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The last interglacial (MIS 5e) sea level highstand from a tectonically stable far-field setting, Yorke Peninsula, southern Australia

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ABSTRACT

Yorke Peninsula in southern Australia is an important region for reconstructing relative sea-level histories due to its location on the eastern margin of the tectonically stable Gawler Craton and in one of the world's geographically most remote far-field locations from the Pleistocene ice sheets. Richly fossiliferous, skeletal carbonate sands of the last interglacial (125 ka) Glanville Formation crop out in the coastal cliffs along large sectors of southern Yorke Peninsula. Sedimentary facies include deepening-upward intertidal to shallow subtidal facies, relict storm beach facies and cobble and boulder beach deposits in more exposed, higher energy locations. During deposition of the Glanville Formation, southern Yorke Peninsula had a different coastal geography with two prominent marine corridors extending across the southern-most portion of the entire peninsula. In a 3 km long coastal cliff section in southern Hardwicke Bay, the Glanville Formation crops out as an upward-deepening intertidal-subtidal succession capped by supratidal and subaerially-exposed sediments with pervasive calcrete development. The sedimentary succession passes upwards from a basal unit of intertidal sand flat facies with abundant gastropods (*Batillaria diemenensis*) near the upper bounding (disconformity) surface, upwards into richly fossiliferous shelly sands (coquina) representing a shallow subtidal facies formed by sediment aggradation in response to a relative sea-level rise. The subtidal facies is dominated by the bivalve molluscs *Katelysia* sp. and *Amesodesma angusta,* signifying a water deepening event. The subtidal facies is in turn overlain by pedogenically modified skeletal carbonate sands with pervasive calcrete development signifying a relative sea level fall at the end of the Last Interglacial Maximum. The upper-bounding surface of the shallow-water subtidal facies ranges from 2.4 to 3.0 m Australian Height Datum (AHD) and by analogy with modern sedimentary environments suggests a maximum palaeo-sea level of 4.8 ± 1.0 m during the Last Interglacial Maximum. Uranium-series ages of 127.3 ± 2.1 to 115.0 ± 5.4 ka on specimens of the solitary coral *Plesiastrea versipora* from the subtidal facies confirm that the succession was deposited during the Last Interglacial Maximum, and are consistent with the independent stratigraphical evidence that the highstand event was represented by a single phase of relative sea-level rise. Correlation with other occurrences of the Glanville Formation in southern Australia has also been confirmed by aminostratigraphy.

1. Introduction

The Last Interglacial Maximum, which is defined as Marine Isotope Substage 5e (MIS 5e) in oxygen isotope records from deep sea and ice cores, occurred approximately 128 to 116 ka ago (Shackleton, 1969; Kukla et al., 2002). It was the warmest period in the past 128 ka as expressed by smaller ice sheet volumes, higher sea levels than in the present Holocene Interglacial and expansion in the geographic range of biota tolerant of warmer waters (Murray-Wallace et al., 2000; Muhs et al., 2002).

In a global context, field evidence for a higher sea level during MIS 5e has been documented from many geomorphological features showing that sea level was between 2 and 9 m higher than present sea level (Murray-Wallace and Belperio, 1991; Stirling et al., 1998; Hearty et al., 2007; Carr et al., 2010; O'Leary et al., 2013; Murray-Wallace and Woodroffe, 2014; Dutton et al., 2015; Murray-Wallace et al., 2016), and that the melt water from the Antarctic ice sheet contributed 5 to 9 m of the sea-level rise (Bamber et al., 2009; Pingree et al., 2011; Dutton and Lambeck, 2012; Kopp et al., 2013). At a global scale, the striking spatial variability in the magnitude of inferred palaeo-sea levels was influenced by contrasting geophysical behaviour of the Earth's crust-mantle system including crustal unloading by the melting of ice sheets, glacio-hydro-isostatic adjustments, crustal flexure, collapse of forbulges (geoid highs) and equatorial ocean siphoning (Mitrovica and Milne, 2002;

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Lambeck et al., 2012; Creveling et al., 2015). These factors resulted in contrasting relative sea level histories around the globe relating to distance from former ice sheets: far-field (e.g. Australia, South Africa, and Seychelles), intermediate-field (e.g. Caribbean Sea), and near-field regions (e.g. northern Europe) (Dutton and Lambeck, 2012; Lambeck et al., 2012; Long et al., 2015).

Tectonically stable, far-field regions are particularly suited for quantifying former sea levels as the palaeo-sea level signature is dominated by ice-equivalent sea level. Southern Australia experienced minimal ice cover during Pleistocene glacials precluding glacio-isostatic rebound within the region from directly contributing to its relative sea level record. In a similar manner, although the relative sea level record of the southern Australian margin is not immune to the influence of Glacio-Isostatic-Adjustments (GIA) that occur within near-field regions, their contribution to the sea level record of this margin is relatively minor compared with the overall magnitude of sea-level change. Present day relative sea-level change within the study area due to elastic deformation of the solid Earth resulting from current deglaciation of glaciers and ice sheets is approximately 0 to 0.3 mm/year (Conrad, 2013). Similarly, postglacial viscous deformation of the wider southern Australian continental margin due to past deglaciation is modelled at between −0.1 and 0.1 mm/year (Conrad, 2013), highlighting the minor contribution to the overall observed relative sea-level changes in this far-field setting.

In a global context, a wide range in elevations and inferred relative sea-level trends has been noted for last interglacial sediments and landforms in far-field regions. The nature of eustatic sea-level oscillations during the Last Interglacial has also been widely debated in terms of whether the interval was characterised by two highstands or a single period of high sea level.

In this paper we present evidence for relative sea-level changes and quantify the maximum level of coastal inundation during the Last Interglacial Maximum (MIS 5e) from a series of carbonate successions of the Glanville Formation on Yorke Peninsula, southern Australia. In addition, we also assess if there is evidence for a bipartite or single sea level highstand within the region, and describe the last interglacial (MIS 5e) coastal palaeogeography of Yorke Peninsula.

2. Regional setting

As the explorer and hydrographer Matthew Flinders (1814, p. 181) noted, Yorke Peninsula has '… some resemblance to a very ill-shaped leg or foot'. The peninsula is 240 km long (North-South), with the 'foot' part 80 km long (East-West) (Fig. 1a). The peninsula is part of the eastern margin of the Gawler Craton, a complex of granites, gneisses and other metamorphic rocks which were last deformed 1450 Ma ago (Parker, 1993). The region shows a high degree of tectonic stability with only rare earthquakes recorded, revealing that magnitude ≥3 earthquakes are fewer than in the adjacent Mount Lofty Ranges and eastern Eyre Peninsula (Quigley et al., 2006). At the regional landscape scale, the recent topography on the peninsula preserves the relicts of east-facing fault scarps and west-tilting fault blocks, revealing that neotectonic movements reactivated north-south trending pre-Quaternary faults during the Pliocene to Early Pleistocene (Crawford, 1965; Zang, 2006). This phase of deformation within the peninsula is also manifested by a minor, gentle upfold within Eocene sandy limestones and Early Pleistocene Hindmarsh Clay, as seen in seacliffs at Port Julia on the central eastern coast (Bourman et al., 2016). This geologically short-term period of uplift and deformation appears to have ceased by the Middle Pleistocene and has not continued through to the present. The absence of shelly limestones older than Last Interglacial age (MIS 5e, 125 ka), at higher elevations within the landscape attests to the current regional stability of the peninsula. Shelly limestones of MIS 11 age relating to a higher sea level are also not evident on Yorke Peninsula.

The modern coastline of western Yorke Peninsula (east coast of Spencer Gulf) is protected from southwesterly winds and waves, resulting in low energy, tide-dominated environments along much of the coastline, which is characterised by low gradient sandflats with subtidal seagrass meadows and shelly sandy beaches backed by vegetated sand dunes (Bourman et al., 2016). Shallow neritic environments in the outer offshore area, within Spencer Gulf, are productive carbonate systems with extensive shallow-water seagrass meadows (James and Bone, 2011). Situated within a semi-arid Mediterranean climate zone, the regional climate is characterised by hot, dry summers, and cold, wet winters. The highest rainfall is confined to the months of June and July (63 and 66 mm respectively), resulting in negligible fluvial input from Yorke Peninsula to adjacent gulfs (Climatic Averages Australia, http://www.bom.gov.au/climate/map/climate_avgs/clim_avg1.shtml). No major rivers or streams drain into the gulfs along the entire peninsula. Beach sediments are derived from offshore sources, principally the shallow gulfs and the inner continental shelf of the Lincoln and Lacepede Shelves (Short, 2010; Bourman et al., 2016).

The last interglacial Glanville Formation, which unconformably overlies the Oligo-Miocene Point Turton Limestone on southern Yorke Peninsula, also crops out over considerable distances along the coastline of southern Australia (Greenway and Phillipps, 1902; Clark, 1928; Cann, 1978; Ludbrook, 1984; Belperio et al., 1995; Murray-Wallace et al., 2010; Murray-Wallace et al., 2016). The Glanville Formation comprises partially consolidated, and in places strongly indurated, medium- to very coarse-grained, mixed quartz-skeletal carbonate sand and is commonly capped by a strongly indurated calcrete. On southern Yorke Peninsula, the dominant fossils include the bivalve molluscs *Katelysia scalarina*, *K. peronii*, *Amesodesma angusta*, *A. cuneata*, *Anapella cycladea*, *Brachidontes rostratus*, the gastropods *Batillaria diemenensis*, *Nerita atramentosa*, and the foraminifers *Elphidium* sp. and *Marginopora vertebralis*. The presence of large individuals of the benthic foraminifer *Marginopora vertebralis* within the Glanville Formation implies a warmer climate in southern Australia during the Last Interglacial (Cann and Clarke, 1993).

Palaeoenvironments of the Glanville Formation include lagoonal facies that interfinger with barrier dune complexes on open ocean coastlines (e.g. the modern coastline of western Eyre Peninsula and River Murray Mouth region), or peritidal mud/sand flats within protected embayments such as the modern coastlines along Spencer Gulf and Gulf St. Vincent (Belperio et al., 1995). The shallow marine successions and fossil molluscs, equivalent to the last interglacial Glanville Formation, occur inland within a topographic depression that extends across a portion of southern Yorke Peninsula, indicating the site of a shallow water sea-way during the Last Interglacial Maximum (Figs. 1b & c) (Crawford, 1965; Bourman et al., 2016).

3. Methods

Measured sections of representative outcrops of the Glanville Formation were described from along the southern coastline of Hardwicke Bay, to the west of Point Turton on southern Yorke Peninsula. The Glanville Formation extends continuously for approximately 3 km from immediately west of Point Turton (Fig. 1b) (Greenway and Phillipps, 1902; Clark, 1928). Sections YP001 (S34° 55′ 47.2″, E137° 20′ 26.6″), YP002, and YP003 (S34° 55′ 52.8″, E137° 19′ 12.2″) are situated towards the eastern limit of outcrop of the Glanville Formation near Point Turton (Fig. 3a). The lithological and sedimentary characteristics of the coastal successions were recorded and summarised in measured stratigraphic sections (Fig. 2). In addition, the species of marine molluscs present and their inferred habitats were identified.

Palaeo relative sea level elevations for the beaches at Point Turton were determined based on sedimentary features related to specific palaeo-tidal levels, in particular palaeo-high tidal level, +0.8 m and palaeo-low tidal level. In doing this, we acknowledge that there may be an uncertainty of several tens of centimetres relating to palaeo-tidal