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Interglacial-glacial climatic signatures preserved in a regressive coastal barrier, southeastern Australia

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Abstract

Regressive barriers persisting in the landscape over interglacial-glacial cycles are important repositories of paleoclimatic signatures such as past sea level and regional aridity. The Gippsland region of Victoria contains a multi-barrier system formed during past interglacial-glacial cycles and the late-Holocene. An extensive series of parallel foredune ridges forming the elongate inner barrier was sampled for luminescence dating with ages indicating deposition ca. 125,000-108,000 years ago coinciding with the later phase of the Last Interglacial (LIG) Marine Isotope Stage (MIS) 5e and the transition to MIS 5d. Ground Penetrating Radar (GPR) imaged beach-face reflectors within the LIG barrier indicate that sea level was within -2 to +3 m of present level during MIS 5e in this far-field location. Significant reworking of the barrier system through blowout and parabolic dune activity occurred between 23,000-18,000 years ago corresponding to the Last Glacial Maximum (LGM) with an estimated 160,000,000 m³ of coastal sediments eroded and redistributed. The morphological changes to this coastal barrier over the most recent interglacial-glacial cycle (MIS 5e to present) also imply significant landscape instability during the LGM in southeastern Australia and are further evidence for extension of the geographical range and intensity of aridity at this time.

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Interglacial-glacial climatic signatures preserved in a regressive coastal barrier, southeastern Australia

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Abstract

Regressive barriers persisting in the landscape over interglacial-glacial cycles are important repositories of paleoclimatic signatures such as past sea level and regional aridity. The Gippsland region of Victoria contains a multi-barrier system formed during past interglacial-glacial cycles and the late-Holocene. An extensive series of parallel foredune ridges forming the elongate inner

barrier was sampled for luminescence dating with ages indicating deposition ca.125,000-108,000 years ago coinciding with the later phase of the Last Interglacial (LIG) Marine Isotope Stage (MIS) 5e and the transition to MIS 5d. Ground Penetrating Radar (GPR) imaged beach-face reflectors within the LIG barrier indicate that sea level was within -2 to +3 m of present level during MIS 5e in this far-field location. Significant reworking of the barrier system through blowout and parabolic dune activity occurred between 23,000-18,000 years ago corresponding to the Last Glacial Maximum (LGM) with an estimated 160,000,000 m³ of coastal sediments eroded and redistributed. The morphological changes to this coastal barrier over the most recent interglacial-glacial cycle (MIS 5e to present) also imply significant landscape instability during the LGM in southeastern Australia and are further evidence for extension of the geographical range and intensity of aridity at this time.

Keywords

Last Interglacial; MIS5e; parabolic dune; foredune ridges; Last Glacial Maximum; past sea level

1. Introduction

The elevation of coastal barriers and their constituent facies such as beach and backbarrier estuarine and lagoons are important indicators of past sea levels (e.g., Thom et al., 1981; Cooper and Flores, 1991; van Heteren et al., 2000; Hearty et al., 2007; Tamura et al., 2010; Orrù et al., 2011; Murray-Wallace et al., 2016). However, barrier systems which persist within marginal marine environments over multiple glacial/interglacial cycles are exposed to a wide range of climatic conditions which can modify or remove a portion of their original sedimentary record. Such reworking means that these systems may act as palimpsest landforms recording palaeoclimatic signatures beyond the timeframe in which the barrier system initially formed. For example, recent

studies have demonstrated aeolian reworking of coastal landforms in South Africa and southern Brazil during glacial periods (Bateman et al., 2004; Porat and Botha, 2008; Lopes et al., 2014).

The southern Australian continental margin preserves a rich and diverse suite of coastal landforms which have yielded excellent records of Quaternary landform evolution and information on past climate (e.g. Bowden, 1983; Bowler, 1976; Hill and Bowler, 1995; Nanson et al., 1992; Sprigg, 1979), sea-level highstands, and neotectonism (e.g. Murray-Wallace, 2002; Murray-Wallace and Belperio, 1991; Murray-Wallace et al., 1999; 2001; Sandiford, 2003). In particular, the temperate carbonate-dominated regions of western and southern Australia have received considerable attention with their long (temporal) record of interglacial barrier ridges and raised coastal successions (Playford, 1988) representing an important record of Quaternary sea-level change (Murray-Wallace et al., 2001) for global sea level reconstructions

The eastern Australian coast is dominated by siliceous sediments (Short, 2010) with barrier sequences of mostly Holocene age with examples of barrier systems dating back to Marine Isotope Stage (MIS) 5 and MIS 7 in central and northern New South Wales (NSW) (Roy et al., 1994; Thom et al. 1994). However, barriers of late Pleistocene age are rare in southern NSW and eastern Victoria, thereby representing a significant gap in understanding of the palaeo sea level, and specifically Last Interglacial (LIG) sea level, in the region between Wilsons Promontory and Sydney (Fig. 1) (see also Fig. 1 in Murray-Wallace and Belperio (1991)). Furthermore, while terrestrial dune activity has been documented at Wilsons Promontory in southernmost Victoria (see Fig. 1 for location) (Hill and Bower, 1995; Gardner et al. 2006) and around Tasmania (Bowden 1983; Duller and Augustinus, 2006; McIntosh et al., 2009; 2012) there has been a paucity of geochronological investigations of dune mobility at the southeastern edge of mainland Australia despite the presence of large parabolic dunes in this region (Lees 2006). In addition, this region is situated in a

climatic zone of Australia likely to be particularly sensitive to shifts in temperature and humidity of the westerly circulation associated with climatic changes during the late Quaternary (Hesse et al. 2004).

The absence of protective caprocks (such as calcretes in carbonate-dominated systems primarily composed of re-cemented marine-derived skeletal carbonate sand) means that the siliciclastic systems of southeastern Australia are susceptible to erosional modification during glacial phases as shown by Thom et al. (1994) in central NSW. Therefore, while some portion of the original barrier sedimentary record may be modified or destroyed during glacial phases, these secondary terrestrial landforms provide insight into palaeoclimatic conditions through the most recent interglacial-glacial cycle. In order to understand the palaeoclimatic significance of both the initial barrier deposition with respect to sea level, and the subsequent terrestrial dune reworking, recent studies have used combinations of remotely sensed high-resolution elevation datasets such as airborne Light Detection and Ranging (LiDAR), Ground Penetrating Radar (GPR) and luminescence dating (e.g. Mallinson et al., 2008). These technologies allow multiple phases of climatic change preserved in a coastal barrier to be distinguished providing an independent record of landscape-climate interactions. Understanding the nature of these landscape-climate interactions is important in determining the effect of future climatic changes on a regional scale.

In this study we examine the Late Pleistocene coastal barrier in the Gippsland region of Victoria (Fig. 1) using Optically Stimulated Luminescence (OSL) dating, sedimentological techniques, geophysics (GPR) and airborne LiDAR. The aim of the work is to determine the age of the pre-Holocene successions to constrain LIG sea level in this far field location. The study also aims to assess the degree of terrestrial dune reworking that a barrier is subjected to during a full glacial

cycle with implications for extracting palaeoenvironmental information from siliciclastic coastal sand barriers that persist over multiple eustatic cycles.

2. Regional setting

The Gippsland region of Victoria is located on the southeastern edge of mainland Australia, approximately 230 km east of Melbourne and forms a wide gently terraced plain south of the Great Dividing Range (Fig. 1). This plain is blanketed by Quaternary sediments of marine and fluvial origin (Fig. 1 and 2) which overlie thick Miocene-Pliocene sediments, principally limestones (e.g. Gippsland Limestone) and sandstones (e.g. Jemmys Point Formation, Jenkin 1968). The Jemmys Point Formation represents a Plio-Pleistocene raised coastal barrier which underlies the coastal dunes dominating the present topography (Holdgate et al., 2003). Ward (1971; 1977) identified a series of raised coastal dune-barriers (25-60 m above present-day MSL) interspersed with other beach, nearshore and tidal marsh facies (Fig. 2) which were assigned relative ages based on their elevation compared with other raised marine terraces around the world. While these older raised dune and beach facies imply a longer-term uplift signature, at present the area is considered to be tectonically stable with no uplift occurring in the last 200 kyr (Holdgate et al., 2003).

Bird (1961) first described the surficial coastal barrier successions of the Gippsland region identifying several phases of barrier deposition which are most clearly expressed in the region around Sperm Whale Head (Fig. 1). Bird (1965) later identified a 'prior barrier', 'inner barrier' and 'outer barrier' interpreted to have formed during successive interglacials (Fig. 3) after comparison with the northern NSW coast and the work of Thom (1964; 1965). The Holocene 'outer barrier' was drilled by Thom (1984) who demonstrated substantial variability in dune and beach evolution along the length of Ninety Mile Beach. Sedimentary evidence for the differentiation of the barrier

111 deposits is principally that the 'inner barrier' and 'prior barrier' contain strongly weathered soil
112 profiles comprising a bleached upper horizon overlying an iron oxide enriched dark orange semi-
113 indurated humate zone or groundwater podzol (Thom et al. 1994) sometimes called 'coffee rock'.
114 This weathering profile is a distinctive feature of Pleistocene sandy deposits in this region and is
115 absent from Holocene barrier successions (Bird 1965). The first geochronological framework for
116 the 'prior barrier', 'inner barrier' and dune systems was presented by Bryant and Price (1997),
117 where thermoluminescence (TL) ages were interpreted to indicate periods of marine barrier
118 deposition between 72-59 ka, 48-40 ka and during the Last Glacial Maximum (LGM). Bryant and
119 Price (1997) rejected the possibility that their reported TL dates younger than 40 ka from the inner
120 barrier were due to widespread surficial reworking of upper barrier sediments during glacial
121 periods (as Bird (1965) had hypothesised) citing three reasons; samples were collected from
122 depths of 1-1.5 m below the land surface, reworking to this depth would destroy ridge and swale
123 morphology, one sample was from a back-barrier flat below a clay horizon. As the inner barrier
124 is at a higher elevation than the known glacio-eustatic sea level at the time, Bryant and Price
125 (1997) inferred that either rapid uplift and or tsunami activity was responsible for the formation of
126 the inner barrier. Bryant and Price (1997) stated that LIG deposits were absent in the Gippsland
127 Lakes region.

128 The Gippsland region is microtidal with a spring tide range of < 1 m (PoM, 2013). Mean
129 significant wave height in the region is 2.4 m, with a period of 8.4 sec (Hughes and Heap, 2010).
130 Mean annual rainfall in Bairnsdale is 650 mm with the lowest monthly mean minimum
131 temperature of 3.9°C in July and the highest monthly mean maximum of 25.9°C in January (BoM,
132 2017). The wind and wave regime of the region is strongly influenced by the position of the
133 subtropical ridge to the north, as well as the size and intensity of the westerly storm belt to the
134 south linked to the Southern Annular Mode (O'Grady et al., 2015). Several rivers draining the Great

135 Dividing Range flow into the extensive Gippsland Lakes system which separates the barrier
136 successions (Fig. 1). This Lake system connects to the ocean via a permanent opening at Lakes
137 Entrance constructed in 1889. The adjacent Gippsland Shelf slopes gently (0.06°) to the southeast
138 and is dominated by mixed carbonate and siliceous sediments (Holdgate et al. 2003). Preserved
139 coastal barriers have been identified on the Gippsland Shelf and are topographically expressed as
140 a series of parallel foredune ridges typical of a prograded barrier in 65–75 m water depth
141 (Beaman et al. 2005; Brooke et al. 2017).

142 3. Methods

143 Airborne LiDAR data were collected in 2007 by the Department of Environment and
144 Primary Industries of the Victorian State Government. The surveying was conducted using a LADS
145 Mk II system coupled with a GEC-Marconi FIN3110 inertial motion sensing system and a dual
146 frequency kinematic global positioning system (kGPS). This dataset was processed to produce a
147 seamless terrestrial 'bare earth' digital elevation model (DEM) mosaic up to elevations of +15–20
148 m above MSL with a final raster grid of 2.5 m resolution (Quadros and Rigby, 2010) using ArcGIS
149 (v. 10.2). Visualisation of this DEM in ArcGIS (v. 10.2) was used to aid landscape interpretation and
150 direct OSL sampling site selection in the field.

151 Samples for OSL dating were collected using light-proof black plastic and aluminium tubes
152 which were hammered into freshly exposed sections or into the end of an auger sampling head
153 which extracted light safe grains from depths of up to 6 m below the ground surface. Samples
154 were also collected during coring at strategic intervals for sedimentological analysis. Mean grain
155 size, sorting and skewness of sediment samples were analysed using a Beckman Coulter LP13320
156 laser particle sizer with a measurement size range from 17 nm to 2000 μm .

Samples for OSL dating were processed at the OSL laboratory at the Geological Survey of Japan. Sediment within 20–25 mm of the ends each sample tube was removed and used for measurements of moisture content and dosimetry. Quartz grains were extracted from bulk samples following the method of Bateman and Catt (1996). Monolayers of quartz were mounted on 9.8 mm diameter disks to form large aliquots, which were then measured with a TL-DA-20 automated Risø TL/OSL reader equipped with blue LEDs for stimulation and a $^{90}\text{Sr}/^{90}\text{Y}$ beta source for laboratory irradiation. Emitted OSL through a Hoya U-340 filter was measured with a photomultiplier.

The single-aliquot regenerative-dose (SAR) protocol was used to determine the equivalent dose (D_e) using the OSL response to a test dose to monitor and correct for sensitivity changes (Murray and Wintle, 2000). OSL measurements were made at 125 °C with a stimulation time of 20 s. Preheat dose recovery test and preheat plateau test were carried out on sample gjs15084 by changing the preheat temperature from 140 to 300 °C in 20 °C increments. A preheat temperature of 240 °C was chosen. A 160 °C cutheat for the OSL response to the test dose was used for all samples. To determine D_e , four regeneration points were measured including 0 Gy and a replicate of the first regeneration point, which was used to check whether the sensitivity correction procedure was performing adequately. Data from aliquots were rejected if recycling ratios were beyond 1.0 ± 0.1 . Feldspar contamination was also checked for three aliquots per sample by using the IR test. All samples showed <5% depletion of post-IR blue OSL compared to blue OSL. The first 0.5 s interval of the signal was integrated, and the background subtraction over an interval of 15–20 seconds after the onset of stimulation was applied.

The contributions of both natural radioisotopes and cosmic radiation were considered for determination of the environmental dose rate. Concentrations of potassium, uranium, thorium,

and rubidium were quantified by inductively coupled plasma mass spectrometry and were converted to dose rate based on data from Adamiec and Aitken (1998) and Marsh et al. (2002). Past changes of moisture content are unknown, so an uncertainty value of 5% was applied to the measured moisture content values. Cosmic dose rate was estimated based on Prescott and Hutton (1994). An internal dose rate contribution of 0.03 ± 0.01 Gy/kyr was assumed based on measurements made on Australian quartz (Bowler et al. 2003). The final D_e value was determined by applying the Central Age Model (CAM) (Galbraith et al., 1999) to all aliquots measured for each sample and further divided by an environmental dose rate to obtain OSL ages. All ages are expressed relative to AD 2015.

GPR transects were collected along a track traversing the 'inner barrier' to the southwest of Loch Sport with a Mala Pro Ex system equipped with a 250 MHz antenna and a fixed antenna spacing of 0.36 m. Horizontal sampling interval was set to 0.02 m. Processing of GPR data was completed using RadExplorer 1.4.2 and standard processing routines were applied including desaturation, first arrival time correction, amplitude correction, bandpass filtering and Stolt F-K migration. Topographic correction of GPR data was completed using an RTK GPS (Trimble R4). A two-layer velocity structure was applied which accounted for changes in radar velocity associated with the groundwater table. Values of 0.14 m/ns above and 0.07 m/ns below the water table were adopted based on an auger borehole to groundwater positioned along the transect and other boreholes drilled for OSL sampling and ground-truthing of strong reflectors within the GPR transect. A targeted subsection of these transects was measured using bistatic 100 MHz antennas connected to a PulseEKKO PE Pro GPR system with a sampling interval of 0.1 m. This transect was processed with similar standard processing routines and served as a comparative dataset to the 250 MHz results while also penetrating deeper into the dune and beach sediments.

203 4. Results

204 4.1 'Inner barrier' morphology

205 The 'inner barrier' is an elongate feature stretching from southwest-northeast for more
206 than 40 km with an orientation parallel to that of the present-day coastline (Fig. 3). The relict ridge
207 topography is clearly distinguishable in the LiDAR imagery to the southwest of Loch Sport (Fig. 3)
208 where ~11 distinct ridges are evident with a crest spacing of 150-200 m. The ridge-swale
209 topography has a relief of 1-2 m. The average elevation of the barrier surface is between 6 - 8 m
210 AHD (Australian Height Datum, approximates MSL around the Australian coastline, Figs. 3 and 4)
211 and the overall barrier width is between 1 and 2 km.

212 More than 30 individual blowouts and parabolic dunes occur on the inner barrier
213 disrupting and reworking the linear ridge morphology with blowouts being particularly well
214 preserved at Sperm Whale Head (Fig. 4F). Three distinct categories of blowout and parabolic dune
215 can be distinguished by size, morphology and location on the barrier. The smallest comprise
216 'saucer' shaped blowouts scattered along the relict ridge crests (Fig. 4F). These range in size from
217 ~80 m to ~150 m. Several solitary 'trough' shaped blowouts up to 800 m in length and 300 m in
218 width also occur within the dune crest sequence (Fig. 4F). These are distinguished from the saucer
219 blowouts by elongate deflation hollows and distinct depositional lobes that have reworked
220 multiple relict dune ridges. The largest comprise shore-attached parabolic dunes up to 2.5 km in
221 length and 800 m wide with distinct deflation hollow, trailing arm and depositional lobe
222 morphologies (Fig. 4F). Dune lengths and widths are expressed relative to the palaeowind axis
223 which ranges from northwest to west-north-west.

224 The northwestern (landward) margin of the inner barrier, which forms the estuarine
225 shoreline of Lake Victoria, has eroded 1-1.5 km since, particularly in the central portion near the
226 coastal town of Loch Sport (Fig. 3). This value is calculated based on the hypothesised prior
227 landward extent of the inner barrier based on the alignment of the preserved ridges and their
228 present-day truncation. The northeastern section of the barrier topography near Sperm Whale
229 Head is extensively modified by dune activity (~14 blowouts or parabolic dunes) (Fig. 4F), while the
230 southwestern portion is less so (~6 blowouts or parabolic dunes) (Fig. 3).

231 4.2 Ground penetrating radar and barrier lithofacies

232 Coring through the barrier at several locations revealed a series of lithofacies
233 corresponding to the GPR-imaged structures and broadly representing a beach and dune
234 succession with further dune sands from later reworking occurring in places. The strong, laterally
235 continuous reflection within 1 m of the barrier surface represented the upper boundary of a
236 horizon of dark brown to dark orange sands which were semi-indurated (termed 'groundwater
237 podzol' hereafter). The sands overlying this groundwater podzol were medium grained and
238 uniformly light grey. Below the groundwater podzol was a medium-coarse sand, yellow in colour
239 grading to light grey near the water table. Auger cores through the parabolic dunes, trough
240 blowouts and saucer blowouts also encountered groundwater podzols and below well- bleached
241 medium-grained sands.

242 The GPR surveys traversing the 'inner barrier' (two sub-sections of which are shown in Fig.
243 5) penetrated through the barrier sediments imaging the water table at a depth concordant with
244 MSL and showing a strong laterally continuous reflector generally within 1 m of the barrier surface.
245 Other than this, distinct reflections were rare within the upper 5 m of the barrier succession, likely
246 a result of the long-term podsolization processes masking original bedding. However, when

traversing through the blowout deflation hollow (Fig. 5 B, C) high-amplitude seaward dipping reflectors perpendicular to the palaeoshoreline alignment with a dip angle of approximately 5 degrees were observed. A borehole produced using a hand auger borehole at 625 m on the transect in Fig. 5B indicated that the high-amplitude dipping reflectors were formed in medium to coarse sands, with a change from medium sand to coarse sand, which was dark grey – black in colour due to organic matter staining, coinciding with the present-day water table.

A deeper GPR survey using a 100 MHz antenna (Fig. 6) across the eastern arm of the blowout near Loch Sport penetrated to a depth of -4 m AHD. Only the thicker uppermost groundwater podzol was visible as a reflection in this scan, but the seaward dipping coarse sand beds imaged in the GPR profile in Fig. 5B, were found to continue in a southeasterly direction (Fig. 6).

4.3 OSL dating

Optical dating of sediments collected from barrier and dune deposits (Table 1) indicates a depositional history concordant with the landform interpretation from the DEM derived from airborne LiDAR (Fig. 3). An auger hole on the terminal crest of a large parabolic dune (Fig. 4D) northeast of Loch Sport contained a 1 m thick bleached upper dune facies overlying a semi-indurated humate-enriched groundwater podzol. Below the groundwater podzol the sand was medium grained, moderately-poorly sorted and deep yellow in colour. Two samples (gsj15089 and gsj15090, Tab.1) were extracted from below this groundwater podzol and returned ages of 20 ± 0.9 ka and 18 ± 0.9 ka coeval with the LGM (Fig. 3).

Sample gsj15088 was collected from an exposure of Pleistocene sands formed by eroding estuarine shoreline of Lake Victoria (Fig. 4 A,B,C) and was dated to 117 ± 6.7 ka indicating

269 deposition during the late MIS 5e and transition to MIS 5d (Lisiecki and Raymo, 2005). At this site
270 the side wall of a large parabolic dune reaching some 17 m in elevation was cross-cut by the
271 present-day lake shoreline and the sample was collected from below a well-developed and
272 hardened groundwater podzol. This sample dated to 117 ± 6.7 ka is at a far lower elevation than
273 the samples gsj15089 and gsj15090 dated to 20 ± 0.9 ka and 18 ± 0.9 ka respectively and within
274 the barrier facies, rather than the reworked dunes.

275 Two samples were collected from an auger hole at depths of 1.9 and 5.6 m respectively
276 from the eastern arm of a trough blowout dune 800 m long and 370 m wide within the linear
277 dune ridges southwest of Loch Sport (Fig. 5B). This auger hole contained a strong weathering
278 profile with a bleached upper dune facies followed by a groundwater podzol at just over 1 m
279 depth under which a yellow, poorly sorted, strongly fine-skewed medium sand occurred (Fig. 7A).
280 A second thin (0.10 m thick) groundwater podzol was found at 4.90 m depth (Fig. 7A). The sample
281 gsj15085 from 5.6 m beneath the lower groundwater podzol and returned an age of 119 ± 6.1 ka,
282 while the shallower sample, between the two groundwater podzols returned an age of 23 ± 1.1 ka.

283 Samples gsj17052, gsj17053 and gsj17054 from depths of 2 m, 3.2 m and 6.05 m
284 respectively were collected from an auger hole located on a prominent ridge of the 'inner barrier'
285 (Fig. 7B). The auger hole at this site revealed a bleached white surface layer overlying yellow
286 poorly sorted medium sand (Fig. 7B). Two groundwater podzols were apparent, the first at 1.0 –
287 1.5 m depth separating the white from yellow sands (Fig. 7B). A second thinner unit (0.1m thick)
288 occurred at around 2.40 m depth (Fig. 7B). An OSL age between the two groundwater podzols
289 was of 145 ± 6.4 ka. OSL ages below the groundwater podzols returned ages of 113 ± 5.4 ka and
290 142 ± 7.7 ka at 3.20 and 6.05 m depth respectively. The shallowest groundwater podzol was
291 concordant with the GPR reflector imaged at around 1.2 m below the ground surface (Fig. 5A).

A sample gs17051 from a series of recurved ridges landward of the 'inner barrier' taken from 1.3 m depth was dated at 77 ± 3.5 ka (Fig. 5C). In order to directly compare the OSL dating with earlier TL results in Bryant and Price (1997) a sample from the Wattle Road sand quarry was also collected and returned an age of 56 ± 2.9 ka (Tab.1, Fig. 4E). This disused quarry site contained a strongly weathered profile evident in the sampled exposure and the OSL sample was collected ~4 m below the dune surface.

5. Discussion

5.1 Geochronology

The 'inner barrier', composed of linear ridges, is shown to have formed during the LIG MIS 5e transitioning to MIS 5d (Figs. 3 and 8) with three independent OSL ages spanning ca. 125-108 ka (considering the uncertainty margins). The anomalously old ages of ca.140 ka for the upper and lower samples in Fig. 5A appears to result from very low dose rates compared with the sample dated to ca.113 ka (Fig. 7B) (Tab.1). The equivalent dose (D_e) values for the two samples with ages of ca.140 ka are actually lower than the equivalent dose (D_e) values for other samples in this study with ages concordant with MIS 5e-5d. Further examination of the dose rates for these anomalously old samples is warranted as intense podsolization and leaching within a sediment profile has the potential to cause underestimation of the dose rate if there is redistribution of radionuclides in the sediment profile over time (Murray et al. 2007). In addition, the use of the CAM for all D_e determinations, chosen based on luminescence properties and prior experience of OSL dating in southeastern Australia, could be changed to the minimum age model (MAM) (Galbraith et al. 1999). If this is justified based on re-examination of individual sample characteristics, younger ages may result.

314 Bryant and Price (1997) TL-dated several samples from locations on the inner barrier at
315 depths of 1-1.5 m which returned ages of ca. 29-95 ka. Bryant and Price rejected the possibility of
316 reworking of MIS 5e barrier sediments as an explanation for the younger than expected ages
317 stating that "reworking would need to be responsible for the complete ridge form, because all
318 samples were taken at a depth of 1.0 to 1.5 m, which approximates the relief of the ridges" Bryant
319 and Price (1997) p.328. However, in this study, all samples dated to MIS 5e were collected at
320 depths of greater than 2 m. This suggests that substantial deflation and reworking of the barrier
321 surface has occurred since deposition in many areas, and it is noted that the TL ages located on
322 Sperm Whale Head (northeast of Loch Sport) presented by Bryant and Prince (1997) are from an
323 area with substantial saucer blowout development (see Fig. 3, Fig. 4F). These saucer blowouts
324 appear to have deepened the ridge swales and heightened the ridge crests, yet the original ridge-
325 swale topography is still distinguishable as each blowout has not become elongated beyond the
326 ridge crest position in planform. Bioturbation may also play a role in reworking the sediment
327 profile above the groundwater podzol as can be seen in the present-day where burrowing ants
328 have brought of orange-stained sand grains to the surface and piled them in small mounds.
329 These orange-stained sand grains contrast markedly with the bleached white sand of the upper-
330 most barrier lithofacies.

331 Another example of the substantial reworking of the barrier after deposition is from the
332 sandy zone found between the distinct foredune ridges and Lake Victoria (Fig. 3 and Fig. 5C)
333 showing recurved ridge-like forms. These ridges are on average 2-3 m lower in elevation than the
334 inner barrier and merge with the inner barrier foredunes to the southwest. A single OSL age of 77
335 $\pm$ 3.5 ka (Fig. 5C, Table 1) from 1.3 m deep within the medium sand of the bleached upper facies is
336 likely indicative of dune reworking during MIS 5a following the onset of a minor fall in relative sea

level. This further emphasises the significance of the reworking and/or bioturbation the barrier has undergone since deposition.

The reworking of the barrier system by aeolian activity demonstrated in this study, has previously been inferred to have occurred during the LGM in the wider Gippsland region based upon the orientation of blowouts and parabolic dunes (Thom et al., 1994; Hill and Bowler, 1995). The present study relates this blowout and parabolic dune activity to the peak of the LGM between 23 ka and 18 ka (Figs. 3 and 6). However, the dunes may have been active prior to this time as noted by Duller and Augustinus (2006) who examined the dune field of northeastern Tasmania. Dune sediment at Wattle road above the marginal bluff (Fig. 3) (OSL age 56 ± 2.9 ka (Table 1)) suggests dune activity prior to the peak of the LGM and a TL age for this site reported in Bryant and Price (1997) of 47.6 ± 5.7 ka overlaps with the OSL age of ca. 56 ka determined in this study at the 1 sigma uncertainty level. Further investigation of the mobility of the older sequences of marine sediments by dune reworking further inland behind the inner barrier is warranted given the range of TL ages of 70-40 ka derived from near-surface sands by Bryant and Price (1997). However, based on the reassessment of luminescence ages from a northeast Tasmanian dune-field by Duller and Augustinus (1997; 2006) it is also possible that the ages reported by Bryant and Price (1997) for this region are incorrect.

5.2 Palaeo sea level during MIS 5 in the Gippsland region

The elevation of beach facies or the contact between beach and aeolian facies within a coastal barrier was used as an indicator of past sea level in southeastern South Australia by Schwebel (1984) and is a well-established sea-level marker in coastal barriers around the world (van Heteren and van de Plassche 1997; van Heteren et al. 2000; Rodriguez and Meyer 2006; Tamura 2012; Dougherty 2014; Mallinson et al. 2014; Coastas et al. 2016). The grain size of the

cored sedimentary units, inner barrier topography and GPR-imaged subsurface structures would suggest the inner barrier sequence represents a regressive foredune ridge plain in a high energy open-coast setting. The elevation of GPR reflections interpreted as relict beach-faces provides an indication of palaeo sea level during the time of barrier formation which is more reliable than the elevation of the barrier surface which has been modified by subsequent dune activity.

In the GPR profile shown in Figure 5B the elevation of the beach-face facies is between -3 to 0 m in relation to present day MSL. This would indicate that MSL would have been around -2 to +3 m in relation to present level taking into consideration likely high-energy beach state and tidal range (Short and Wright, 1984). This is at the lower end of the 2-6 m highstand range shown from stratigraphical marine successions elsewhere in southeastern Australia during MIS 5e (Murray-Wallace, 2002; Murray-Wallace et al., 2016). The three OSL ages between 125-108 ka for the inner barrier suggest the possibility that this regressive barrier system formed after the peak of MIS 5e (at ca. 125 ka) in the transition to MIS 5d as sea level fell from a highstand between +2 m and +6 m above present MSL. However, OSL dating uncertainties of between 5-7 ka preclude a robust evaluation of this hypothesis.

5.3 Palaeoclimate during MIS 2 (LGM) in the Gippsland region

During the period 23-18 ka sea level was approximately 125 m below present level (Hill et al., 2009; Murray-Wallace and Woodroffe, 2014) with the open ocean shoreline >70 km seaward and the preserved inner barrier separated from the shoreline by the low-relief exposed sea-floor of Bass Strait (Fig. 8). It has been proposed that river systems adjusted to this lower sea level displayed distinct seasonality with summer discharges amplified by snowmelt (Hesse et al., 2004). The moderate sized rivers which currently flow into Lake Wellington and Lake King drain catchments which include parts of the Great Dividing Range with elevations above 1000 m (Fig. 1).

383 These catchments would likely have been subject to the effect of summer snowmelt amplifying
384 discharges and potentially providing a source of dune sediments mobilised during dry seasons to
385 nourish dunes in the Gippsland region and on the Bass Strait shelf more broadly. Saucer and
386 trough dune blowouts are likely to be primarily derived from reworking of *in situ* barrier sediment
387 (Fig. 5C) as they have formed within the margin of the barrier.

388 Conversely, enhanced fluvial activity may have directly contributed to erosion and
389 sediment redistribution of the inner margin of the barrier during MIS 4 to MIS 2 (Fig. 8) as the
390 overall size of the barrier has diminished by around 10 km² based on the reconstruction from
391 LiDAR in Figure 8 c.f. barrier size in MIS 5e to MIS 2. This reconstruction takes into consideration
392 the likely extent of the back-barrier facies, and the location of ridge truncations which have been
393 joined by dotted lines shown in the top left pane of Fig. 8. Based on this reconstruction, erosion of
394 the landward edge of the inner barrier and the deflation and reworking of the barrier since its
395 original deposition (reconstructed) during the LGM constitutes substantial volumes of sediment in
396 the order of ~160,000,000 (or 1.6×10^8) m³. This estimate is indicative only, as there are several
397 assumptions involved, including the previous barrier alongshore extent and continuity of the
398 ridges, the thickness of the barrier sediments and whether the barrier extended further seaward in
399 the past.

400 The variability of the surface reworking suggests that the blowouts and parabolic dunes
401 may have been initiated by several perturbations that affected the barrier surface at different
402 spatial and temporal scales. For example, areas of the barrier which are modified by only small
403 individual saucer blowouts (in the region near Sperm Whale Head (Fig. 3) for example) would
404 suggest short-lived localised disturbances, whereas the large parabolic dunes evident to the
405 northeast of Loch Sport (Fig. 3) imply greater instability that may be linked to active erosion of the

406 inner margin of the barrier (Hesp and Walker, 2013). Other smaller blowouts and parabolic dunes
407 in this area to the northeast of Loch Sport suggest the wind-vegetation balance tipped slightly
408 towards stability during the active lifespan of these landforms preventing widespread dune
409 destabilisation and broader scale destruction of the original morphology (Hesp and Walker, 2013).
410 OSL dating of typesets of these landform features may help to interpret the complex reworking
411 pattern evident in planform although it is possible temporal variability in dune activity may be
412 masked by dating uncertainties if the dune activity is mainly confined to the peak of the LGM.

413 The preserved LGM dunes in the Gippsland region resemble those found elsewhere in
414 southeastern Australia. Linear and parabolic dunes have been identified and dated using TL in the
415 Port-Stephens Myall Lakes region of NSW, Australia (Thom et al., 1994). Samples from these dunes
416 have ages between 36.0 ± 3.6 ka to 14.2 ± 1.6 ka and these dunes have reworked significant
417 portions of the surface of the 'inner barrier'. This 'inner barrier' was assigned a maximum age of
418 142 ± 12 ka to 118 ± 9 ka by $^{230}\text{Th}/^{234}\text{U}$ dating of corals found near the landward margin of the
419 sandy barrier facies (Marshall and Thom, 1976). The reactivation of the barrier surface and dune
420 building activity led to the hypothesis that during much of the LGM there was significant
421 landscape instability throughout eastern Australia (Thom et al., 1994; Hill and Bowler, 1995). West
422 of the Gippsland region at Cape Liptrap near Wilsons Promontory (Fig. 1), LGM aeolian dune
423 activity was associated with landscape instability (Gardner et al. 2006). The palaeowind direction
424 indicated by the large parabolic dunes in the Gippsland region is consistent with the proposed
425 wind trends in the LGM by Thom et al. (1994) and Gardner et al. (2006). Further west in South
426 Australia, Hindmarsh Island near the entrance of the Murray River in the Coorong region (Fig. 1),
427 terrestrial dunes have been dated to the LGM (Murray-Wallace et al. 2010) and forms part of a
428 geographically extensive sequence of longitudinal dunes in this region.

LGM dune activity in northeastern Tasmania has been identified by Duller and Augustinus (1997; 2006) and in southeastern Tasmania (Oliver et al., 2017) and these dune fields form part of a broader low-mid altitude LGM dune system preserved throughout Tasmania (McIntosh et al., 2009; 2012) which indicate phases of aeolian activity in Tasmania between 60-45 ka and 35-15 ka. OSL ages for the aeolian dunes in this study (56 ± 2.9 ka and 23-18 ka) broadly align with the phases of dune activity identified by McIntosh et al. (2009; 2012). Sigleo and Colhoun (1982) considered the LGM in southeastern Tasmania to be relatively cold and dry based on geomorphic and stratigraphic evidence from source bordering dunes. Bass Strait was considered to be an important source of sediment nourishing the dunes in northwestern Tasmania (Duller and Augustinus, 2006) and given the extent of LGM dune activity in Tasmania and the observations of this study, there was likely significant dune development in Bass Strait during this period of lower (-125 m below present (Hill et al. 2009)) sea level (Fig. 8). Further evidence for Bass Strait dune activity in the LGM are the large dunes along the western coastline of King Island (Fig. 1) described by Jennings (1959) although these have not yet been quantitatively dated.

The observations of aeolian dune activity during the LGM presented in this paper contribute to a larger discussion on the climatic conditions and landscape dynamics between MIS 4 to MIS 2 in southeastern Australia with evidence for more arid conditions and sparser vegetation (Bowler, 1976; Colhoun 1988). Further evidence of more arid conditions in this region during these glacial periods comes from marine cores from the Tasman Sea showing higher dust production from the Australian continent during these periods (Hesse, 1994; Hesse et al., 2004; Hesse and McTainsh, 1999; 2003; Farebrother et al., 2017). The OSL ages and aeolian landforms in Gippsland support the notion of intensification of aridity and geographical extension in its range in this southeastern region of Australia during the LGM.

452 6. Conclusions

453 The Pleistocene barrier systems in the Gippsland region offer a unique insight into the LIG
454 sea level and landscape response to glacial climate of this marginal marine setting in southeastern
455 mainland Australia. The regressive 'inner barrier' is dated to the LIG MIS 5e and GPR-imaged
456 beach-faces preserved within the barrier stratigraphy place sea level between -2 to +3 m of
457 present level during this time. Since deposition, the barrier surface has undergone substantial
458 modification by terrestrial dune activity dated to the LGM. The nature of the terrestrial dune
459 reworking was quantified using airborne LiDAR with saucer and trough blowouts distinguished
460 from the foredune ridges which formed the original barrier topography. Large parabolic dunes
461 reworking the barrier surface, especially around the region of Sperm Whale Head, are indicative of
462 sustained landscape instability during the LGM likely due to enhanced regional aridity.

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666 Figures:

668 Figure 1: Regional map of the Gippsland region of Victoria in relation to southeastern Australia.
669 Dotted rectangle denotes LiDAR data displayed in Figure 3. Ward (1997) transect A-A' (see Fig. 2)
670 is displayed with prominent dune barriers demarcated 'a' to 'e'.

672 Figure 2: Ward (1997) transect A-A' in cross-section with prominent dune barriers demarcated 'a'
673 to 'e' corresponding to Figure 1.

Figure 3: Elevation map of the landscape features in Gippsland derived from LiDAR with OSL ages in their respective sampling locations. Topographic profile B-B' to the northeast of the town of Loch Sport is shown with the colour scheme beneath the profile corresponding to the colour scheme used to classify the DEM. Note the difference in elevation between the 'inner barrier', the parabolic dunes and Holocene barrier.

683 Figure 4 (above): Photos of several field sites sampled for OSL dating with LiDAR DEM map of the
684 region around Sperm Whale head displaying photo locations and key morphological features.
685 Photo A shows an exposed section of Pleistocene sands with a deeply weathered groundwater
686 podzol. The material overlying this groundwater podzol forms the side wall of a large parabolic
687 dune. Sample gsj15088 (Tab.1) dated to 117 ± 6.7 was extracted from the base of the groundwater
688 podzol shown in photo C. Photo B is taken from the top of this parabolic dunes' side wall standing
689 directly above the sampling site in photo A and C. Photo D shows the location of an auger hole at
690 the terminal end of the same parabolic dune in photos A, B and C, where two samples were
691 extracted gsj15089 and gsj15090 (Tab.1) and dated to 20 ± 0.9 ka and 18 ± 0.9 ka respectively.
692 Photo E shows a weathered dune exposure in a disused quarry near Wattle Road dated to $56 \pm$
693 2.9 ka; the same site sampled by Bryant and Price (1997) and TL dated to 47.6 ± 5.7 ka. LiDAR
694 DEM in F shows the Pleistocene inner barrier with photo locations demarcated and identifies the
695 various dune morphologies which dominate the present-day barrier topography.

Figure 5 (above): A, B Interpreted subsections of two longer GPR transects traversing the 'inner barrier' with OSL samples demarcated at respective depths (the two full un-interpreted GPR transects are available as supplementary data) and C DEM showing the location (grey lines) of GPR subsections A and B on the full transect spanning the 'inner barrier' with auger hole locations. See Figure 3 for location of C in relation of broader DEM. An OSL sample near Beacon Swamp is located on the recurved ridges landward of the 'inner barrier' in C. The y-axis on both GPR transects set to m AHD (AHD approximates MSL around the Australian coastline).

Figure 6: Interpreted 100 MHz GPR section traversing the blowout crest of the 'inner barrier'. Location of this transect can be seen in Fig. 5B. For this section a two-scale y-axis is used to indicate depth in m AHD.

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709 Figure 7: A) Sedimentology and chronology for the auger hole demarcated on the GPR transect
 710 in Fig. 5A which penetrates a prominent ridge on the 'inner barrier', B) sedimentology and
 711 chronology for the auger hole demarcated on the GPR transect in Fig. 5B from the eastern arm of
 712 a blowout dune on the 'inner barrier'.

Figure 8: Schematic planform model of landscape evolution in the Gippsland region with barrier morphology at LIG MIS 5e ca.125,000 years ago, LGM MIS 2 ca.20,000 years ago and present day. Position of relict foredune ridges in MIS 5e which have been subsequently reworked by dune development are shown as dotted lines. During the LGM (MIS 2) there is substantial reworking of the barrier by dune activity and a hypothesised river channel has been indicated draining to the sea level at 125 m below present. Bass Strait is also likely blanketed by dune systems during this time. The present-day landform morphology shows the Holocene dune barrier forming the current open ocean shoreline and impounding Lake Reeve which separates the Holocene barrier from the LIG MIS 5e 'inner barrier'. A graph of past changes in sea level with time, modified after Hill et al. 2009), demonstrates how the OSL ages presented for the inner barrier and parabolic dunes in this study correspond with the LIG MIS 5e and LGM MIS 2.

726

727 Supplementary Figure 1: Full un-interpreted GPR transects across the 'inner barrier'. Red boxes
 728 indicate the sections shown in Fig. 5A and Fig. 5B.