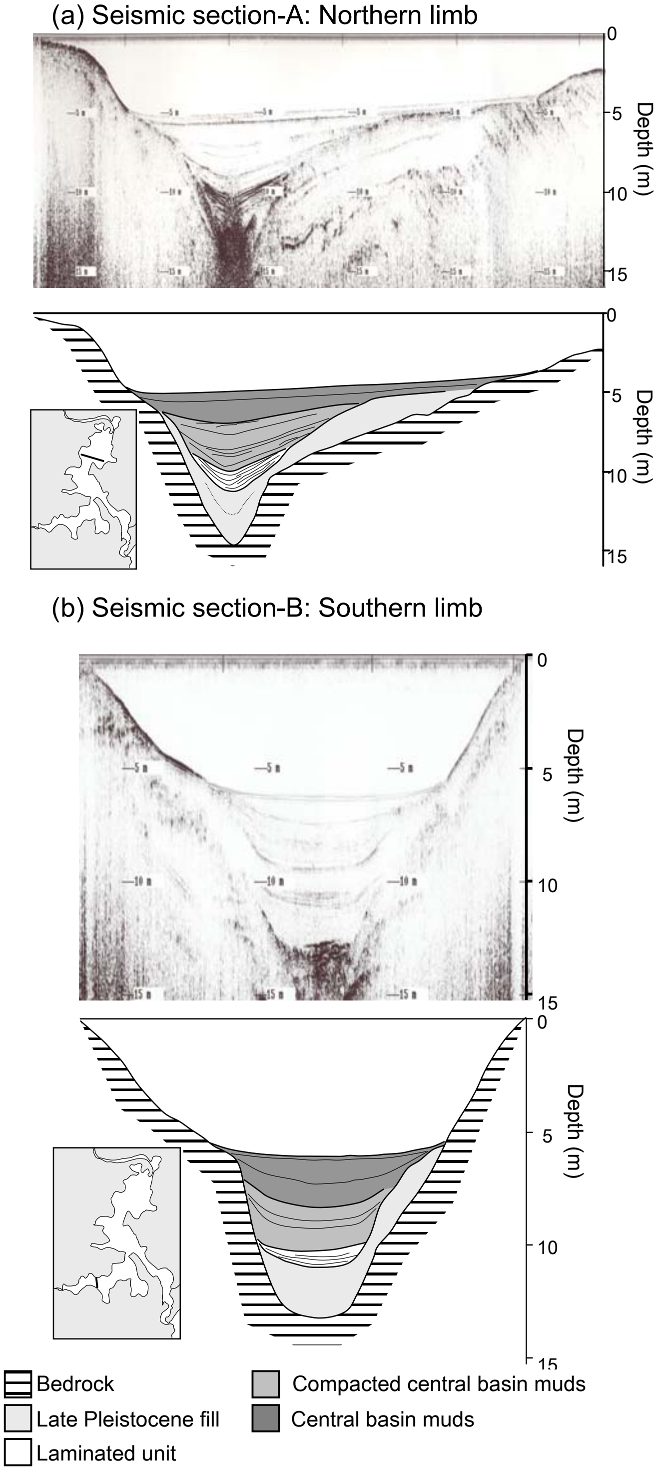
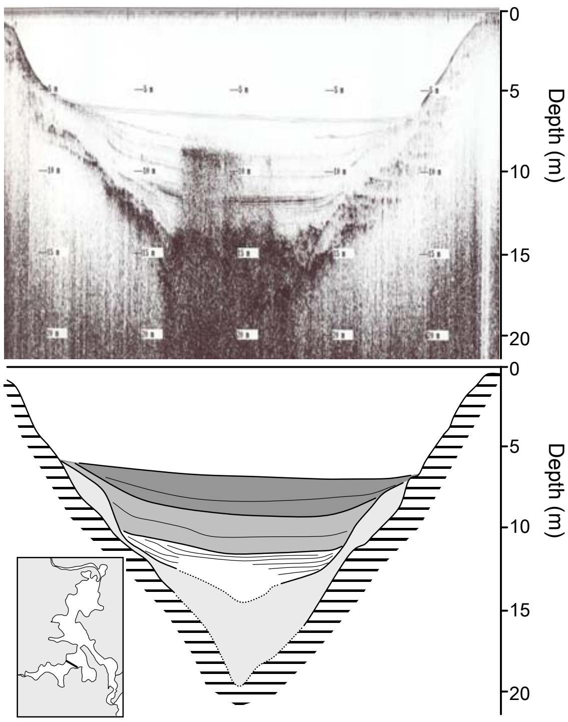
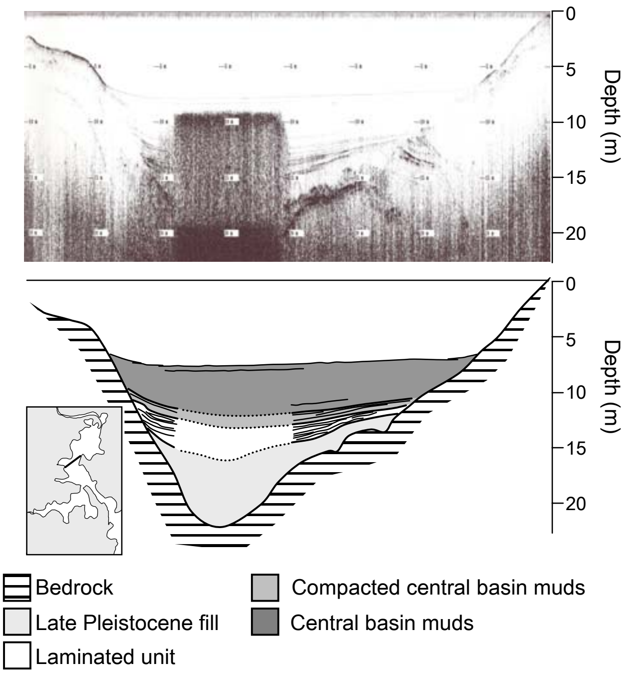


Figure 6 (single column)

(a) Seismic section-C: Central basin



(b) Seismic section-D: Southern limb



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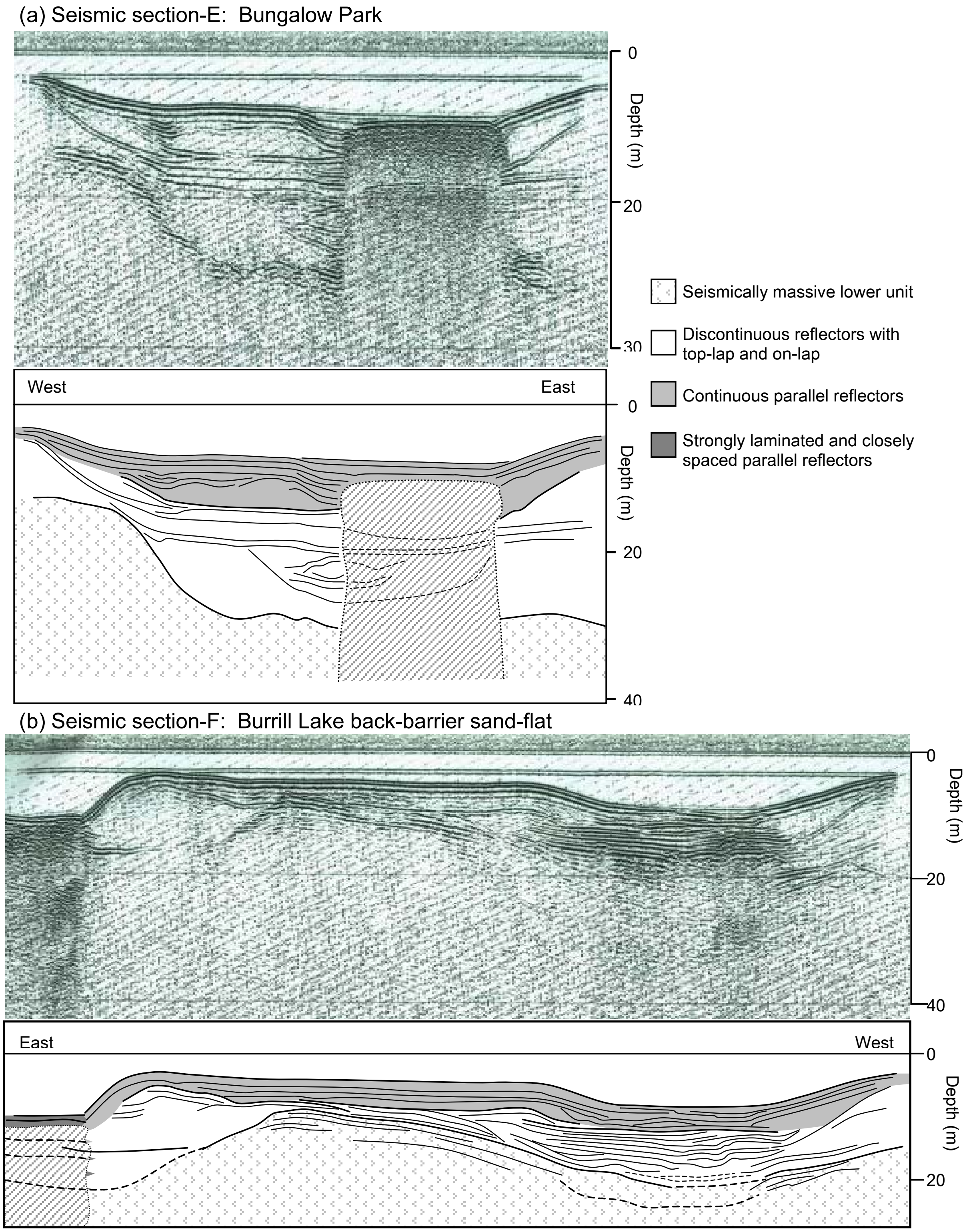

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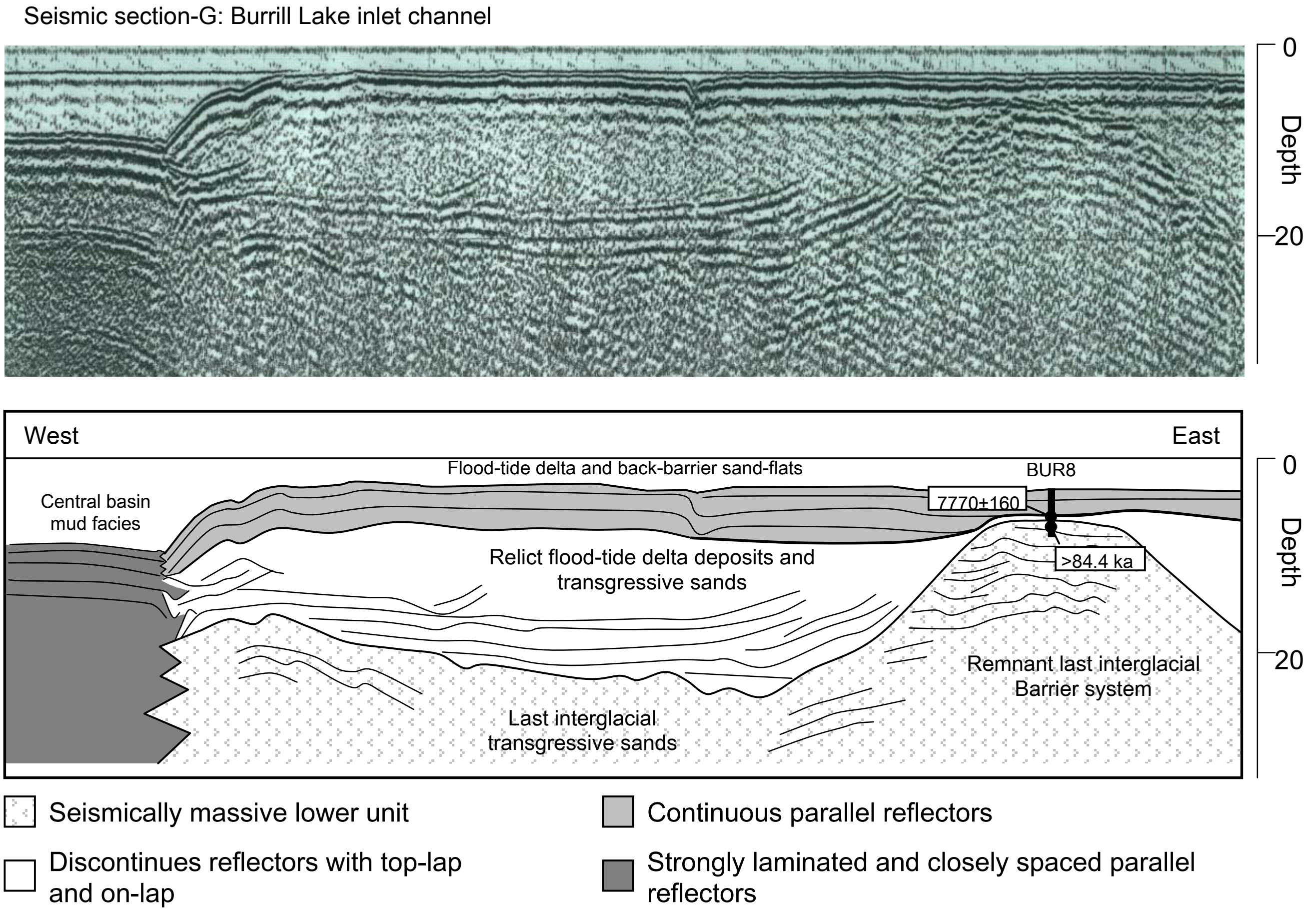
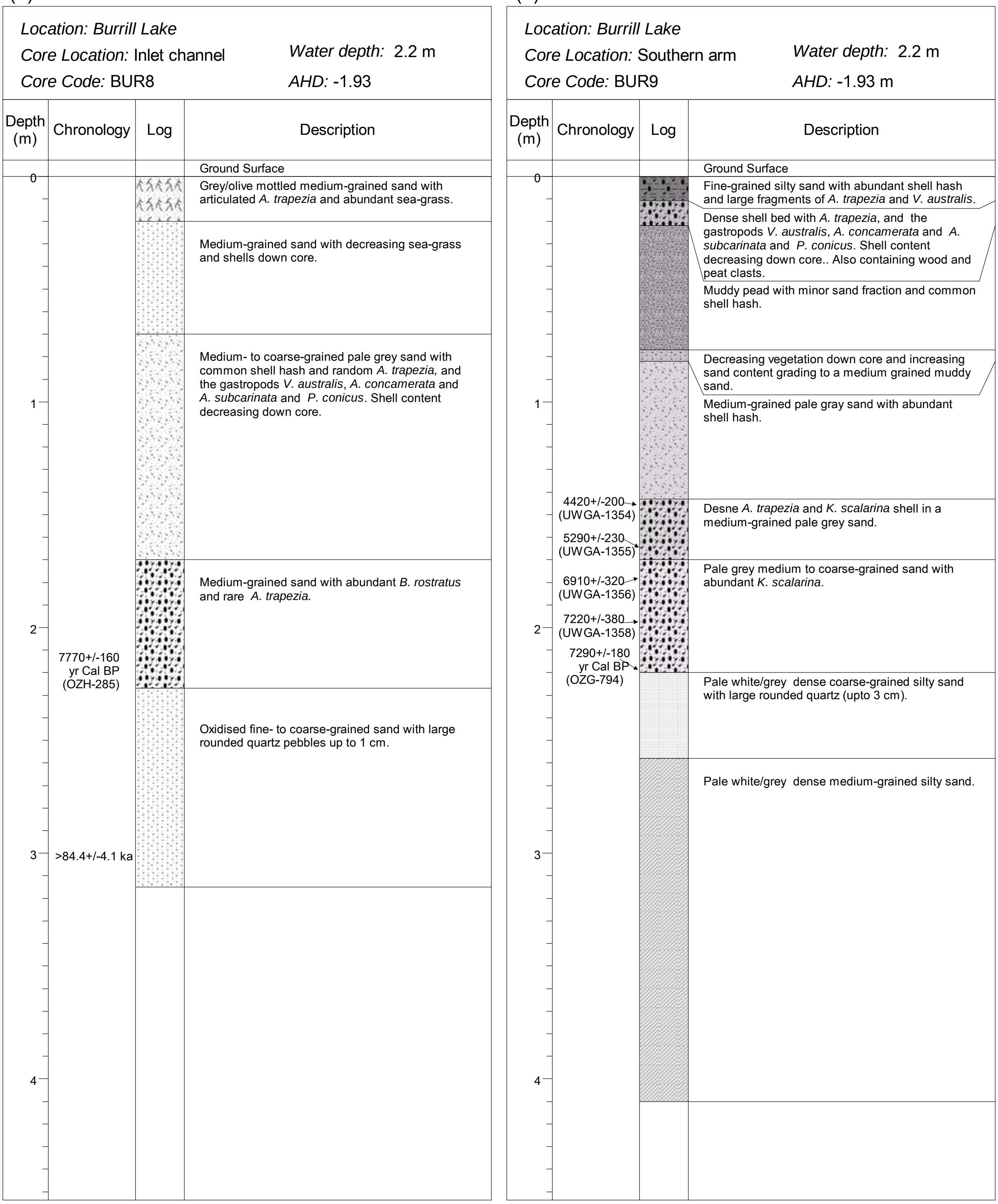


Figure 9 (double column)

Representative vibracores

(a) Burrill Lake inlet channel (b) Southern Limb



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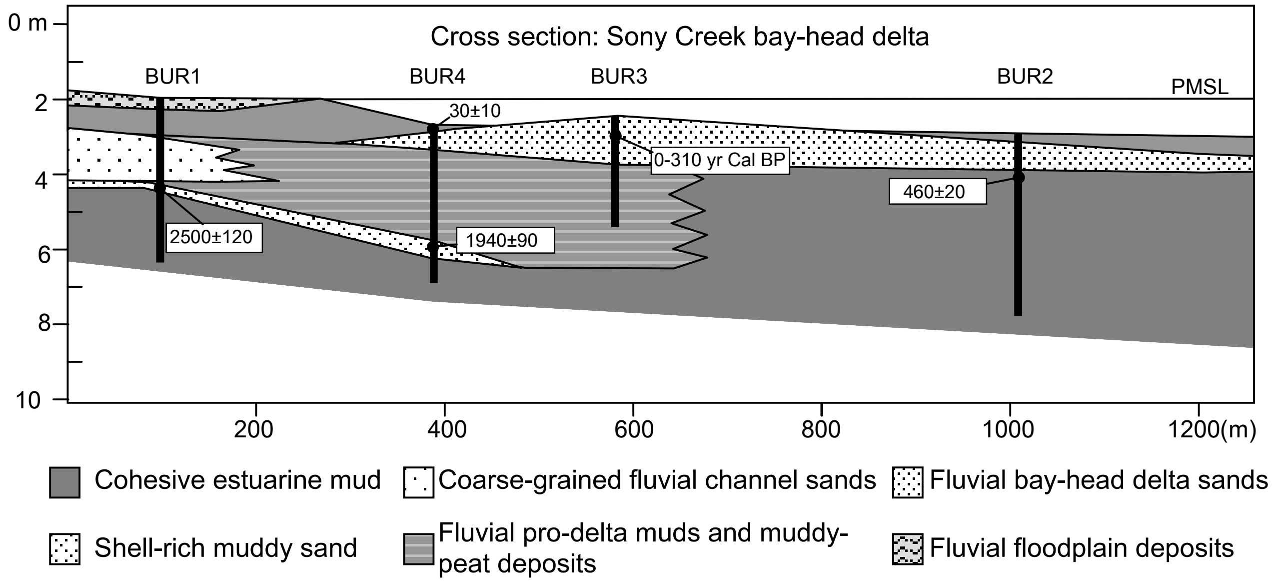

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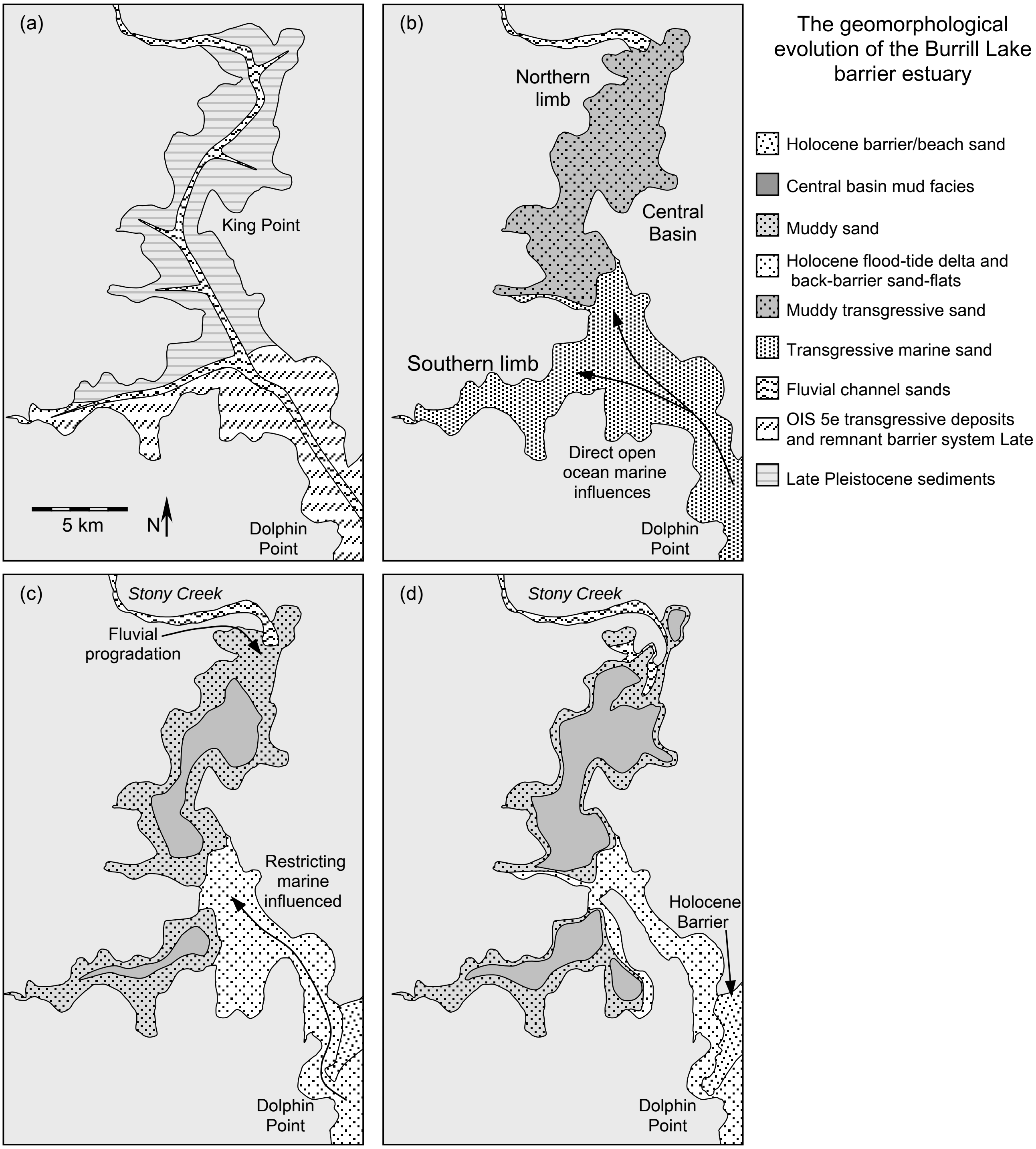

Figure 12 (double column)