ARTICLE IN PRESS

Quaternary International xxx (2009) 1–10

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Geomorphic evidence for mid–late Holocene higher sea level from southeastern Australia

Adam D. Switzer [a,*], Craig R. Sloss [b], Brian G. Jones [c], Charles S. Bristow [d]

[a] Department of Earth Sciences, The University of Hong Kong, Hong Kong SAR, China
[b] The School of Natural Resources, Queensland University of Technology, GPO Box 2434, Brisbane, 4001 Queensland, Australia
[c] School of Earth and Environmental Sciences, University of Wollongong, NSW 2522, Australia
[d] Department of Earth Sciences, Birbeck College, University of London, UK

A R T I C L E I N F O

Article history:
Available online xxx

A B S T R A C T

An elevated sheltered pocket beach sequence at Batemans Bay, NSW, Australia, composed of shelly fine- to medium-grained sand provides geomorphic evidence of higher than present sea level during the mid–late Holocene. The sequence is composed of a sand facies with variable amounts of shell and contains a number of well-defined dipping reflectors identified in ground penetrating radar (GPR) profiles indicative of a small prograded beach system. This beach succession is overlain by storm or tsunami deposits. The beach deposit accumulated between 2500 and 5000 cal BP under relatively high energy conditions within a more open immature estuary during a period of higher sea level. Both deposits have been preserved by a low energy mangrove facies that accumulated after the recent fall in sea level cut off ocean wave activity from the area approximately 2000–2500 cal BP. This beach sequence provides new evidence for a period of higher sea level 1–1.5 m higher than present that lasted until at least c. 2000–2500 cal BP and adds complementary geomorphic evidence for the mid to late Holocene sea-level highstand previously identified along other parts of the southeast Australian coast using other methods.

1. Introduction

Recent reviews of Holocene sea level histories from eastern Australia (Fig. 1a) have shown that the tectonically stable coast provides evidence for an extended period of relatively higher sea level during the mid to late Holocene (Sloss et al., 2007; Lewis et al., 2008). Records from elevated estuarine deposits indicate that sea level attained its present level between 7900 and 7700 cal BP and continued to rise to a maximum of +1.5 m by 7400 cal BP (Jones et al., 1979; Sloss et al., 2007). Evidence primarily obtained from coastal stratigraphy and Fixed Biological Indicators (FBI) indicates that the culmination of the postglacial marine transgression (PGMT) was followed by a sea-level highstand that lasted until approximately 2000 cal BP, followed by a relatively slow and smooth regression of sea level from +1.5 m to present level (see reviews of Sloss et al., 2007; Lewis et al., 2008). A series of minor negative and positive oscillations in relative sea level during the mid to late Holocene are superimposed over the Holocene sea-level highstand (Baker and Haworth, 1997, 2000a,b; Lewis et al., 2008). However, the precise nature of the oscillations is difficult to quantify due to problems associated with accurately determining palaeo-tidal and wave regimes, climatic conditions and the antecedent morphology of the shallow marine environments during the mid Holocene (Sloss et al., 2007).

Although most evidence for higher Holocene sea level on this coast has been based on stratigraphic studies (Jones et al., 1979; Sloss et al., 2005, 2006a,b, 2007) and FBI (Flood and Frankel, 1989; Baker and Haworth, 1997, 2000a,b; Lewis et al., 2008) scattered geomorphic evidence from various sites along the southeast Australian coast have assisted in extending and chronologically confining a period of Holocene higher sea level that extends from 7500 to around 2500 cal BP (Sloss et al., 2007). The study of Jones et al. (1979) documented the stratigraphy of a receding beach sequence at Bulli (Fig. 1b). They suggested an early Holocene higher sea level ~7500–6500 cal BP was indicated by ^{14}C dating of in situ tree stumps, shell material and wood fragments from a back barrier estuarine sandy mud unit found between mean sea level and +1.45 m. Examples include Thermoluminescence (TL) dating of elevated beach deposits lying above the remnant Pleistocene dune at Bulli (Fig. 1b) at 4.5 m above PMSL that yielded TL ages of

* Corresponding author. Tel.: +852 2241 5484; fax: +852 2517 6912.
E-mail addresses: aswitzer@hkucc.hku.hk, aswitzer@ntu.edu.sg (A.D. Switzer).

1040-6182/$ – see front matter © 2009 Elsevier Ltd and INQUA. All rights reserved.
doi:10.1016/j.quaint.2009.06.035

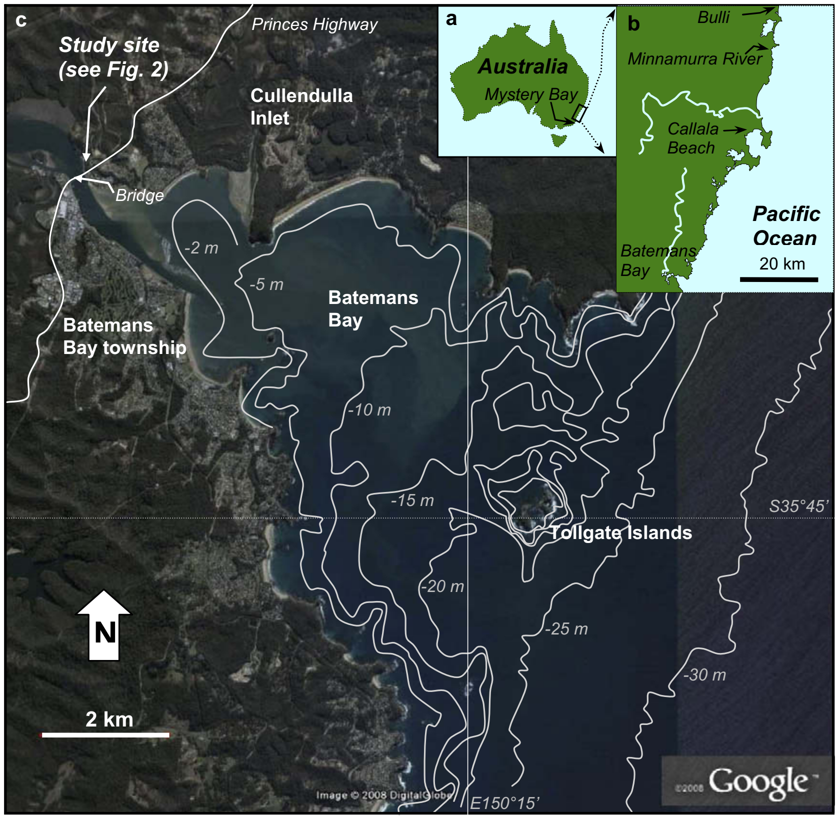

Fig. 1. a) Location map of the southeast Australian coast. Batemans Bay and other sites mentioned in the text are marked in (b). c) Bathymetry of Batemans Bay overlain on a Google Earth image of the area. The sheltered study site is located in a small pocket embayment west of the bridge that is landward of a large tidal delta which shelters the site from open ocean swells.

6100 ± 140 and 5200 ± 200 a (Bryant et al., 1992a). Elevated beach deposits were also reported at Mystery Bay approximately 80 km south of the study site (Fig. 1a). Here beach sands at an elevation of 5.8 m above PMSL yielded a similar TL age of 5400 ± 900 a (Young et al., 1993).

Further evidence of earlier and higher mid Holocene sea level has also been obtained from estuarine shells embedded in a deposit described as a caliche at ~2.5 m above PMSL in back-barrier deposits exposed on the banks of the Minnamurra River (Fig. 1c). Here, shell material gave an age range of 5950 ± 120 cal BP to 3450 ± 90 cal BP (Carne, 1981; Young et al., 1993).

Young et al. (1993) also identified similar raised estuarine deposits behind Callala Beach on the northern shore of Jervis Bay (Fig. 1b). Here, a sandy mud unit containing fifteen different estuarine species of molluscs preserved in growth position was identified (Young et al., 1993). The deposit rises to an elevation of 1.8 m above PMSL and a radiocarbon age of 5890 ± 50 cal BP obtained on an in situ specimen of *Anadara trapezia* indicates that sea level was ~1.5–2 m above PMSL c. 5900 years ago.

These sites provide consistent geomorphic evidence for a Holocene highstand of sea level that lasted from at least c. 7000 to 5000 cal BP. However, with the exception of one beach rock sample studied by Sloss et al. (2007), little geomorphic evidence for mid to late Holocene (c. 5000–2000 cal BP) higher sea levels has been found on this coast. The apparent lack of geomorphic evidence presents a conceptual problem as significant evidence for higher mid to late Holocene has been provided by FBIs (Flood and Frankel, 1989; Baker and Haworth, 1997, 2000a,b; Lewis et al., 2008).

The aim of this study is to contribute new data from an elevated sheltered beach sequence identified at Batemans Bay (Fig. 1c). The beach sequence was deposited during a higher sea level in the mid to late Holocene and was subsequently stranded by a combination of sea-level fall and estuarine infilling. The presence of this elevated beach and its age address a key conceptual problem related to contrasting palaeo-sea-level interpretations derived from FBIs compared with other forms of evidence.

2. Study site

The 12 km long, funnel-shaped Batemans Bay located 280 km south of Sydney is a drowned river estuary subject to fluvial influences from the Clyde River with a catchment of approximately 1800 km^2 (Hennecke, 2004). Batemans Bay faces southeast into the dominant storm swell direction on this coast and its shoreline morphology consists of sandy beaches lying between rocky headlands (Fig. 1). The contemporary embayment exhibits considerable bathymetric complexity, particularly around the offshore Tollgate Islands. A large marine sand body confines a channel along the southern margin of the estuary. The channel is of variable width (usually less than 300 m) and averages 8 m deep at the seaward end (Fig. 1). Little previous research has focused on the Quaternary evolution of Batemans Bay; however the embayment is most likely to have evolved in a similar fashion to other drowned river valleys on this coast (Roy et al., 2001). These deeply incised valleys were partially filled by marine sediment following the culmination of the most recent postglacial marine transgression (c. 7500 cal BP). However, unlike barrier estuaries they exhibit little attenuation of tidal range and are permanently open to the ocean (Roy et al., 2001; Sloss et al., 2006a,b).

A chenier beach ridge sequence found at Cullendulla Inlet on the northern margin of Batemans Bay provides the only site detailing the Holocene geomorphic evolution of the region (Donner and Junger, 1981; Thom et al., 1981, 1986; Bryant et al., 1992b; Bryant, 2001). Radiocarbon ages on shell material collected from the cheniers and beach ridges show a disjointed record of progradation that Donner and Junger (1981) related to a complex period of nearshore shallowing and shoaling. In contrast, Bryant et al. (1992b) suggested that the ridges are geomorphic forms related to tsunami sedimentation pointing out that consistently young radiocarbon age determination can be explained by the incorporation of younger material into the ridge forms during large-scale washover by tsunami.

The case study examined in this research represents a small sheltered embayment informally called Old Punt Bay approximately 150 m to the west of the Princes Highway bridge (Fig. 1c). The embayment is on the northern bank of the river where it broadens landward following the bedrock constriction at the site of the Princes Highway bridge. The small pocket beach contains an abundance of marine sand and shell with little fluvial sediment. The embayment fill is currently undergoing active erosion due to human clearance of mangroves, burrowing fauna (wombats) and river floods. The Quaternary sediments forming the deposit lie in a small amphitheatre-shaped basin incised into heavily folded Ordovician metasedimentary rocks (predominantly turbidites) of the Adaminaby Group (Glen, 1994).

3. Methods

A large number of sediment samples were obtained from a series of excavated faces, vibracores, and hand augers (Fig. 2). Coring of the sedimentary sequence was problematic due to the shell-rich nature of the deposit and only shallow cores were obtained from the grassy area between the road and the river bank (Fig. 2).

3.1. Sediment recording, description and sampling

Sediment analysis and detailed facies associations were initially investigated in sedimentary successions exposed in three excavated faces cut into the river (Fig. 2). The faces were measured and levelled to a local survey mark and the tide level at the time of sampling. Heights were then corrected to Australian Height Datum (AHD), the official height datum for Australian mean sea level which equates to present mean sea level (PMSL) on the NSW south coast (Umitsu et al., 2001; ICSM, 2002; Sloss et al., 2007). Bulk samples were taken at 10 cm intervals with extra samples taken at unit boundaries. Samples collected from the excavated faces were analysed for particle size, mineralogy, and macro- and microfauna, along with determination of organic and carbonate content. Samples were sieved at 2000 μm to remove the gravel fraction. The gravel fraction was analysed for rock clasts and recognizable shell content (macrofossils). The sand and mud fractions were analysed for mean grain size using laser diffraction particle size analysis conducted with a Malvern Mastersizer 2000 and carbonate content was determined by weight loss after treatment with 10% HCl.

3.2. Ground penetrating radar (GPR)

Two GPR transects were conducted at Batemans Bay (Fig. 2) following the methods and processing procedures outlined in Switzer et al. (2006). The first transect (BBGPR-1) was conducted

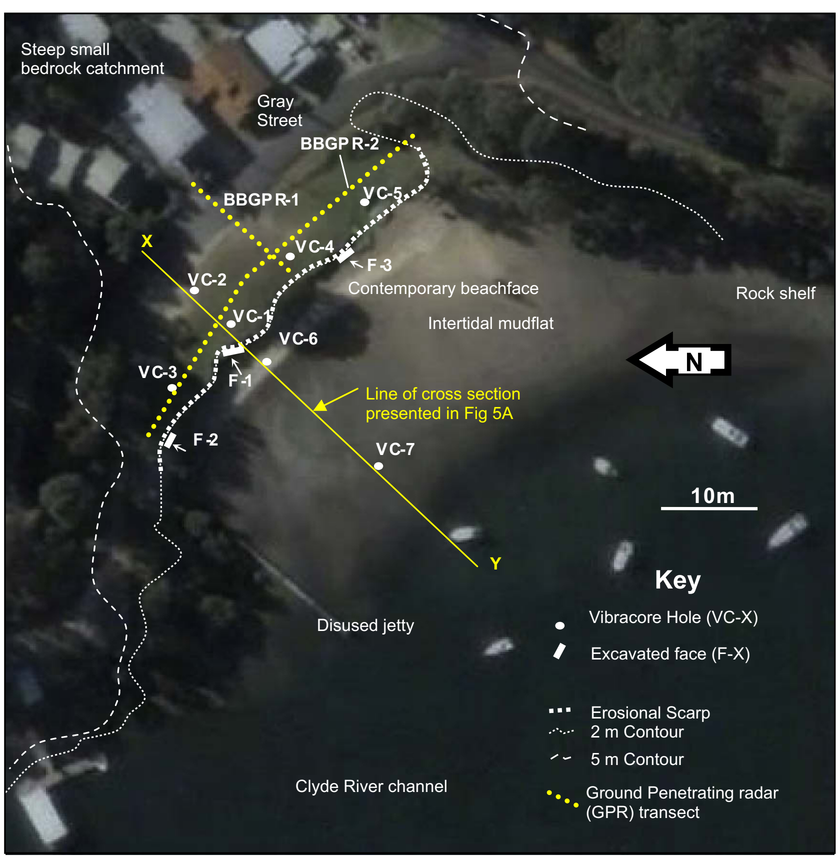

Fig. 2. Aerial photo of the study site at Batemans Bay showing the location of vibracores (VC1–VC7), excavated faces (F1–F3) and ground penetrating radar (GPR) transects. Samples ASB1 and ASB2 for optically stimulated luminescence dating (OSL) were taken from F2. The schematic cross-section in Fig. 5a is located as X–Y.

Please cite this article in press as: Switzer, A.D., et al., Geomorphic evidence for mid–late Holocene higher sea level from southeastern Australia, Quaternary International (2009), doi:10.1016/j.quaint.2009.06.035

parallel to the hypothesised direction of beach accretion while the second transect (BBGPR-2) was conducted parallel to the shore. The GPR profiles were collected using a Pulse Ekko PE 100 with 1000 V transmitter and 200 MHz antennas with spacing of 0.5 m and a step size of 0.1 m. Velocities of 0.11 and 0.13 m ns^{-1} were determined from common mid-point (CMP) surveys. The vertical scale for the profile is in two-way travel time (ns) with an interpreted depth scale in metres based on the measured wave velocity. The ground wave arrivals are present as the uppermost continuous reflection and should not be considered part of the stratigraphic data.

3.3. Micro- and macro-palaeontological sampling and analyses

Selected bulk samples of approximately 10 g weight collected from excavated faces, cores and grab sampling ($N = \sim 60$) were soaked in distilled water and wet-sieved at 63 and 2000 μm. These samples were used for macro- and microfaunal analysis. Macrofossils >2 mm were identified using the reference work of Jensen (1995). After standard picking techniques, foraminifers were divided into taxonomic counting groups established using Yassini and Jones (1995), Everett (2004) and Haslett (2007).

3.4. Dating

Three samples were taken for conventional radiocarbon dating; two separate valves of the estuarine bivalve *A. trapezia* (Deshayes) were taken from the basal shelly sand (Wk9440 – taken from face 1; Wk9441 – taken from vibracore 3) and an articulated *A. trapezia* (Wk9439) was taken from the overlying large shelly layer exposed in excavated face 2. The radiocarbon ages were obtained from the Waikato University, New Zealand. Radiocarbon ages were calibrated to sidereal years using the radiocarbon calibration program CALIBTM REV5.0.1 (Stuiver and Reimer, 1993). Calibration for fossil molluscs used the marine model calibration curve (Marine04) with a Δr value of 11 ± 85 yr to correct for the marine reservoir effect and convert ages into sidereal years (expressed as cal BP; Gillespie, 1977; Gillespie and Polach, 1979; Stuiver et al., 1998; Table 1; Fig. 4a). Calibrated radiocarbon ages (cal BP) are presented using a 2-sigma uncertainty term (95% degree of confidence; Table 1).

To complement the radiocarbon results amino acid racemisation (AAR) analyses were run on the remaining valve of the articulated bivalve dated using conventional radiocarbon (UWGA702 – taken from excavated face 2) plus three individual *A. trapezia* valves collected from the basal shelly sand facies in excavated face 1 (UWGA698 and UWGA699) and vibracore 3 (UWGA703). Additionally two single valves of *A. trapezia* from the overlying large shelly layer (UWGA700 and UWGA701) were also subject to AAR analysis. The age determinations made by amino acid racemisation dating method were based on the racemisation reaction of aspartic acid, one of the fastest racemising amino acids. The fast rate of racemisation of aspartic acid makes it particularly useful for dating fossils of Holocene age (Goodfriend, 1991, 1992; Goodfriend and Stanley, 1996; Sloss et al., 2004, 2006a). 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. (2004).

Optically stimulated luminescence (OSL) ages were obtained from the quartz sand of the basal shelly sand facies (ASB1 and ASB2). The OSL dating was performed at the University of Wollongong luminescence laboratories. OSL ages were processed using the single aliquot regenerative dose (SAR) protocols (Murray and Wintle, 2000).

Table 1
Characteristics of the five facies identified in excavated faces and vibracores from the study site at Batemans Bay.

Unit	Sediment description	Faunal characteristics
1	Fine- to medium-grained quartz to shell-rich quartz sand with occasional small rounded pebbles. The entire sequence is dominated by small bivalves. In places these small shells contribute ~70% of the sample.	Mostly composed of *N. trigonella* (up to 70% of the sample) and shell hash with a small percentage of microfauna (almost exclusively foraminifera). Macrofauna (>2 mm) in order of abundance, *N. trigonella*, *Tellina* sp. with rare *A. trapezia* and small fragments of *S. glomerata*. The microfauna consist of very few recognizable foraminiferal tests (*Elphidium* sp.).
2	Coarse shelly deposit dominated by fine- to medium-grained quartz sand with large shells and occasional rock clasts.	This unit has a diverse coarse shelly macrofauna including *A. trapezia* (several articulated) and *S. glomerata*. Microfauna include intact foraminifera that have become brittle and crumbly from in situ weathering.
3	Organic-rich soil and several lenses composed of organic-rich clays with sub-angular to sub-rounded quartz/lithic fine-grained sand.	The minor shells and shell fragments are heavily corroded. Sparse macrofauna (>2 mm) in order of abundance: *N. trigonella*, *Tellina* sp. with rare *A. trapezia* and small fragments of *S. glomerata*. No recognizable microfauna were identified in this unit.
4	Clean- to shelly sand deposits dominated by fine- to medium-grained quartz sand with a minor component of similar size lithic grains and some larger gravel clasts.	This shelly sand facies is dominated by *N. trigonella* and shell fragments but contains very few microfauna, although a few heavily weathered but unidentifiable foraminiferal tests were present.
5	Muddy sediments dominated by silt with a small component of quartz and lithic sand. Sand content increases with depth and the middle of core VC7 exhibits considerable mottling.	This unit contains a small population of bivalves, gastropods and carbonate microfauna including *Ammonia aoteana* and several *Elphidium* sp.

4. Results

The present morphology of the small embayment consists of a flat-lying grassy area with several small trees along the river bank. The river bank exposes a vertical section approximately 0.3–2.5 m above present mean sea level (PMSL) (Fig. 2). Below the bank is a small modern beach, and towards the river there is a tidal mudflat (Fig. 2). The stratigraphy of the embayment was investigated in cores VC1–VC5 where a basal shelly sand facies (Unit 1) is overlain by a large shelly unit (Unit 2) which grades vertically into a shell-rich soil (Unit 3). The whole sequence is now undergoing active erosion and the three main units observed in the faces and vibracores (Units 1–3) are now onlapped by a modern shelly sand unit (Unit 4) and shell-rich muddy sand that is composed of much finer sediments (Unit 5). A schematic cross-section (Fig. 5) constructed through vibracores (VC1, VC2, VC6 and VC7) and excavated face 2 shows the stratigraphic relationships between the five units. Stratigraphically the embayment can be divided into five main units (Table 1) that were observed in vibracores (Fig. 3) and excavated faces (Fig. 4). Five units and four clearly distinguishable facies (Units 1 and 4 share many sediment characteristics) were defined based on organic content, shelly fauna and sediment size characteristics. The sand fraction of both Units 1 and 2 is composed of fine- to medium-grained quartz sand with a minor lithic component. Both facies contain little variation in grain size (1.7–2.2 φ). Units 1 and 2 are separated based on major variation in the presence of macrofauna and rock clasts which are recorded as % gravel. Fig. 5b shows

Please cite this article in press as: Switzer, A.D., et al., Geomorphic evidence for mid–late Holocene higher sea level from southeastern Australia, Quaternary International (2009), doi:10.1016/j.quaint.2009.06.035

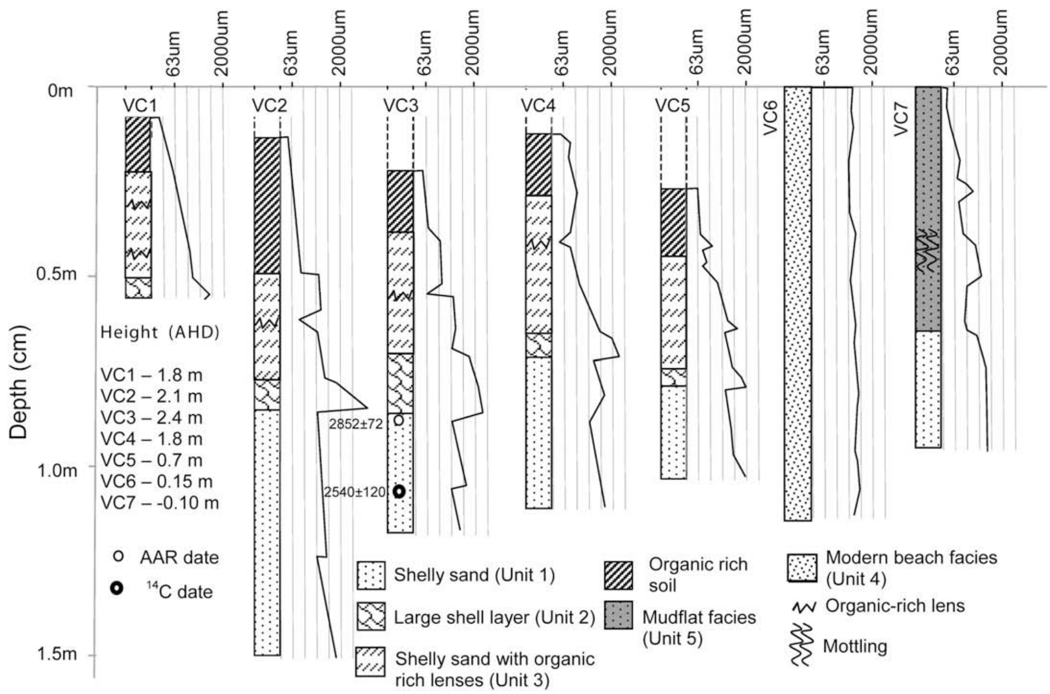

Fig. 3. Graphic logs and raw (sieved) grain size results for seven vibracores collected from the pocket embayment at Batemans Bay. Five units were identified in the system; three mid to late Holocene units (1–3) and two modern units (4–5).

a graph of mean (inclusive graphical mean) against sorting (inclusive graphic standard deviation) along with a plot of organic content (loss on ignition) against percent greater than 2000 μm (Fig. 5c) for 60 samples. Comparison of grain size parameters including inclusive mean and inclusive standard deviation along with percent greater than 2000 μm and carbonate and organic content classifies four facies. The soil and organic lenses cluster with the fine-grained sediments of the modern tidal flat and are only separated by organic and carbonate content. Both facies are representative of low energy environments with the mudflat containing slightly higher shell content and much greater organic content.

The excavated faces (F1–F3 in Fig. 2) allowed detailed analysis of the sandy shell-rich facies, the coarse shelly facies and the soil in both lateral and vertical detail. Fig. 5 shows excavated BBF2 and the interpretation of sedimentary features.

4.1. Ground penetrating radar results

The first GPR transect, BBGPR-1, was conducted at 90° to the shore face (Fig. 2) and returned a series of shallow seaward dipping reflectors (Fig. 6). A second profile, BBGPR-2, was conducted in a shore–parallel direction and revealed a series of irregularly shaped undulating reflectors.

4.2. Results of faunal analysis

The faunal assemblage of Unit 1 is composed of *Notospisula trigonella* (Lamarck) (up to 70% of the sample) and shell hash with a small percentage of microfauna (almost exclusively foraminifera). Macrofauna (>2 mm) in order of abundance, *N. trigonella*, *Tellina* sp. with rare *A. trapezia* (Deshayes) and small fragments of *Saccostrea glomerata* (Gould) (the Sydney rock oyster). The microfauna found in Unit 1 consist of very few recognizable foraminiferal tests that are most likely broken and partially dissolved *Elphidium* species.

Unit 2 has a diverse coarse shelly macrofauna including *A. trapezia* (Deshayes) (several articulated) and *S. glomerata*. Microfauna include foraminifera that were well preserved but had become brittle and crumbly from in situ weathering. Detailed investigation of this unit is ongoing: however, Switzer et al. (2009) showed that this unit contains a mixed faunal assemblage derived from a number of seaward sources.

There are minor shells and shell fragments found throughout Unit 3. The majority appears heavily corroded. Sparse macrofauna (>2 mm) are found and include in order of abundance, *N. trigonella*, Tellina sp. with rare *A. trapezia* and small fragments of *S. glomerata*. There were no recognizable microfauna identified in Unit 4 whilst Unit 5 was found to consist of shelly sand facies with a faunal assemblage that is dominated by *N. trigonella* and shell fragments but contains very few microfauna although a few heavily abraded or partially dissolved but unidentifiable foraminiferal tests were identified.

4.3. Dating results

All ^{14}C, AAR and OSL dating results from Batemans Bay are provided in Table 2. All ages from Unit 1 indicate a mid to late Holocene age for Unit 1 with deposition occurring between c. 5000 and 2500 years ago. A younger coarse shell-rich Unit 2 overlies the basal sequence but returned mixed young and old ages. A radiocarbon and aspartic acid derived AAR age on a specimen of *A. trapezia* (Wk9439 and UWGA702) gave ages of ~1000 BP (Table 2). However, two individual disarticulated valves of *A. trapezia* from the same unit yielded amino acid racemisation derived ages in excess of 2000 BP (UWGA700 and UWGA701). This apparent mixing of ages is most likely the result of reworking of older material into the younger overlying unit.

5. Depositional units

Unit 1 is found up to ~2.25 m above PMSL and consists of fine- to medium-grained quartz to shell-rich quartz sands with occasional rounded pebbles. In places it is almost entirely dominated by small

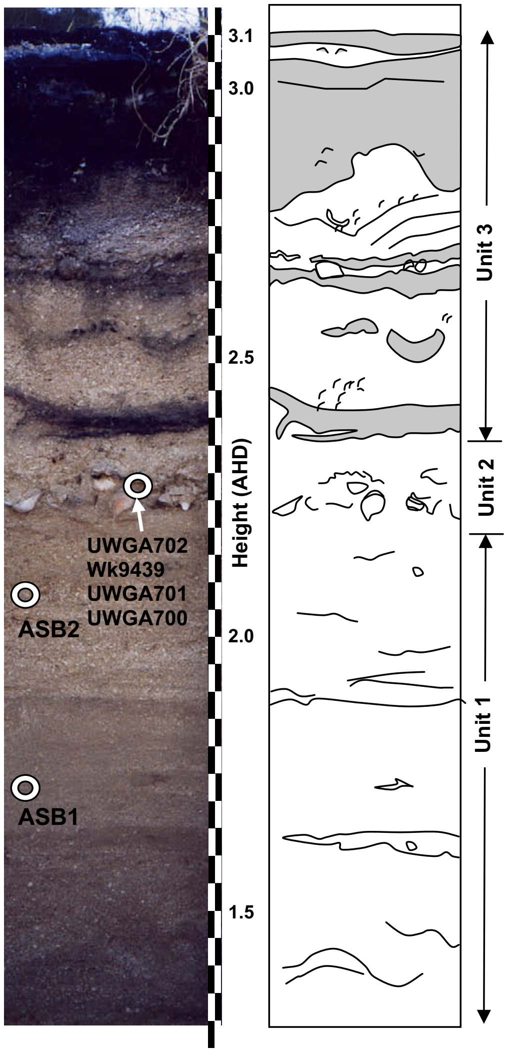

Fig. 4. Photographic and graphic representation of sedimentological characteristics in excavated face 2 (see Fig. 2 for location) at Batemans Bay. Units 1–3 are clearly visible. Interbedded sandy shell layers in the lowest unit (Unit 1) are overlain by a distinct large shelly layer (Unit 2). The top of the sequence (Unit 3) contains numerous organic-rich silty lenses and an organic-rich soil. Locations of dated samples listed in Table 2 are shown.

bivalves (*N. trigonella*) in medium-grained sand matrix. The sedimentary characteristics, lack of intact microfauna and the presence of shallow dipping reflectors identified by GPR suggest that this unit exhibits considerable evidence for accretionary beach activity. Such a beach environment defies its current sheltered location. The evolution of the shelly sand facies is hypothesised to be the product of higher energy deposition in a beach face during an elevated period of mid to late Holocene sea level (~1–1.5 m) under the influence of a different seaward morphology and a more open embayment (Figs. 2 and 5a).

5.1. Deposition of the basal shelly sand facies (Unit 1)

The basal shelly sand facies exhibits a number of well-defined dipping reflectors that are found approximately 0.8–1.8 m above PMSL and identified in GPR profile BBGPR-1 (Fig. 6). These dipping beds are indicative of a small prograded beach system deposited during a period of higher energy. Based on the presence of the shallow marine and estuarine fauna as well as the low angled seaward dipping reflectors this facies has been interpreted as a nearshore beach face. Accordingly, this facies would have been deposited within a few metres of contemporary sea level at the time, suggesting that sea level at the time must have been at least 1 m higher. It is most likely that the sandy beach sequence was deposited during a mid to late Holocene sea-level highstand (Sloss et al., 2007; Lewis et al., 2008) when the embayment was more open to direct nearshore marine processes.

This hypothesis is supported by radiocarbon and amino acid racemisation derived ages on fossil molluscs preserved in the beach sequence and supplemented by OSL dating of the beach sequence. These geochronological results constrain deposition of this beach face to be between 2500 and 4000 cal BP and suggest that much of this material was deposited during the sea-level highstand (Baker and Haworth, 1997, 2000a,b; Sloss et al., 2007; Lewis et al., 2008). During this time the estuarine system would have had a more open morphology prior to sedimentary infilling of the incised valley system. The higher than present sea level and more open conditions would have resulted in higher energy depositional environments being located farther into the incised valley (Fig. 7). Similar open embayment morphologies during the early to mid Holocene have been described in both broad and narrow incised valleys that are now occupied by barrier estuaries (Sloss et al., 2006a,b, 2007).

Following the mid Holocene highstand sea level fell to its present level from c. 2000 years ago (Sloss et al., 2007). As a result of this sea level regression, wave energy would be significantly dissipated stranding the beach sequence in the small embayment allowing the accumulation of the present low energy intertidal to subtidal mudflat.

5.2. Deposition of the large shelly layer (Unit 2)

The large shelly layer that overlies Unit 1 exists in all excavated faces and vibracores suggesting the deposit covers much of the embayment and exists from 0.7 m to 2.25 m above PMSL. This unit has previously been described as a late Holocene high-energy deposit (possibly tsunami) based on its unique sedimentology and position in the landscape and was deposited 1000–1300 cal BP (Switzer et al., 2001, 2005, 2009). In summary, results from these studies indicate that this shell-rich layer contained a mixed assemblage of large shelly fauna and is potentially coeval with other high-energy deposited sediments identified by Switzer et al. (2005, 2006) and Switzer and Jones (2008) approximately 130 km north of Batemans Bay at Killalea and Dunmore near the Minnamurra River (Fig. 1b) (Switzer et al., 2009).

5.3. Development of the organic-rich soil and organic lenses (Unit 3)

An organic-rich soil and several organic-rich lenses (Unit 3) are found in both the cores and excavated faces and overlie the large shelly layer. Unit 3 exists from approximately 0.8 m to 2.5 m above PMSL (Fig. 4). The organic-rich facies is characterised by high silt and clay content (up to 50%) and the presence of dark organic debris, sub-angular to sub-rounded fine-grained siliciclastic sand and a minor component of fractured shelly debris. Sediments grade down from the soil to a fine- to medium-grained shelly sand sequence with organic lenses. The genesis of the organic lenses is problematic but they are either modified (weathered) artefacts of aboriginal occupation (firepits) or post-depositional features resulting from groundwater movement through the porous sandy units.

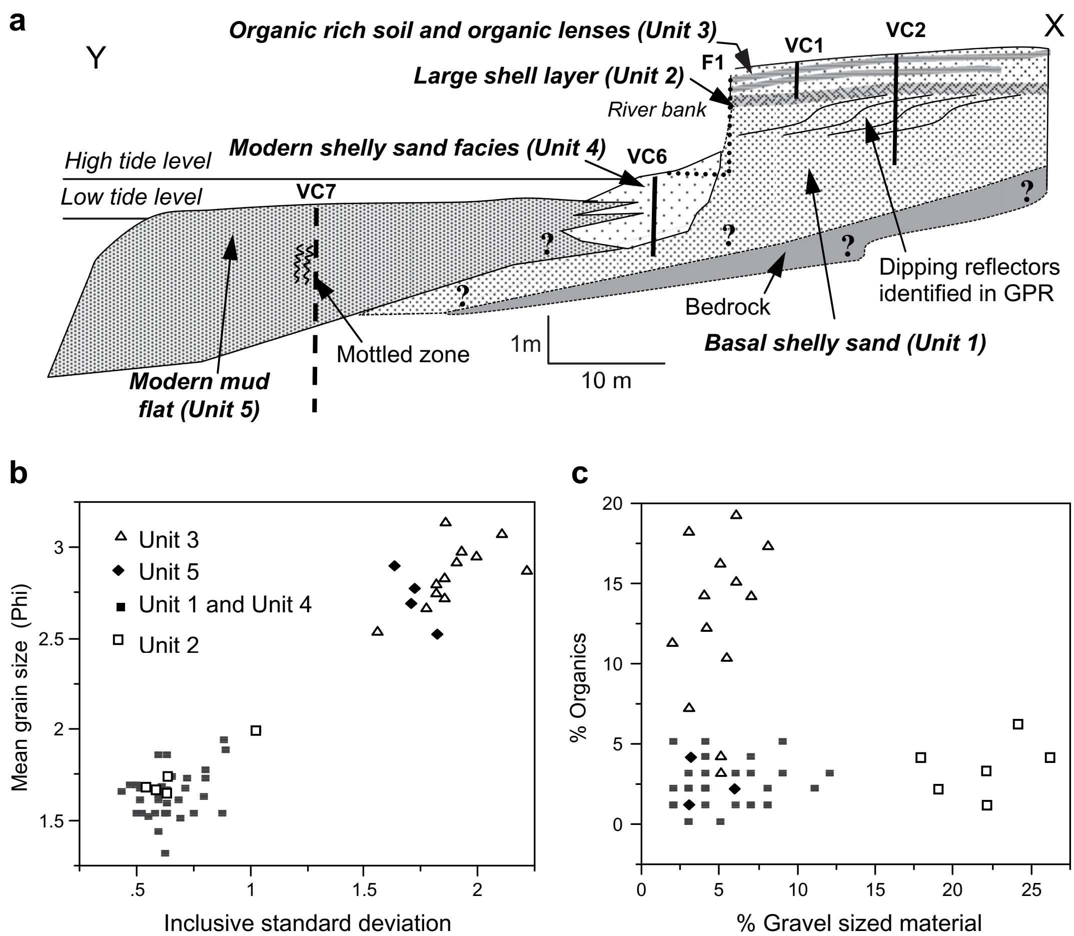

Fig. 5. (a) Stratigraphy of the pocket embayment deposit showing the stratigraphic relationship between the five sedimentary units and depositional environment. The modern beach facies (Unit 4) is predominantly reworked and shares many characteristics of the basal shelly sand facies (Unit 1). Bivariate plots of (b) inclusive mean grain size vs sorting (inclusive graphical standard deviation; phi notation) and (c) % organic matter vs % greater than 2 mm (sieved). Both Units 1 and 4 have similar sediment size characteristics but are differentiated by differences in organic and shell content. The same can be said for Units 3 and 5.

5.4. Sedimentation on the modern beach (Unit 4) and tidal mudflat (Unit 5)

The modern beach and tidal mudflats are represented by Units 4 and 5. The modern beach is composed of clean- to shelly sand deposits dominated by fine- to medium-grained quartz sand with a minor component of medium- to coarse-sand size lithic grains. Ongoing erosion of the river bank appears the most likely source for the modern beach sediments and much of the material appears to be reworked from Units 1 to 3 (see Fig. 5a). The tidal mudflat (Unit 5) contrasts with the modern beach facies (Unit 4). The muddy sediments are dominated by silt with a small component of quartz and lithic sand. The sand content increases with depth in core VC7 and the mottled nature of the sediment in the mid parts of VC7 possibly records the former presence of a mangrove community before removal for development in the 1950s.

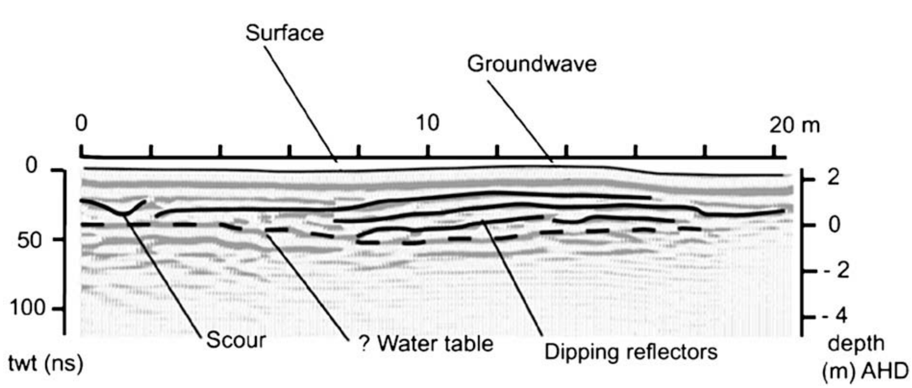

Fig. 6. Interpreted shore–normal ground penetrating radar transect (BBGPR-1) shows a prograding sequence of dipping beds in Unit 1.

Table 2
Dating results from the Batemans Bay sequence. The majority of ages come from the basal shelly sand (Unit 1) and date to approximately the mid Holocene.

Sample (height AHD)	Specimen number	Technique	Material dated	Facies/unit	Sample notes	Age (cal BP)	Age range (BP)
ASBBF2 (2.25 m)	UWGA702	AAR	*Anadara* shell (articulated)	Unit 2	Articulated shell	1060 ± 50	1010–1100
ASBBF2 (2.25 m)	Wk9439	^{14}C	*Anadara* shell (articulated)	Unit 2	Articulated shell	1284 ± 58	1226–1342
ASBBF2 (2.23 m)	UWGA700	AAR	*Anadara* shell	Unit 2	Single valve	2060 ± 100	1960–2160
ASBBF2 (2.25 m)	UWGA701	AAR	*Anadara* shell	Unit 2	Single valve	2670 ± 120	2550–2790
ASBBVC3 (1.2 m)	UWGA703	AAR	*Anadara* shell	Unit 1	Single valve	2540 ± 120	2420–2660
ASBBF1 (0.8 m)	UWGA698	AAR	*Anadara* shell	Unit 1	Single valve	3610 ± 170	3440–3780
ASBBF1 (1.2 m)	UWGA699	AAR	*Anadara* shell	Unit 1	Single valve	7840 ± 350	7490–8190
ASB1 (2.10 m)	ASB1	OSL	Quartz sand	Unit 1	Central age model	2840 ± 840	2000–3680
ASB2 (1.75 m)	ASB2	OSL	Quartz sand	Unit 1	Central age model	2390 ± 210	2180–2600
ASBBF1 (2.2 m)	Wk9440	^{14}C	*Anadara* shell	Unit 1	Single valve	2506 ± 67	2439–2573
ASBBVC3 (1.8 m)	Wk9441	^{14}C	*Anadara* shell	Unit 1	Single valve	2852 ± 72	2780–2924

6. Previous studies utilizing geomorphologic evidence for higher than present mid Holocene sea level

On the southeast coast of Australia, several studies have documented geomorphologic expressions of higher than present sea level (Table 3). These include raised estuarine deposits and raised beach facies. For example, on MacCauleys Beach and Sandon Point Beach at Bulli, raised shelly estuarine deposits surround a freshwater tree stump and contain mangrove stumps (Jones et al., 1979). They provide clear evidence that following the last glacial maximum, rising sea level attained present sea level c. 7700 years ago and continued to rise to between 1 and 1.5 m above present mean sea level (PMSL) by 7200 cal BP (Jones et al., 1979; Sloss et al., 2007).

Similar raised estuarine deposits have also been identified behind Callala Beach on the northern shore of Jervis Bay where a sandy mud unit containing numerous estuarine mollusc species in growth position was identified. The unit rises to an elevation of 1.8 m above PMSL and a radiocarbon age of 5890 ± 50 cal BP obtained on an in situ specimen of *A. trapezia* indicates that sea level was close to 2 m above PMSL c. 5900 cal BP (Pease, 1992; Young et al., 1993).

Additional geomorphologic studies on the southeast coast of Australia that support a higher sea level associated with the culmination of the most recent postglacial marine transgression include raised beach deposits (Table 3) (Bryant et al., 1992a; Young et al., 1993). However, Sloss et al. (2007) pointed out that elevated beach deposits can only be used as relational sea-level indicators and do not accurately constrain palaeo-sea levels. Nevertheless, assuming similar wave power and run-up to those of the present day, Bryant et al. (1992a) and Young et al. (1993) concluded that the elevated beach facies indicate that sea level was ~2 m above PMSL between 6000 and 5000 BP.

Although all these mid to late Holocene deposits that provide geomorphic evidence for a higher sea level are individually small, they occur sporadically over about 250 km of the southeast Australian coast. Their sporadic preservation is not unexpected on a high energy coast where storm-generated erosion can easily remove small coastal exposures. However the raised deposits listed in Table 3 do provide good corroborating evidence for the highstand of sea level in the early to mid Holocene (c. 7700–3500 cal BP) that was mainly derived from transgressive sandsheet and back-barrier deposits in shallow incised valleys along the southeastern Australian coast (Sloss et al., 2007).

Evidence for a mid to late Holocene higher sea level is less widespread. The best evidence for mid to late Holocene higher sea level probably comes from the estuarine shells embedded in back-barrier deposits incised by the Minnamurra River (Carne, 1981; Jones, 1990; Young et al., 1993) where an *A. trapezia* sample gave an age of 3450 ± 90 BP (Carne, 1981; Young et al., 1993) and a sample of beach rock studied by Sloss et al. (2007) returned an age of 1430 ± 160 cal BP. Results from this case study indicate that sea level between c. 5000 and 2500 cal BP was at least 1 m higher in

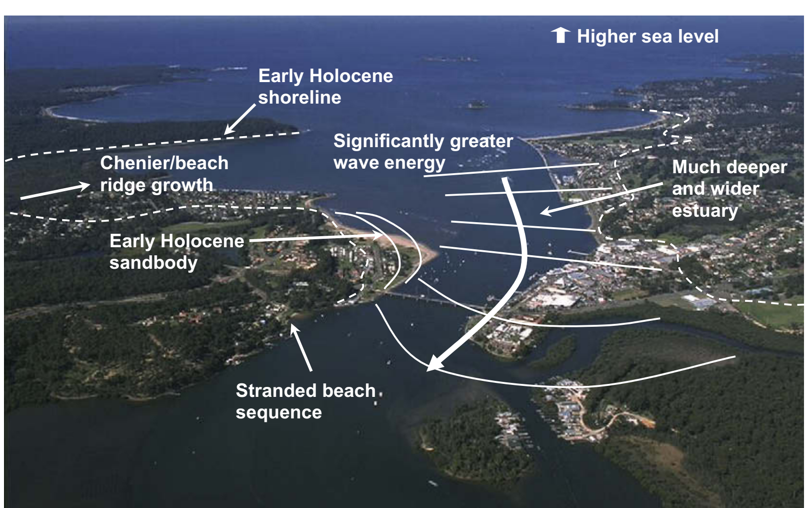

Fig. 7. Schematic figure demonstrating the hypothesis of a more open embayment in the mid Holocene. A more open embayment would account for the higher energy system indicated by the prograded beach facies. It is also likely that possible higher mid Holocene sea levels (Sloss et al., 2007; Lewis et al., 2008) would increase wave energy in the small embayment.

Please cite this article in press as: Switzer, A.D., et al., Geomorphic evidence for mid–late Holocene higher sea level from southeastern Australia, Quaternary International (2009), doi:10.1016/j.quaint.2009.06.035

Table 3
Comparison table of geomorphic evidence from raised estuarine and beach deposits from the southeast Australian coast. Thermoluminescence (TL), optically stimulated luminescence (OSL) and radiocarbon (^{14}C) chronology indicates a Holocene highstand between 7700 cal BP and about 2000 cal BP (see Sloss et al., 2007). All sites are marked in Fig. 1.

Location	Sample height above PMSL (m)	Inferred height of sea level (m)	Age range (BP)	Age (cal yr BP)	Method and material	Laboratory code	Source
Long Reef	0.3	~0.5	3978–4823	4440 ± 420	^{14}C Freshwater swamp mud	LJ-451	Thom et al., 1969
North Wollongong	1.29	~1.5–2	6699–7415	7060 ± 360	^{14}C Wood in estuarine mud	NSW-148	Jones et al., 1979
	1.49	~1.5–2	6965–7423	7190 ± 230	^{14}C Wood in estuarine mud	NSW-147	
	1.05	~1.5–2	7069–7756	7410 ± 340	^{14}C Estuarine shell	NSW-953	
	1.05	~1.5–2	7438–7947	7690 ± 250	^{14}C Mangrove root in situ	NSW-150	
	1.84	~1.5–2	7506–8042	7770 ± 270	^{14}C *Callicoma* stump in situ	NSW-131	
	0.05	~1.5–2	7979–8544	8260 ± 280	^{14}C *Callicoma* stump in situ	NSW-149	
Kurnell	1	~1	3802–4560	4180 ± 380	^{14}C *Anadara* shell	SUA–518	Roy and Crawford, 1976
Minnamurra River	2.5	~2	3534–4225	3880 ± 350	^{14}C Estuarine shell fragments	NSW-371	Carne, 1981
	2.5	~2	6008–6681	6340 ± 340		NSW-370	
North Wollongong	~2	~1.5	3200–7200	5200 ± 2000	(TL) Elevated beach deposits	W877	Bryant et al., 1992b
(Bulli)	~2	~1.5	4700–7500	6100 ± 1400		W882	
Mystery Bay	5.8	~2	4500–6300	5400 ± 900	(TL) Elevated beach deposits	W1201	Young et al., 1993
Minnamurra River	3	~2	5840–5940	5890 ± 50	^{14}C Oyster shell	W1201	Young et al., 1993
Minnamurra River	0.91	~1	2517–2962	2740 ± 220	^{14}C Organic muds with *zostera*	SUA-2424	Jones, 1990
	0.79	~1.5	2345–2741	2540 ± 200	^{14}C Organic muds with *zostera*	SUA-2406	
	2.25	~1.5	2349–2925	2640 ± 290	^{14}C Organic muds with *zostera*	SUA-2421	
Sandon Point	0.93	~1	7293–8155	7720 ± 430	^{14}C *Myrtaceae* stump in situ	SUA-1078	Bryant et al., 1992b
	1.09	~1	7332–8177	7750 ± 420	^{14}C *Myrtaceae* stump in situ	SUA-1079	
Shellharbour	0.5	~1	5658–6265	5960 ± 300	^{14}C peat in dune	NSW-151A	Young et al., 1993
	0.5	~1	5913–6400	6160 ± 240	^{14}C peat in dune	NSW-151	
Minnamurra River	0.5	~0.5	1278–1588	1430 ± 160	^{14}C Beach rock	Wk-14308	Sloss et al., 2007
Batemans Bay	1.2	~1–1.5	2420–2660	2540 ± 120	(AAR) *Anadara* shell	UWGA703	This study
	0.8	~1	3440–3780	3610 ± 170	(AAR) *Anadara* shell	UWGA698	
	1.2	~1–1.5	7490–8190	7840 ± 350	(AAR) *Anadara* shell	UWGA699	
	2.2	~1.5–2	2439–2573	2506 ± 67	(^{14}C) *Anadara* shell	Wk9440	
	1.8	~1.5–2	2780–2924	2852 ± 72	(^{14}C) *Anadara* shell	Wk9441	
	2.1	~1.5–2	2000–3680	2840 ± 840	(OSL) Quartz sand	ASB1	
	1.75	~1.5–2	2180–2600	2390 ± 210	(OSL) Quartz sand	ASB2	

this area and add to the growing geomorphic and sedimentological evidence for a higher mid to late Holocene sea level along the southeastern Australian coast.

7. Conclusions

The pocket beach at Batemans Bay preserved a sedimentary unit of fine- to medium-grained, shelly sands (Unit 1). The sequence is interpreted as a prograded beach sequence that is the result of a combination of a more open embayment and higher than present sea level during the mid to late Holocene c. 2500–5000 cal BP. The beach succession suggests that sea level was at least 1 m higher than present for much of the mid to late Holocene. The beach succession is overlain by a shell layer and further sand deposits (Units 2 and 3) that may result from major storm or tsunami activity that also occurred while the estuary was more open than it currently is. These deposits were both preserved following a reduction in sea level that restricted the opening of the estuary and prevented access to large waves. Under the lower energy conditions the beach deposits were protected by the establishment of a coastal mangrove community (Unit 5). Removal of the mangrove forest has now opened the embayment to considerable erosion during flooding of the Clyde River.

Acknowledgements

This project was supported by Dunmore Sand and Soil Pty Ltd. and The Landscape Research Centre (now GeoQuEST) at the University of Wollongong. Kerry Steggles, Managing Director of Dunmore Sand and Soil, is thanked for his enthusiasm for this research. The authors would like to thank the residents of Gray Street for access to the site. Funding for the project came from ARC SPIRT grant C00107062 (now ARC Linkage grants). Luxurious home style accommodation at Batemans Bay during various visits to the area was provided by the Gowen family and Ross Hawke. Ben Ackerman and Kevin Pucillo are thanked for their assistance with fieldwork. Charles Bristow thanks Birkbeck College for a Faculty Research Grant. The OSL dating program benefited from the assistance of Kira Westaway and Jose Abrantes at the School of Earth and Environmental Sciences, University of Wollongong. We also thank Colin Murray-Wallace and the University of Wollongong for assistance in the use of the amino acid racemisation laboratory. This paper is a contribution to IGCP Project 495 "Quaternary Land–Ocean Interactions" and the INQUA working group on "Coastal and Marine Processes".

References

Baker, R.G.V., Haworth, R.J., 1997. Further evidence from relic shellcrust sequences for a late Holocene higher sea level for eastern Australia. Marine Geology 141, 1–9.
Baker, R.G.V., Haworth, R.J., 2000a. Smooth or oscillating late Holocene sea-level curve? Evidence from cross-regional statistical regressions of fixed biological indicators. Marine Geology 163, 353–365.
Baker, R.G.V., Haworth, R.J., 2000b. Smooth or oscillating late Holocene sea-level curve? Evidence from the palaeozoology of fixed biological indicators in south east Australia and beyond. Marine Geology 163, 367–386.
Bryant, E.A., 2001. Tsunami: the Underrated Hazard. Cambridge University Press, Stanford, 350 pp.

Bryant, E.A., Young, R.W., Price, D.M., Short, S.A., 1992a. Evidence for Pleistocene and Holocene raised marine deposits, Sandon Point, New South Wales. Australian Journal of Earth Sciences 39, 481–493.
Bryant, E.A., Young, R.W., Price, D.M., 1992b. Evidence of tsunami sedimentation on the southeastern coast of Australia. Journal of Geology 100, 753–765.
Carne, R.J., 1981. Landform–vegetation relationship in the Minnamurra Estuary, New South Wales. B.Sc. Honours thesis, University of Wollongong, 118 pp (unpublished).
Donner, J., Junger, H., 1981. Radiocarbon dating of marine shells from southeastern Australia as a means of dating relative sea level change. Annals Academy Sciences Fennic (Soumalainen Tiedeakatemia Toimituksia) 131, 5–14.
Everett, D.M., 2004. The role of extreme events in estuarine and coastal evolution: a case study of the Clyde River estuary (N.S.W., Australia). B.Sc. Honours dissertation, Bath Spa University College, UK, 80 pp (unpublished).
Flood, P.G., Frankel, E., 1989. Late Holocene higher sea-level indicators from eastern Australia. Marine Geology 90, 193–195.
Gillespie, R., 1977. Sydney University natural radiocarbon measurements IV. Radiocarbon 19, 101–110.
Gillespie, R., Polach, H.A., 1979. The suitability of marine shells for radiocarbon dating of Australian prehistory. In: Berger, R., Suess, H. (Eds.), Proceedings of the Ninth International Conference on Radiocarbon. University of California Press, Los Angeles, pp. 404–421.
Glen, R.A., 1994. Cambro-Ordovician sedimentary/metamorphic rocks. In: Lewis, P.C., Glen, R.A., Pratt, G.W., Clarke, I. (Eds.), Bega–Mallacoota 1:250,000 Geological Sheet SJ/55-4, SJ/55-8: Explanatory Notes. Geological Survey of New South Wales, Sydney, pp. 15–33.
Goodfriend, G.A., 1991. Patterns of racemization and epimerization of amino acids in land snail shells over the course of the Holocene. Geochimica et Cosmochimica Acta 55, 293–302.
Goodfriend, G.A., 1992. Rapid racemization of aspartic acid in mollusc shells and potential for dating over recent centuries. Nature 357, 399–401.
Goodfriend, G.A., Stanley, D.J., 1996. Reworking and discontinuities in Holocene sedimentation in the Nile delta: documentation from amino acid racemization and stable isotopes in mollusk shell. Marine Geology 129, 271–283.
Haslett, S., 2007. The distribution of foraminifera in surface sediments of the Clyde River estuary and Bateman's Bay (New South Wales, Australia). Revista Española de Micropaleontología 39, 63–70.
Hennecke, W.G., 2004. GIS modelling of sea-level rise induced shoreline changes inside coastal re-entrants – two examples from southeastern Australia. Natural Hazards 31, 253–276.
Intergovernmental Committee on Surveying and Mapping (ICSM), 2002. Geocentric Datum of Australia, Technical Manual 2.2. ICSM, Canberra, Australia.
Jensen, P., 1995. Seashells of Central New South Wales: a Survey of the Shelled Marine Molluscs of the Sydney Metropolitan Area and Adjacent Coasts. Patty Jensen, Belgian Gardens, Queensland, 302 pp.
Jones, R.L., 1990. Late Holocene vegetation change on the Illawarra coastal plain, New South Wales, Australia. Review of Palaeobotany and Palynology 65, 37–46.
Jones, B.G., Young, R.W., Eliot, I.G., 1979. Stratigraphy and chronology of receding barrier-beach deposits on the northern Illawarra coast of New South Wales. Journal of the Geological Society of Australia 26, 255–264.
Lewis, S.E., Wust, R.A.J., Webster, J.M., Shields, G.A., 2008. Mid–late Holocene sea-level variability in eastern Australia. Terra Nova 20, 74–81.
Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.
Murray-Wallace, C.V., 1993. A review of the application of the amino acid racemisation reaction to archaeological dating. The Artefact 16, 19–26.
Murray-Wallace, C.V., Kimber, R.W.L., 1987. Evaluation of the amino acid racemization reaction in studies of Quaternary marine sediments in South Australia. Australian Journal of Earth Sciences 34, 279–292.
Pease, M.I., 1992. Geomorphology of Callala, Huskisson and Vincentia, Jervis Bay, New South Wales. B.Sc. (Hons) thesis, University of Wollongong, 102 pp (unpublished).
Roy, P.S., Crawford, E.A., 1976. Holocene geological evolution of the southern Botany Bay-Kurnell region, central New South Wales coast. Records of the Geological Survey of New South Wales, Department of Mineral Resources 20, 159–250.
Roy, P.S., Williams, R.J., Jones, A.R., Yassini, I., Gibbs, P.J., Coates, B., West, R.J., Scanes, P.R., Hudson, J.P., Nichol, S., 2001. Structure and function of southeast Australian estuaries. Estuarine, Coastal and Shelf Science 53, 351–384.
Sloss, C.R., Murray-Wallace, C.V., Jones, B.G., Walin, T., 2004. Aspartic acid racemisation dating of mid Holocene to recent estuarine sedimentation in New South Wales, Australia: a pilot study. Marine Geology 212, 45–59.
Sloss, C.R., Jones, B.G., Murray-Wallace, C.V., 2005. Holocene sea level change and the evolution of a barrier estuary: a case study, Lake Illawarra, NSW, Australia. Journal of Coastal Research 21, 943–959.
Sloss, C.R., Murray-Wallace, C.V., Jones, B.G., 2006a. Aminostratigraphy of two Holocene wave-dominated barrier estuaries in southeastern Australia. Journal of Coastal Research 22, 113–136.
Sloss, C.R., Jones, B.G., McClennen, C.E., de Carli, J., Price, D.M., 2006b. The geomorphologic evolution of a wave-dominated barrier estuary: Burrill Lake, New South Wales, Australia. Sedimentary Geology 187, 229–249.
Sloss, C.R., Murray-Wallace, C.V., Jones, B.G., 2007. Holocene sea-level change on the southeast coast of Australia: a review. The Holocene 17, 1001–1016.
Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C calibration program. Radiocarbon 35, 215–230.
Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. Radiocarbon 40, 1127–1151.
Switzer, A.D., Jones, B.G., 2008. Large-scale washover sedimentation in a freshwater lagoon from the southeast Australian coast: tsunami or exceptionally large storm? The Holocene 18, 787–803.
Switzer, A.D., Bryant, E.A., Jones, B.G., 2001. Rapid deposition of an elevated shell-rich sand in a drowned river valley, Batemans Bay, NSW Australia. In: Proceedings Volume of the Consortium of Ocean Geosciences (COGS) Conference, Hobart, Tasmania, July 2001, p. 71.
Switzer, A.D., Pucillo, K., Haredy, R.A., Jones, B.G., Bryant, E.A., 2005. Sea-level, storms or tsunami; enigmatic sand sheet deposits in sheltered coastal embayment from southeastern New South Wales Australia. Journal of Coastal Research 21, 655–663.
Switzer, A.D., Bristow, C.S., Jones, B.G., 2006. Investigation of large-scale overwash of a small barrier system on the southeast Australian coast using ground penetrating radar. Sedimentary Geology 183, 145–146.
Switzer, A.D., Mamo, B.L., Dominey-Howes, D., Jones, B.G., Haslett, S.K., Everett, D.M., 2009. New findings of tsunami deposits extend known geographic impact of late Holocene tsunami, southeast Australia. Geophysical Research Abstracts 11 EGU2009-8888.
Thom, B.G., Hails, J.R., Martin, A.R.H., 1969. Radiocarbon evidence against higher postglacial sealevels in eastern Australia. Marine Geology 7, 161–168.
Thom, B.G., Bowman, G.M., Gillespie, R., Temple, R., Barbetti, M., 1981. Radiocarbon Dating of Holocene Beach-ridge Sequences in Southeast Australia, vol. 11. Department of Geography, Royal Military College, Duntroon, 36 pp.
Thom, B.G., Roy, P.S., Short, A.D., Hudson, J., Davis, R.A., 1986. Modern coastal and estuarine environments of deposition in southeastern Australia. In: 12th International Sedimentology Conference. Guide to Excursion 4A. Department of Geography, University of Sydney, 279 pp.
Umitsu, M., Buman, M., Kawase, K., Woodroffe, C.D., 2001. Holocene palaeoecology and formation of the Shoalhaven River deltaic-estuarine plains, southeast Australia. The Holocene 11, 407–418.
Yassini, I., Jones, B.G., 1995. Foraminiferida and Ostracoda from Estuarine and Shelf Environments on the Southeastern Coast of Australia. University of Wollongong Press, Wollongong, 482 pp.
Young, R.W., Bryant, E.A., Price, D.M., Wirth, L.M., Pease, M., 1993. Theoretical constraints and chronological evidence of Holocene coastal development in central and southern New South Wales, Australia. Geomorphology 7, 317–329.

Please cite this article in press as: Switzer, A.D., et al., Geomorphic evidence for mid–late Holocene higher sea level from southeastern Australia, Quaternary International (2009), doi:10.1016/j.quaint.2009.06.035