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Determining the impact of the Holocene highstand at the coastal-fluvial interface, Shoalhaven River, south-eastern Australia

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Determining the impact of the Holocene highstand at the coastal-fluvial interface, Shoalhaven River, south-eastern Australia

Abstract

With enhanced rates of sea-level rise predicted for the next century, the upstream extent of sea-level influence across coastal plains is a topic of public importance. Australian coastal rivers provide a testing ground for exploring this issue because the area is tectonically stable, was not glaciated, and experienced a Holocene highstand between 7.4 and 2ka of up to 1.5m above Australian Height Datum (AHD). In the Shoalhaven River of New South Wales, investigation of a confined bedrock reach at Wogamia, 32km inland, has identified a unit of dark, cohesive silt and sand with marine diatoms, shell fragments, and enhanced pyrite content, interpreted as estuarine. The unit is up to 13m thick, thickens downstream, and is overlain by fluvial channel and floodplain deposits. The estuarine unit on-laps a remnant Pleistocene terrace and extends to approximately +2.2m AHD. Optically stimulated luminescence (OSL) and radiocarbon ages suggest that estuarine deposition commenced prior to 7.8kcal bp, predating the highstand by ~500years, and that marine influence in the area continued to 5.3±0.7ka. During this period, a delta probably persisted at Wogamia, where a narrow upstream reach opens out, and subsequently advanced to fill the broad Shoalhaven coastal embayment. Although the effect of sea-level rise depends on many factors, the results suggest that, during a highstand at or above present sea level, a strong marine influence may extend for tens of kilometres inland and penetrate confined bedrock reaches landward of coastal embayments.

Keywords

Base level, fluvio-deltaic sequences, Holocene, sea-level, southeastern Australia, GeoQuest

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Determining the impact of the Holocene highstand at the coastal-fluvial interface, Shoalhaven River, southeastern Australia

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ABSTRACT

With enhanced rates of sea-level rise predicted for the next century, the upstream extent of sea level influence across coastal plains is a topic of public importance. Australian coastal rivers provide a testing ground for exploring this issue because the area is tectonically stable, was not glaciated, and experienced a Holocene highstand between 7.4 to 2 ka and up to 1.5 m above Australian Height Datum (AHD). In the Shoalhaven River of New South Wales, investigation of a confined bedrock reach at Wogamia, 32 km inland, has identified a unit of dark, cohesive silt and sand with marine diatoms, shell fragments, and enhanced pyrite content, interpreted as estuarine. The unit is up to 13 m thick, thickens downstream, and is overlain by fluvial channel and floodplain deposits. The estuarine unit on-laps a remnant Pleistocene terrace and extends to approximately +2.2 m AHD. OSL and radiocarbon ages suggest that estuarine deposition commenced prior to 7.8 ka cal B.P., predating the highstand by ~ 500 years, and that marine influence in the area continued to 5.3 ± 0.7 ka. During this period, a delta probably persisted at Wogamia, where a narrow upstream reach opens out, and subsequently advanced to fill the broad Shoalhaven coastal embayment. Although the effect of sea-level rise depends on many factors, the results suggest that, during a highstand at or above present sea level, a strong marine influence may extend for tens of kilometres inland and penetrate confined bedrock reaches landward of coastal embayments.

Key words: Base level, fluvio-deltaic sequences, Holocene, sea-level, southeastern Australia

INTRODUCTION

The timing of Holocene sea-level highstand in southeastern Australia is well established (Thom and Chappell, 1975; Jones et al., 1979; Flood and Frankel, 1989; Young et al., 1993; Baker and Haworth, 2000; Sloss et al., 2007). The present study evaluates how far upstream environmental impacts propagated during the sea-level rise and subsequent highstand in association with this considerable rise of base level. Many studies of fluvial response to base-level change have focused on catchments that had glacial ice in their headwater regions, experienced melt-water pulses, or were influenced by isostatic adjustments. In contrast to some of these areas, southeastern Australia is an ideal location to assess highstand effects on fluvial systems because the region is relatively tectonically stable, has low sediment yields, and did not experience widespread Quaternary glaciation.

The impact of rising sea level on fluvial systems has been examined, often with contention, for decades in unconfined systems of the northern hemisphere, with key studies carried out especially for the Mississippi River and Texas Gulf Coast (Fisk, 1944; Saucier, 1994; 1996; Blum and Törnqvist, 2000; Blum and Aslan, 2006). The cause of contention is in part the complexity of landscape response to a rise in sea level linked to variables such as sediment supply and discharge, the role of tectonics, variability of space for sediment accumulation, and varied coastal morphology. Detailed studies of latest Cenozoic landforms and deposits have been carried out in Australian coastal rivers and former fluvial tracts that underlie the modern continental shelf (Nichol et al., 1997; Fielding et al., 2003, 2005; Rustomji et al., 2006; Ryan et al., 2007; Hill et al., 2009). Less well understood, however, is the facies architecture associated with the fluvial-marine transition zone.

Sloss et al. (2007) combined previously published geochronological records with a new set of radiocarbon and amino-acid racemisation results, yielding a revised sea-level curve for southeastern Australia. The combined dataset shows that the post-glacial transgression reached present mean sea level (PMSL) by 7.9-7.7 ka cal BP, 700-900 years earlier than previously reported. A highstand then occurred at +1 to +1.5 m, from 7.4 ka cal BP to 2.0 ka cal BP, after which sea level fell to present levels (Sloss et al., 2007). This fits the tectonic model observations of Lambeck and Nakada (1990). Oscillations may have occurred during the highstand (Baker and Haworth, 2000), although this remains unresolved. Thus, a robust record of sea-level variation is now available for the region, with which age records for Australian coastal rivers may be compared.

The Shoalhaven River reaches the Tasman Sea downstream from Nowra in New South Wales (NSW), and the river estuary is at a mature stage of estuarine development (Wright, 1976; Roy, 1984). Sediments of the estuarine fill are primarily Holocene in age, but remnants of Pleistocene terraces border the embayment and are present in the subsurface (Young et al., 1996). Approximately 6000 years ago, a coastal barrier was constructed that partially enclosed an embayed estuary that has since filled with marine sands and fluvial sediments (Young et al., 1996; Umitsu et al., 2001). Umitsu et al. (2001) described the evolution of the estuarine deposits east

of Nowra from an earlier birdsfoot delta-distributary complex to the current barrier estuary. The Pleistocene basement was inundated when sea level reached its current elevation ~ 7.8 ka cal BP, and sea level has been no higher than +1-1.5 m since then (Umitsu et al., 2001, Sloss et al., 2007). Radiocarbon ages on shells (uncalibrated; Umitsu et al., 2001) show that, from 6 to 5 ka, sedimentation occurred on the eastern margin of the embayment (sands and shells derived from marine sources) and the western margin (fluvial sands and muds of the birdsfoot delta).

To date, there has been no contribution to sea-level scenarios from the Shoalhaven River upstream of Nowra, although fluvial terrace deposits have been described from upstream areas (Nott et al., 2002; Kermode et al., 2012). Just upstream of Nowra, the river is confined within a valley cut into bedrock and forms discontinuous floodplains. The largest of the discontinuous floodplains was selected for a detailed investigation using a variety of stratigraphic and geochronological approaches. We have identified marine-influenced beds within the subsurface record at precisely determined levels, allowing us to evaluate the inland extent of marine conditions at certain times within the Shoalhaven valley. This study discusses (a) fluvio-estuarine stratigraphy, including local variability; (b) the upstream limit of Holocene estuarine facies to expand current understanding of the fluvio-deltaic system; and (c) the nature of the fluvial response to Holocene sea level rise and highstand. With predictions that sea level may rise considerably above present levels over the next century (IPCC, 2007), the study may help to provide a geological context for discussions of sea-level impacts on coastal communities in Australia and elsewhere.

REGIONAL SETTING

The Shoalhaven River rises in the Great Dividing Range and is 340 km long, with a catchment area of 6920 km² at its outlet to the Tasman Sea on the southeastern coast of NSW (Fig. 1). The upper regions of the catchment are in the Palaeozoic Lachlan Fold Belt, whereas the middle and lower reaches of the river pass through near-horizontally bedded strata of the Permo-Triassic Sydney Basin (Nott et al., 1996). The study reach lies in a valley cut into the Nowra Sandstone, immediately upstream of the alluvial coastal plain.

The Shoalhaven River catchment has an annual average rainfall of 890 mm/yr increasing to 1500 mm/yr close to the coast (Environmental Protection Agency, 1997). Tallowa Dam, ~ 40 km upstream from the study site, was completed in 1976. It has a low operational capacity relative to annual inflows (3.3% and 5.5% of mean and median annual inflows, respectively) but it acts as a significant bedload sediment trap (Reinfelds et al., 2006). In other words, while only a small proportion of floods are retained by the dam, much of the sediment load is trapped.

The study site at Wogamia is located within the tidal reaches of the lower Shoalhaven River ~ 32 km from the current river mouth (Fig. 1). Low-flow water level is ~ 0.35 m AHD at this site, with a tidal range of <30 cm. The channel is 100-200 m wide and ~ 15 m deep, and floodplain elevation is 7-12 m Australian Height Datum (AHD). The study site is a 1.58 km² floodplain pocket (Fig. 2A), with maximum

length of 1.1 km and maximum width of 1.4 km, with a prominent levee bordering the river. The site is currently used as farmland with both cattle and cropping activities, and there is a sand extraction pit on the southern side (Fig. 1).

METHODS

Sedimentology and stratigraphy

Coring techniques combined with mechanical and hollow head hand-augering were undertaken to retrieve sediments along north-south and east-west transects (Fig. 1). Maximum drilling depth was 24 m (-19 m AHD), and 25 holes and sections were sampled. Hand augering penetrated to the water table, and was combined with truck-mounted drilling for deeper penetration. Coring techniques penetrated up to 9 m, although in several instances as little as 4 m as the material became impenetrable.

The sand extraction pit provided sedimentological information that aided greatly in interpreting the sub-surface records. In the western part of the pit (Fig. 2B), accessible sections up to 4.7 m high, were compiled into composite section WOG 3. The aggregate thickness of the section was confirmed using a theodolite survey, which also provided elevations. With the drilling rig sited at a bench low in the pit, drill hole WOG 1 was obtained to extend the section to greater depth. Section WOG 4 was measured in the eastern part of the pit.

Grain sizes <2.0 mm were assessed using a Malvern Mastersizer 2000 with those >2 mm determined by sieving. Typical sediment colour for each facies was recorded on dry sediments using a Munsell soil colour chart. Sediment textures were described using the Australian texture diagram (Marshall, 2003),

Cores were opened under subdued red light with half set aside for dating using optically stimulated luminescence (OSL) and half for logging and sampling. Stratigraphic data from the auger holes was overlain onto surveyed cross-sections with elevations tied to AHD using aerially obtained LIDAR data from the NSW Office of Water (vertical error of 0.2 m).

X-Ray Diffraction

Mineralogical analysis using X-ray diffraction (XRD) was undertaken at the University of Wollongong using normal procedures (Williams, 2012). In particular, samples were selected from an inferred estuarine unit in the combined Core 9/Drill Hole [DH] 5 from which shell material was retrieved, in addition to the combined Auger/Drill Hole 3. Samples collected by truck mounted drilling (DH3, 5) had noticeably oxidised on the outside, and both outer oxidised and inner unoxidised materials were tested. Outputs were analysed using Siroquant Version 3.

Microfossil assessment

Samples were prepared and examined for ostracods and foraminifera, which were not detected. The focus was therefore shifted to diatoms. Diatom samples were prepared according to Batterbee (1986). Preliminary identification was undertaken at the University of Adelaide, and counts were conducted at the University of Wollongong with reference to standard texts (Krammer, 1986, 1988, 1991a, 1991b;

Sonneman et al., 2000; Witkowski et al., 2000). Of the six samples prepared, only two yielded enough diatoms to attempt statistically meaningful counts. The sample at 1.7 m depth yielded a count of 424, and the sample at 13.5 m yielded a count of 218 after ten 15 mm transects. For one additional sample, from DH5 at 10.5 m, only a species list was compiled, due to the low number of counts (25) after ten 15 mm transects and the high degree of fragmentation and dissolution of the diatoms present.

Due to the small number of samples and low counts, common statistical approaches such as transfer functions and component analysis were not possible. Instead, Pearson's 2-parameter and 3-parameter chi-squared tests were applied. Species were categorised for analysis according to marine, brackish or freshwater affinity, based on the literature (Hartley, 1986; Day et al., 1995; M'harzi 1999; Aboal et al., 2003; Bostock and Holland, 2010; Guiry and Guiry, 2012; WoRMS, 2012). For the Pearson's 2-parameter chi-squared test, marine and brackish species were grouped as one category. For species that exist in multiple environments and for specimens that could not be identified with sufficient certainty to confirm environment, a fourth category was set up and excluded from analysis.

Radiocarbon dating

Radiocarbon dating was conducted at The Australian National University (ANU) and the Australian Nuclear Science and Technology Organisation (ANSTO), using both conventional and accelerator mass spectrometry (AMS) techniques. ANU samples are denoted in Table I by lab codes beginning with 'ANU', whereas those from ANSTO begin with 'OZM'. Ages are reported as conventional radiocarbon ages and calibrated ages, calculated using CalPal (Weninger et al., 2007). The exception is the shell material recovered from Drill Hole 5 at 12 m (OZM600) for which a marine reservoir corrected age was also calculated (Gillespie and Polach, 1979).

Thermoluminescence dating

Thermoluminescence dating of four multi-grain samples was conducted at the University of Wollongong. Samples were prepared using the methods of Aitken (1985), and analysed using a regenerative-additive coarse-grained quartz method, essentially that of Readhead (1988). Lithogenic radionuclide activity concentrations were determined using thick-source alpha-counting in conjunction with X-ray fluorescence and atomic emission spectroscopy (Table II).

Optically stimulated luminescence dating

Samples were collected from the light-protected portion of the cores under subdued red light. Particular care was taken to sample away from stratigraphic boundaries in accordance with the advice of Wallinga (2002).

Single grain OSL dating of five samples was conducted at the University of Wollongong. Quartz grains from each of the samples were obtained and prepared in the standard manner (Aitken, 1998). The etched quartz grains were loaded on to custom-made aluminium discs drilled with a 10 x 10 array of chambers, each of 300 µm depth and 300 µm diameter (Bøtter-Jensen et al., 2000). The OSL measurements were made on a Risø TL/OSL DA-15 reader using a green (532 nm) laser for optical

stimulation, and the ultraviolet emissions were detected by an Electron Tubes Ltd. 9235QA photomultiplier tube fitted with 7.5 mm of Hoya U-340 filter. Laboratory irradiations were conducted using a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ beta source mounted on the reader.

Equivalent doses (D_e) were determined using a modified SAR protocol (Olley et al., 2004). A dose-response curve was constructed for each grain. The OSL signals were measured for 1 s at 125°C (laser at 90% power), using a preheat of 240°C (held for 10 s) for the 'natural' and regenerative doses, and a preheat of 160°C (held for 10 s) for the test doses (0.5 Gy). The OSL signal was determined from the initial 0.1 s of data, using the final 0.2 s to estimate the background count rate. Each disc was exposed to infrared (IR) radiation for 40 s at 125°C prior to measurement of the OSL signal to bleach any IR-sensitive signal. Grains were rejected if they did not produce a measurable OSL signal in response to the 2 Gy test dose, had OSL decay curves that did not reach background after 1 s of laser stimulation, or produced natural OSL signals that did not intercept the regenerated dose-response curves ('Class 3' grains of Yoshida et al. (2000)).

Thick-source alpha and beta counting were used for dosimetry (Table III); with dose rates calculated using the conversion factors of Stokes et al. (2003). β -attenuation factors were taken from Mejdahl (1979). Cosmic dose rates were calculated from Prescott and Hutton (1994).

Water contents were measured directly from each sample. Saturation levels were assumed to have been constant since burial, with samples variously collected from above or below the current water table. However, errors of 50% were assigned to account for the high degree of uncertainty in this parameter.

SEDIMENTOLOGY

Sedimentary units identified in the subsurface (Figs 3-5, Table IV) are interpreted as floodplain and levee deposits (Unit A), estuarine and backswamp deposits (Unit B), channel sands (Unit C), and remnant Pleistocene material (Unit D). Four selected logs represent the 25 cores/sections recorded and the pit sections (Figs 4, 5). The basis for the interpretation is provided following the description of each unit.

Floodplain and levee deposits (Unit A)

In cores and auger holes, these deposits are predominantly silt to fine sand, fining with distance from the channel. Texturally the facies is typically silty loam, with coarser flood deposits recognisable. Sediments are massive or laminated with bedding especially apparent in cores (e.g. Core 3, 254-281 cm; Core 5, 66-87 cm; Core 8, 505-512 cm) but also evident in some hollow auger samples (Auger 3, 118-145 cm; Auger 4, 75-135 cm). Multiple fining upwards sequences are evident, typically decimetres thick, with coarse-grained, fining upward flood deposits up to 50 cm thick (Fig. 4A). A slight overall fining upwards within the unit reflects the transition from a floodplain setting strongly influenced by river floods with coarse material to a setting with predominantly finer flood material, in accord with

progressive elevation of the floodplain. This is also supported by a change in the degree of sorting, with a lower degree of sorting evident in the levee crest of Core 1, where the standard deviation is typically ~2.3, compared to <1 for the underlying channel facies (Unit C₂).

Charcoal is common and locally present as layers in cores, for example, in Core 9 at 113-119 cm, where five ~2 mm layers are interspersed with 8 mm beds of fine sand without charcoal. Similar occurrences were noted in Auger 4 at the 90-120 cm level and in the upper metre of Core 4.

The basal contact of the floodplain sediments corresponds with the current low-flow water surface at 1 m AHD (Fig. 3), and is transitional upwards from channel or estuarine deposits. Colours are typically grey-brown, except near or below the water table where orange and grey mottling appears or the samples are completely waterlogged and grey (Table IV).

Pit section WOG 3, cut into the highest part of the levee, exposes 9.4 m of Unit A deposits (Fig. 5), and 4.4 m of strata are exposed in section WOG 4. The topmost deposits in the two sections have elevations of 11.01 and 11.15 m AHD, respectively. The strata comprise two contrasted facies sets of silt to fine sand, and medium to very coarse sand. The finer facies set consists of decimetre-scale beds that fine upward from pale, very fine-grained sand and silt to dark silty clay (Fig. 2C). The beds are erosively based, and are faintly stratified or unstratified, with sediment-filled burrows up to 10 cm deep and 5 mm wide. Below sandy bed bases, thin seams and patches of sand commonly penetrate a few centimetres down into the top of the underlying silt. A prominent charcoal layer with 1 cm clasts is present at the base of Unit A. Thin coarser sands exhibit basal groove casts, ripple cross-lamination, and contain fragments of tough red clay up to 10 cm in diameter, which resemble Unit D muds. Unit A fines upward progressively towards the modern levee surface (Fig. 5), but the topmost 50 cm of the section includes two fining-up layers of very coarse, cross-bedded sand.

The coarser facies set comprises two bedsets of medium- to very coarse-grained sand, 4 m and 7 m above the section base. The bedsets have planar to low-angle stratification, a planar cross-set 80 cm thick, and charcoal fragments. The upper bedset cuts through silt to form a lensoid channel-fill 1.2 m thick (Fig. 5).

The sediments accord closely with levee and floodplain deposits elsewhere in Australia (e.g., Ferguson and Brierley, 1999; Rustomji et al., 2006). In the pit section, the finer facies set is interpreted as levee deposits, formed as Shoalhaven River floods overtopped the banks, eroded the surface sediments, and laid down fining-upward units under waning-flow conditions. The presence of burrows implies some degree of pedogenesis following deposition, although individual graded beds remain distinct. Thin, coarser beds may be crevasse splays that extended across the floodplain from levee breaks, but they may also represent floods of exceptional strength, such as those that deposited the topmost beds on the levee crest. The coarser facies set represents the fills of shallow crevasse channels that cut the levee, or of adjacent floodplain channels such as those present on the modern Wogamia floodplain level. The planar

cross-set represents a small barform, and the planar stratification indicates high-strength flows.

Estuarine and backswamp deposits (Unit B)

These deposits are known only from sub-surface records, and are brown and highly cohesive, with a mean size of silt to very fine sand (Table IV). Even above the water table these sediments are more moist and cohesive in character than either unit A or C. The unit has indeterminate shell fragments, an elevated organic content and commonly a sulphurous smell, particularly evident in continuous cores. The unit lies near or below the water table with a maximum elevation of 4 m above the current low-flow water surface, and it extends to -10 m depth in Drill Hole 5 and to -7 m in Drill Hole 1 (Fig. 3). The unit attains its greatest thickness at the downstream end of the floodplain pocket (up to 13 m), where it broadly coarsens upwards, and it thins upstream to ~2 m in Auger holes 1 and 2. The unit was not recorded in Core 6 or the exposed pit section (WOG 3), but the drilling of WOG 1 in the pit penetrated a 1.2 m interval of the unit at depth. The base of the unit is possibly a sheet of muddy sand, but this was difficult to confirm because sample structural integrity was not maintained by the truck-mounted augering.

Subunits B₁ and B₂ were recognised. The former includes the thickest deposits with shell fragments, whereas the latter includes thinner deposits at the highest elevations and contains a considerable amount of organic material.

The generally fine grain size, elevated organic content and dark colouration of Unit B₁ suggests deposition under relatively quiet-water conditions, probably in standing water. The presence of shells, marine diatoms and pyrite (see below) indicates periodic or prevailing estuarine conditions, although lacustrine conditions cannot be ruled out for some intervals. Unit B₂ is attributed to backswamp and possibly salt-marsh deposits laid down near the landward and upper limits of the unit.

Channel deposits (Unit C)

These sediments are the coarsest encountered and are similar in colour to the coarser floodplain material of Unit A (10YR 5/2) but lack evidence for pedogenesis. The maximum elevation of the unit is ~3 m above the low-flow water surface (1 m AHD; Fig. 3A). Based on stratigraphic evidence, the unit is divided into units C₁ and C₂, which respectively underlie and overlie or border the estuarine and lacustrine deposits of Unit B (Figs 3, 4).

Unit C₂ was encountered in numerous cores and pit section WOG 3. The sediments have mean grain size in the very fine to coarse sand range (Table IV). Minor mud and gravel layers are present, but sand typically constitutes >75% and commonly >90% of the unit. Colour is typically dark grey, reflecting its location below the water table. The unit is well exposed in the lowermost part of the pit (Figs 2B, 5), where it consists of poorly sorted, pebbly coarse- to very coarse-grained sand with a 15 cm gravel layer that contains pebbles up to 6 cm in diameter. The sand contains intervals of planar stratification, trough cross-sets 15 cm thick with down-

valley palaeoflow orientation, logs and charcoal. The unit is estimated to be 6 m thick in drill hole WOG 1, resting on a thin interval of Unit B.

Unit C₁ was penetrated in only two holes (Fig. 3). The sediments are finer, with mean grain size in the silt to fine sand range. In drill hole WOG 1, this material underlies Unit B, and includes some coarser layers, sparse pebbles and charcoal.

The predominance and relatively coarse grade of sand indicates a fluvial-channel setting with strong bedload transport, and the sediment is similar to that transported by the modern Shoalhaven River and other Australian coastal rivers (e.g. Brooks and Brierley, 1997; Erskine et al., 2009). The differences in grain size between units C₁ and C₂ are discussed below.

Remnant Pleistocene material (Unit D)

This material was detected in several cores and auger holes (Wog 2, Cores 3-4, DH1 and DH5). It is predominantly fine silt with some fine sand, loamy in texture, very cohesive, and has a distinctive, mottled yellow-red colour (5YR 4/6, 7/5YR 4/1, 7.5YR 5/4), with evidence of pedogenesis. The elevation of the upper boundary varies greatly, from 6.73 m AHD in pit section WOG 4 to ~-16 m AHD in DH5.

Unit D is well exposed in pit section WOG 4 on the eastern side of floodplain pocket. Here, more than 2.5 m of tough red-brown, mottled silt and clay are exposed (Fig. 2D), with ferruginous nodules up to 1 cm in diameter and dark goethite cavity fills and stains. The deposits are abruptly overlain by alluvium of Unit A with a contact that dips south-westward towards the pit section of WOG 3 with Unit A and C deposits, although the contact is largely obscured (Fig. 2B).

Unit D deposits underlie Units A, B and C (Fig. 3). Their highly cohesive nature and the presence of colour mottling distinguishes them from all other sediments at Wogamia, and they resemble materials extracted by drilling from below the alluvial plain downstream of Nowra and dated as Pleistocene (Young et al., 1996). Their relatively fine grain size and colour mottling suggests alteration through pedogenesis of floodplain deposits. Lateral changes in the pit suggest that Unit D forms a terrace with a relatively steep, southwest-facing margin that was overlapped by levee and floodplain deposits of Unit A. The latter appear to thin northeastwards across the terrace and towards the bedrock valley margin. Red mudclast fragments in Unit A suggest that the terrace deposits were periodically eroded. As noted below, Pleistocene ages were obtained from samples. An attempt was made to date the ferruginous nodules using uranium series dating, but the samples failed to pass geochemical tests for suitability.

X-RAY DIFFRACTION

Samples from Unit B in Core 9 and Drill Hole 5 were the primary focus of mineralogical study due to the presence of shell material in Drill Hole 5, which suggested marine influence, and the thickness of Unit B at this location. Samples from Units A and D in Core 9/Drill Hole 5 and samples from Auger/Drill Hole 3 were also analysed.

Typical proportions of constituent minerals are 30-80% quartz, 1-22% feldspar, 5-29% micaceous material, and 6-28% clay. Key minerals of interest were pyrite, gypsum and jarosite, which may be indicative of estuarine conditions. Oxidised iron minerals were of secondary interest but, given their amorphous texture, are not readily detected using this technique, although small percentages were detected in some samples (up to 2.1%).

Samples from Unit A in Core 9, to a depth of ~4 m (0.6 m AHD), showed no evidence of gypsum, jarosite or pyrite, which is consistent with an inference of floodplain conditions.

In Unit B samples, pyrite was detected in proportions of 0-3.1% in the unoxidised samples; 0.4 and 3.1% at 8.5 m depth (-3.9 m AHD; repeated sample), 2.7% at 12 m (-7.4 m AHD), and 2.1% at 13.5 m (-8.9 m AHD). Pyrite was detected in the oxidised material at 2.6% at 8.5 m depth. The presence of pyrite supports an estuarine setting with available marine sulphate, and is consistent with sulphidic Holocene estuarine sediments elsewhere in Australia (Walker 1972; Willet and Walker, 1982; Bowman, 1993; Bush and Sullivan 1999). This inference is supported by the presence of gypsum, a product of pyrite oxidation, in all samples from 8.5-13.5 m depth, in proportions of 0-7.9% in unoxidised material and 9.1-57.3% in oxidised material. Pyrite was not detected in the sample from 10.5 m but gypsum was detected in proportions of 0.4% in unoxidised material and 57.3% in the oxidised outer portion; the high gypsum proportion was associated with an error of 11% rather than the typical ~4%. Jarosite, which also forms by oxidation of sulphur-bearing material, was detected in samples at 8.5, 9 and 12 m depths (up to 3%).

Samples from Unit D at 20.5 m depth did not yield evidence of these minerals in either unoxidised or oxidised samples. For the combined Auger/Drill Hole 3, a similar pattern is seen. Floodplain material is present to 6.5 m depth, followed by 2.5 m of estuarine material. Gypsum was detected in proportions of 3.2 % at 6.85 m and 14.4% in oxidised material at 8.5 m, with 0.3% pyrite in the unoxidised portion.

FOSSILS

Highly fragmented, but unidentifiable shell material was retrieved from DH5 at 11-12.5 m depth (-6.4 to -7.9 m AHD), equating to deposition during transgressive inundation. Diatoms however were able to provide more definitive environmental information and Figure 7 shows the species distribution for samples with statistically significant counts according to their environmental affinities.

The sample from Unit A floodplain deposits at 1.7 m was compared to the inferred estuarine unit (sample at 13.5 m) using chi-squared analysis. Both the two-parameter test that compares grouped marine and estuarine species with freshwater species and the three-parameter test with the three categories distinguished show a significant statistical difference, with $P = 0.000$. The assumptions of the chi-squared test were met in both instances. An adjusted residual of 12.2 for the two-parameter test shows a considerable difference between these populations. For the three-parameter test, adjusted residuals are 14.9 for the marine species category, 1.1 for the brackish category and 12.2 for the freshwater category. This indicates that the

difference primarily relates to the counts of marine and freshwater species, with no considerable difference in the counts of brackish species. This is expected as the tidal limit is upstream of Wogamia and, although the saline wedge will be pushed seaward during flood events large enough to inundate the floodplain, some signature is still likely to remain. These results support the interpretation of these facies as distinct stratigraphical units.

Due to the low count in the 10.5 m sample, this sample was excluded from analysis; however the species composition shows marine and fresh water influence, with 9 brackish/marine valves and 10 freshwater valves counted. When identified fragments are included (176 counts), 50% are of brackish/marine origin, supporting an estuarine interpretation.

CHRONO-STRATIGRAPHY

On the basis of the data set out above, chrono-stratigraphical relationships were determined for the site. Two transects (Figs 3A, B) and an interpretive schematic model (Fig. 6) were developed. The topography for the two transects illustrates levee development adjacent to the Shoalhaven River, with up to 6 m of vertical relief between levee crest and distal floodplain. The floodplain pocket also exhibits topographic variability associated with flood channels that dissect the floodplain surface.

The seventeen ages for the Wogamia area yielded reasonable consistency, with generally good correspondence between ages obtained using OSL, TL and radiocarbon on wood, charcoal and shells. The tough red mottled material of Unit D at the base of cores and below young alluvium is consistent with remnant Pleistocene material described and dated elsewhere in the catchment (Young et al., 1996; Kermode et al., 2012) and yielded TL ages of 50.1 ± 4.3 ka, 66.7 ± 5.7 ka, and 83.7 ± 4.9 ka (Table II).

The Pleistocene unit is overlain by channel deposits of Unit C₁ in its more proximal locations, and distally by estuarine and backswamp sediments of Unit B, the top of which reach an elevation of about +2.2 m AHD (Fig. 3). Unit C₁ is exclusively overlain by sediments of Unit B₁. No suitable material for age determination was extracted from Unit C₁, but ages produced for Unit B₁ provide a minimum age. Radiocarbon results are presented in Table I, and support a Holocene age for Units A to C.

All five OSL samples exhibited good luminescence characteristics and good reproducibility, yielding Holocene ages (Table III; Fig. 8). Over-dispersions were in the range of 27-35%, which is common in fluvial samples (e.g. Olley et al., 2004; Rodnight et al., 2006; Arnold et al., 2009) and other OSL samples from the region (Kermode et al., 2012). The chronology for the site shows that estuarine material (Unit B₁) was being deposited on remnant Pleistocene and channel material by at least 7.8 ± 0.1 ka, although the lowermost and uppermost sediments of Unit B₁ were not dated. Rapid deposition is implied for ~13 m of sediment at the downstream end of the floodplain pocket, with transition to subaerial swampy environments of Unit B₂ from 7.5 ± 0.6 ka and 5.3 ± 0.7 ka. The broadly coarsening upward nature of the unit

in Core 9/DH5 suggests that the Shoalhaven River delta lay at this location and prograded during and following a period of high sea-level at or before 7.8 ka, based on an age at 12 m depth.

Transect B (Fig. 3B) highlights the extent of Unit B estuarine and backswamp material, which thickens markedly down valley. Shells in Unit B₁ are highly fragmented and probably experienced considerable breakup during transport. The distal portion of the cross-section (Fig. 3A) displays an apparent age anomaly within Unit B₂. An age of 7.5 ± 0.6 ka was obtained for the upper, more proximal sample from Core 3 whereas an age of 5.3 ± 0.7 ka was obtained from a slightly deeper level from Core 4. Water content estimates for these two samples may account for some of this apparent anomaly; nonetheless, these two age estimates overlap within 2 sigma error and are statistically the same age. Additionally within this environment, aggradation is not uniform, and spatial heterogeneity is anticipated.

Also of note is the age inversion from Unit B₂ samples in drill hole WOG2. Sample Wog94-14 MG gave an age of 6.9 ± 0.1 ka cal BP at 6.3 m depth (5 ml wood sample), and sample Wog94-15 MG gave a date of 3.3 ± 0.3 ka cal BP at ~11 m depth (0.3 ml charcoal). The laboratory could not find any discrepancy with the results. Without further chronology from this auger hole, we are unable to confirm either age although, in view of the small volume of the younger sample, contamination is considered most likely; no evidence of reworking was present for the older sample and an older age fits better with other ages at a similar depth. Other ages from Unit B range between 5.3 ± 0.7 ka and 7.8 ± 0.1 ka.

Floodplain and levee sediments (Unit A) rest on channel deposits (Unit C₂) near the Shoalhaven River in the west and on estuarine and backswamp deposits (Unit B) to the east. Unit A comprises the uppermost 3-12 m and is associated with aggradation during floods that continue to the present. Apart from one anomalously old TL age, these overlying floodplain and levee deposits of Unit A yielded five ages between 1.9 and 4.2 ka, implying rapid deposition of 9.4 m of sediment in less than 2500 years (Fig. 5). Sample WOG94-4 from section WOG 3 yielded an age of 38.1 ± 4.2 ka, much older than radiocarbon ages of 1.9 ± 0.1 ka cal BP and 3.6 ± 0.1 ka cal BP above and 4.2 ± 0.1 ka cal BP below the sampled level. This anomalous age suggests partial bleaching of reworked older sediment, probably eroded from upstream deposits and deposited rapidly during a river flood.

The combination of Core 9 and DH5 (Fig. 4C) played a key part in the interpretation. Core 9 was only able to penetrate to ~4 m as the material was too cohesive for our method of continuous coring. Based on information from nearby DH5, a change at ~5 m depth represents a transitional boundary from Unit B to Unit A. Samples from 8.5-13.5 m confirm an estuarine origin, based on sedimentological and mineralogical analysis. The lower boundary of Unit B is difficult to precisely pinpoint, as collapse of the hole occurred at 15 m depth and samples were retrieved from the basal portion of the hole only. A change from estuarine to fluvial sediments below was inferred to take place between 13.5 and 20.5 m depth based on XRD analysis (Table IV), and this coincides with a change in the consistency of material at

18 m, the sediments becoming easier to drill. The boundary between fluvial and Pleistocene material occurs at 21 m depth.

Unit C₁ constitutes a thin sheet that rests on Pleistocene deposits and is overlain by Unit B. Unit C₂ constitutes younger channel deposits at the southern and northern ends of the transect, below the floodplain pocket but adjacent to the modern Shoalhaven River, where the channel deposits pass upward into fluvial overbank deposits of Unit A. At Wogamia, some post-transgression channel migration has occurred, with channel sediments yielding ages of 4.8 ± 1.9 ka at the northern margin of the pocket (Fig. 3B) and 3.4 ± 0.2 ka at the southern margin (Fig. 3A). An upward transition to floodplain and levee deposits of Unit A took place in proximal regions of the floodplain after 3.4 ka.

Wog94-9 MG was an *in situ* tree stump in an exposed bank, and was sampled because it could have been exhumed from older material in the adjacent bank. However, it yielded a modern age (165 ± 120 cal yr BP), and represents a young tree that grew near the water line.

The study was not designed to fully explore the Quaternary deposits across the Wogamia area. However, drill hole WOG1 in the pit encountered at 17.8 m depth (-15.5 m AHD) a tough gravelly horizon that is inferred to represent a thin layer above bedrock. Of three boreholes E1 to E3 drilled for the land owner across the floodplain in 1980 (Fig. 1), E1 and E2 encountered clay-rich gravel at depths of 21 m and 24 m below surface, with bedrock shale at 24 m and 28 m, respectively (not corrected for elevation). We infer that bedrock lies a relatively short distance below our cross-sections and that our study represents much of the younger Quaternary history of the Wogamia area.

DISCUSSION

The widespread preservation of Pleistocene alluvium beneath the Holocene deposits at Wogamia and below the Shoalhaven coastal plain indicates that the valley floor was not completely eroded during the last sea-level lowstand. Thus, complete sediment evacuation did not take place in response to sea-level lowering to as much as 120 m below PMSL during the Last Glacial Maximum (Ferland et al., 1995; Murray-Wallace et al., 2005), in contrast to many conceptual models. In fact, channel incision occurred to -40 m AHD in the Shoalhaven coastal area (Buman, 1995). This suggests that some of the adjustments to gradient change during the Last Glacial Maximum included changes in hydraulic geometry, such as planform or cross-sectional modification; our dataset was not designed to test these possibilities.

Sea level rose rapidly following the climatic transition at the end of the Pleistocene from about 120 m below PMSL to current levels by 7.9 to 7.7 ka cal BP (Sloss et al., 2007). Ages from the estuarine deposits at Wogamia match well with this assessment. As the post-glacial marine transgression inundated the lower reaches of the Shoalhaven River to create an estuary, river sediment is inferred to have produced a transgressive sand-sheet reworked by waves and tides. Although drilling procedures prevented a high-resolution of grain size, the base of Unit B₁ at -12 m AHD was locally muddy sand, possibly corresponding to a transgressive sheet. After attainment

of highstand conditions, a delta would have formed close to the bedrock confinement immediately upstream from Wogamia, subsequently prograding through the broader Wogamia area and eventually advancing some 32 km to the modern coast. The thickness of estuarine deposits at the downstream end of the study site (Fig. 3B) suggests that the delta was positioned near the confining upstream bedrock for some time, although Unit B may also have accumulated in small embayments bordered by remnant Pleistocene material and the bedrock valley walls (Fig. 3B).

Estuarine material was deposited in the Wogamia area by at least 7.8 ± 0.1 ka cal BP (Fig. 3B) at a depth of -7.4 m AHD, and the ~7 m of marine transgressive sandsheet and estuarine sediments below this sample level suggest that the Wogamia area was inundated well before highstand was reached along the Australian coast (Sloss et al., 2007). Delta progradation may have begun prior to attainment of PMSL and the highstand. Shortly after this time, at 7.5 ± 0.6 ka, transitional environments began to appear in some areas at Wogamia, with distal areas of the modern floodplain emerging first during a transition from estuary through inferred salt-marsh to fluvial over bank deposits. Backswamp sediments from Core 4 at ~3 m AHD are as young as 5.3 ± 0.7 ka, resting on a Pleistocene remnant that borders the eastern bedrock valley margin, and are inferred to indicate the presence of a shallow estuarine-mangrove swamp (Figs 3, 6). With the low-flow water surface at this site currently at 1 m AHD, these areas would have experienced modest sub-aerial exposure with the 1.5 m sea level highstand imposed.

Fluvial deposits differ below and above the estuarine deposits. Unit C₁ sands underlie Unit B across much of the level, and their finer grain size may reflect deposition upstream of an expanding water body. In contrast, Unit C₂ sands appear to cut into Unit B below the eastern side of the floodplain pocket, and their relatively coarse grain size is in accord with re-establishment of fluvial conditions, local incision, and the extension of the Shoalhaven River past the Wogamia reach and onto the alluvial plain. The C₂ deposits also imply migration of the channel from an eastern position to the present western position of the Shoalhaven channel at Wogamia (Figs 3, 6).

The persistence of estuarine conditions at Wogamia until this time is supported by downstream ages for fluvial deposits, which did not reach the current embayment until ~6 ka (Umitsu et al., 2001). Marine influence remained predominant in the embayment downstream of Nowra until 6.1 ± 0.1 ka cal BP (Young, 1996), almost two thousand years after attainment of PMSL (Sloss et al., 2007). Coastal sand barrier formation commenced at 6 ka (Umitsu et al., 2001). From 6-5 ka cal BP, the river began to prograde as a birdsfoot delta into the estuary from the west to the present coast, although marine influence continued to predominate in eastern parts of the embayment.

The Wogamia data indicate that, on this stable continental margin, estuarine conditions were established some 32 km inland of the current coastline in association with the Holocene highstand. The location of the Shoalhaven delta near Wogamia early in the Holocene is inferred to reflect local flow conditions such as backwater effects from a constriction ~5 km downstream from Wogamia (Garratt, 2009) or

narrowing of the gorge between Wogamia and Bundanon (to ~460 m valley width), producing a change in gradient between the two sites. No evidence of estuarine material has been found 4 km upstream at Bundanon, suggesting that fluvial deposition prevailed in the confined reach upstream of Wogamia or that the migration of the channel over the last ~3 ka (Garratt, 2009) excavated any estuarine deposits.

Eastern Australia is essentially tectonically stable and was not glaciated, and thus the effects of sea level in coastal rivers may be closely related to the geomorphic setting and physical characteristics of the river. Studies in northeastern Australia have recorded similar findings to this study. The fluvio-coastal interface of the Fitzroy River moved inland as far as Rockhampton, some 40 km from the current river mouth by ~7 ka, immediately prior to attainment of PMSL in the region at 5-6 ka (Yokoyama et al., 2005; Bostock et al., 2006; Ryan et al., 2007). Other studies from southeastern Australia provide evidence to support marine incursion for tens of kilometres from the current coastline. The Tuross River in southern NSW has a bedrock profile which crosses 0 m AHD at 35 km inland, demonstrating the extent of incision which occurred during previous lowstand conditions, subsequently recording some 23 km of fluvio-deltaic progradation (Rustomji et al., 2006). Likewise, the Macdonald River records estuarine material some 35 km inland, with bedrock incision 55 km inland that is assumed to equate to the PMT maximum (Rustomji et al., 2006).

How far future geomorphic responses may extend upstream with ongoing sea-level rise, compared to the Holocene record for the Shoalhaven River, will depend on many factors. As sea level rises over the next century (IPCC, 2007), the response of the coastal area may differ from that experienced during the earlier Holocene, primarily because the accommodation space in the embayment downstream of Nowra, which was available for earlier Holocene sedimentation, has now been filled. An additional factor is the trapping of much of the Shoalhaven bedload at the Tallowa Dam, upstream of the study area. For the Shoalhaven River, confined by bedrock constriction, past base-level rise has been accommodated by rapid deposition in the broader reach downstream from Nowra. Nevertheless, our dataset from Wogamia shows that the impact of Holocene sea-level rise and a highstand 1.5 m above present sea level extended some 32 km from the current coastline and into a confined reach upstream, well inland of the coastal-deltaic plain.

CONCLUSIONS

Estuarine facies were identified in the Holocene record at Wogamia, 32 km from the current coastline of the Shoalhaven River in southeastern Australia. The estuarine deposits are dark, cohesive silts and sands that contain marine diatoms and have an enhanced level of pyrite and other sulphur-bearing phases, and they extend to 2.2 m above present sea level (AHD). OSL and radiocarbon ages suggest that marine influence in this area predated 7.8 ka, considerably before sea level reached its highstand along the Australian coast at 7.4 ka. The Shoalhaven delta was probably located upstream from Wogamia at this time and prograded to fill a coastal embayment downstream over the next few thousand years.

The study shows that, even in a setting where bedrock constrictions strongly influence river conditions, the influence of sea-level rise may extend for tens of kilometres inland and into confined reaches. The results from Wogamia serve as a potential model for predicting the effects of sea-level rise over the next century.

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Table I. Radiocarbon results. *AMS ages, Fink et al., 2004. **Reservoir corrected age and propagated error according to Gillespie and Polach (1979).

Core/section; sample depth	Elevation (AHD)	Sample	Lab Code	Material	$\Delta(^{13}\text{C})$ per mil	Conventional Radiocarbon age, yrs BP, 1 σ error	Calibrated Radiocarbon age, yrs BP, 1 σ error
Wog.3; 10.6 m	0.4 m	Wog94-1 MG	ANU 9666	carbonised log	$-26.5 \pm 0.2 \text{ ‰}$	3780 ± 60	4167 ± 98
Wog.3; 9.2 m	1.8 m	Wog94-2 MG	ANU 9667	20 cm charcoal fragment	N/A	3340 ± 70	3582 ± 86
Wog.3; 2.0 m	9.0 m	Wog94-3 MG	ANU 9668	Log	$-26.3 \pm 0.2 \text{ ‰}$	1950 ± 60	1906 ± 67
Wog.5; 12.8 m	0.5 m	Wog94-9 MG	ANU 9669	In situ tree stump	$-26.9 \pm 0.2 \text{ ‰}$	190 ± 60	163 ± 119
Wog.1; 6.3 m	-3.8 m	Wog94-13 MG	ANU 9670	Woody fragment in dark clay	$-27.7 \pm 0.2 \text{ ‰}$	6980 ± 90	7818 ± 93
Wog.2; 6.3 m	2.3 m	Wog94-14 MG	ANU 9671	5 ml wood	N/A	6050 ± 70	6914 ± 98
Wog.2; ~11 m	-2.4 m	Wog94-15 MG	ANU 9672	0.3 ml charcoal	$-27.3 \pm 0.2 \text{ ‰}$	3130 ± 290	3341 ± 355
C1 850 cm	4.29 m	OZM599*	OZM599	Charcoal	-27.3 ± 0.1	3305 ± 40	3538 ± 50
DH5; 12 m	-7.4 m	OZM600*	OZM600	Shell	-2.0 ± 0.1	7380 ± 45	$8229 \pm 45 (7779 \pm 57)^{**}$

Table II. Thermoluminescence results

Section and sample depth	Elevation (AHD)	Sample	Lab code	Environmental Dose Rate (Gy/ka)	D_e (Gy)	Age (ka)
Wog.3; 9.1 m	1.9 m	Wog94-4MG	W1867	3.499 ± 0.061	133.36 ± 14.48	38.1 ± 4.2
Wog.4; 5.9 m	5.2 m	Wog94-8 (red unit)	W1868	3.681 ± 0.060	245.68 ± 20.75	66.7 ± 5.7
Wog.2; 16.2 m	-7.6 m	Wog94-11MG (red unit)	W1869	3.505 ± 0.055	175.57 ± 14.64	50.1 ± 4.3
Wog.2; 22 m	-13.4 m	Wog94-12MG (red unit)	W1870	2.202 ± 0.046	184.34 ± 10.00	83.7 ± 4.9

Table III. Optically stimulated luminescence results

Core and depth (Sample name)	Elevation (AHD)	Moisture content (%)	Dose rates (Gy/ka)			Total dose rate (Gy/ka)	D_e	Age model	OD (%)	Optical age (ka)
			Beta	Gamma	Cosmic					
C1 850 cm	4.29	5.5 ± 2.8	1.375 ± 0.050	1.038 ± 0.082	0.111 ± 0.011	2.557 ± 0.155	9.197 ± 0.3	CAM	27 ± 3	3.597 ± 0.264
C2 795 cm	0.82	5.6 ± 2.8	1.143 ± 0.040	0.773 ± 0.046	0.115 ± 0.011	2.063 ± 0.108	7.03 ± 0.328	CAM	28 ± 4	3.410 ± 0.249
C3 660 cm	4.54	8.0 ± 4.0	1.557 ± 0.052	1.177 ± 0.105	0.121 ± 0.012	2.888 ± 0.202	21.6 ± 0.737	CAM	32 ± 3	7.480 ± 0.596
C4 5 m	2.96	23 ± 12	1.529 ± 0.064	1.061 ± 0.070	0.115 ± 0.012	2.737 ± 0.327	14.6 ± 0.512	CAM	35 ± 3	5.334 ± 0.672
C5 556 cm	-4.36	34 ± 17	1.145 ± 0.050	0.836 ± 0.084	0.102 ± 0.010	2.114 ± 0.334	10.2 ± 0.370	CAM	27 ± 3	4.828 ± 1.909

Table IV. Facies descriptions. *Luminescence ages are presented as ka in normal script, radiocarbon ages in italics as ka cal BP. **Represent a paired sample. ***Indicates the reservoir corrected, calibrated age. Bracketed colours indicated minor presence

Unit	Grain size and facies trends	Texture (USGS)	Sedimentary features	Munsell Colour	Organic material	Environment and processes	Age*
A	Multiple fining upwards sequences, and overall upward fining trend, inter-bedded sand and coarse silt, high variability in grain size between layers.	Dominantly fine sandy loam, with loamy sand, loam and silty loam	Poorly sorted, many samples are bimodal. Charcoal and bioturbation present. Bedding prominent. Erosional surfaces present.	10YR 4/2 10YR 5/2 (10YR 5/3)	Charcoal, freshwater diatoms dominant	Levee and floodplain, with crevasse or floodplain channels ; overbank flooding	<i>1.9 ± 0.1</i>
							<i>3.4 ± 0.2</i>
							<i>3.5 ± 0.1</i> **
							<i>3.6 ± 0.1</i>
							<i>3.6 ± 0.3</i> **
B₁	Mean fine silt, mode fine silt to fine sand	Loam	Cohesive, moist to wet. Pyrite, gypsum and jarosite present in XRD samples.	10YR 5/3	Shells, charcoal, marine and estuarine diatoms dominant	Estuary/ lacustrine	<i>4.2 ± 0.1</i>
							<i>7.8 ± 0.1</i>
							<i>7.8 ± 0.1</i> ***
B₂	Mean fine silt, mode fine silt to fine sand	Loam	Cohesive, moist to wet.	10YR 5/3	Carbonaceous material, woody fragments	Backswamp/salt marsh/ mangrove	<i>5.3 ± 0.7</i>
							<i>6.9 ± 0.1</i>
							<i>7.5 ± 0.6</i>
C₁	Clean sands, mean mode coarse silt and fine-medium sand	Loam	Moderately to poorly sorted	10YR 5/2 (10YR 5/3)	None	Pre-highstand fluvial channel	-
C₂	Mean very fine to coarse sand, mode fine to coarse sand	Sands, sandy loam	Massive or bedded; planar stratification, trough and planar cross bedding.	10YR 4/1 (10YR 5/2)	Charcoal	Post-highstand fluvial channel	<i>4.8 ± 1.9</i>
D	Mean dominantly fine silt, some very fine sand; mode silt to fine sand	Loam	Highly cohesive, typically distinctive red/yellow colour and mottling	5YR 4/6, 7.5YR 4/1 7.5YR 5/4	None	Highly weathered Pleistocene sediments	<i>50.1 ± 4.3</i>
							<i>66.7 ± 0.1</i>
							<i>83.7 ± 4.9</i>

List of Figures

Figure 1. Locality map; (A) Wogamia field site and core locations. (B) Shoalhaven Region, NSW, Australia. (C) Location of the study reach within the Shoalhaven River catchment. DH = drill hole; E1 to E3 are drill holes obtained by the owner in the sand pit.

Figure 2. Photos of the field site at Wogamia. (A) Southward view from drill hole WOG2 along line of north-south traverse, with truck-mounted auger system. (B) Sand pit in southern part of floodplain pocket, southward view with measured sections (see Fig. 1). A, C and D denote stratigraphic units (see Table IV). In section WOG3, fluvial sand and gravel of Unit C is capped by finer alluvium of Unit A. Drill hole WOG1 extends down from the bench level. In section WOG4, alluvium of Unit A rests on a terrace remnant of red Pleistocene alluvium of Unit D. (C) Close-up of topmost part of Unit A in section WOG3 to show erosionally based couplets of buff-coloured, massive silt capped by dark clayey silt. Hammer is 30 cm long. (D) Close-up of section WOG4, showing red terrace deposits of Unit D overlain abruptly by alluvium of Unit A.

Figure 3. Stratigraphical relationships and facies locations for cross-sections (A) and (B). Topographical survey was cross-referenced with LIDAR from NSW Office of Water (© NSW Dept. of Water & Energy 2004-07) to convert elevations to AHD. Samples from Garratt (2009) were reanalysed for DH1. As per convention, radiocarbon ages are presented as ka cal BP, and luminescence ages in ka.

Figure 4. Grain size and supplementary information for selected logs. (A) Auger and DH3. (B) Core 3. (C) Combined Core 9 and DH5. Bold text refers to facies descriptions as detailed in Table IV. Dashes refer to the depth of XRD samples where no environmental indicator minerals were found, G represents samples in which gypsum is found, J = jarosite and P = pyrite.

Figure 5. Section WOG3 in sand pit, near the highest point of the modern levee. Sand grades: vf = very fine, f = fine, m = medium, c = coarse, vc = very coarse. The section top has an elevation of 11.007 m AHD, and the highest point of the levee is at 11.81 m.

Figure 6. Inferred river location from stratigraphical relationships at ~7.5 ka and present.

Figure 7. Diatom counts and distribution according to species and environmental affinity for the samples obtained at 1.7 m and 13.5 m depth.

Figure 8. Radial plots for OSL samples displaying equivalent doses (D_e) and age model predictions for (A) UOW430, (B) UOW431, (C) UOW432, (D) UOW433 and (E) UOW434.

Legend	
A	Floodplain and levee deposits
B₁	Estuarine mud
B₂	Saltmarsh/backswamp
C₁	Pre-transgression channel deposits
D	Pleistocene deposits
•	Dating sample

(A) 7 ka

(B) Present

Legend:

- Levee and floodplain deposits
- estuarine mud and backswamp
- channel sand deposits
- pleistocene deposits
- water
- high land (+20m)

(A) UOW430 (Core 1, 8.5 m)

(B) UOW431 (Core 2, 7.95 m)

(C) UOW432 (Core 3, 6.6 m)

(D) UOW433 (Core 4, 5 m)

(E) UOW434 (Core 5, 5.83 m)