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The palaeogeography of the Bass Strait land-bridge, a vital zone of human and biological connectivity across southeastern Australia

David M. Kennedy [a,c,*], Ali Jalali [b], Bruno David [c,d], Matthew C. McDowell [c,d], Rachel A. Nanson [e], Ashleigh J. Rogers [c,d], Russell Mullett [c,f], Joanna Fresløv [f], Jessie Birkett-Rees [d], Juliet Sefton [a], Daniel Ierodiaconou [b]

[a] School of Geography, Earth and Atmospheric Sciences, The University of Melbourne, Parkville, Vic, 3010, Australia
[b] School of Life and Environmental Sciences, Deakin University, Warrnambool Campus, Warrnambool, VIC, 3280, Australia
[c] ARC Centre of Excellence for Australian Biodiversity and Heritage, Monash University, Victoria, 3800, Australia
[d] Monash Indigenous Studies Centre, 20 Chancellors Walk, Monash University, Clayton Campus, Victoria, 3800, Australia
[e] Marine and Coastal Geoscience Section, Geoscience Australia, GPO Box 378, Canberra, ACT, 2601, Australia
[f] Gunaikurnai Land and Waters Aboriginal Corporation, Kalimna West, Victoria, 3909, Australia

ABSTRACT

Land-bridges are key regions of human connectivity, yet how geography affected peoples' movement during flooding is poorly understood. Bass Strait is one of the most important land-bridges in Australasia, separating Lutruwita/Tasmania from the mainland of Australia. The land-bridge forms a key part of Country among the region's First Peoples, with people able to move across the clan estates and residential places of the exposed Bass Strait by foot until its flooding after the Last Ice Age. In this study, we utilise high-resolution bathymetry to understand landscape change during sea-level rise. We find that rates of shoreline transgression can exceed 30 m/yr, signalling that 15 km of land would have been drowned in a persons lifetime. This rapid rate of change is within a person's life-span and would have profoundly affected individuals as they resided in and travelled across Country. We also find that people first crossed the land-bridge very soon after its exposure during climate cooling events. The analysis provides a benchmark for understanding land-bridge flooding and in turn its impact on human migrations.

1. Introduction

Sea levels during the Quaternary period have oscillated between 130 m below to more than 5 m above present elevations (Rohling et al., 2009). In fact, eustatic sea level at present or higher elevation is unusual, occurring for less than 15 % of the last glacial cycle (spanning the past 128,000 years) (Lambeck and Chappell, 2001). This means that much of the currently submerged continental shelves of the world were exposed as dry land during their periods of human habitation. This is especially the case during the cold glacial maxima when sea levels were around 120–130 m lower than today's, and shorelines were positioned on the edges of continental and island shelves (Murray-Wallace and Woodroffe, 2014). During these periods of lower sea level, many of today's major island archipelagos were also connected as dry land, allowing people, vegetation and animals to freely move between locations across dry land now separated by the sea. For example, during the Last Glacial Maximum (26,000–18,000 cal BP), it would have been possible for people to walk overland from the Afro-Eurasian supercontinent across Beringia—from Siberia to Alaska—onto North and then South America; in Southeast Asia from Taiwan to Java; in western Europe across the English Channel; and across Sahul from Papua New Guinea to the southern tip of Lutruwita/Tasmania through mainland Australia (Voris, 2000). Such low-lying areas, previously terrestrial landscapes now submerged, are commonly referred to as 'land-bridges', and they have played a significant role in human migration and adaptation as well as in the biogeography of many parts of the world (Allen et al., 1977; Clark et al., 2014; Crabtree et al., 2021; Gautney, 2018; Hoffecker et al., 1993).

In Australia, major now-submerged land-bridges lie in the northeast beneath Torres Strait, between New Guinea and Australia, and beneath Bass Strait in the southeast, between the states of Tasmania and Victoria. Today Bass Strait is c. 350 km wide (west to east) and 230 km long (north to south), with an average depth of about 60 m, but during periods of lower sea level it connected mainland Australia and what is now the island of Lutruwita/Tasmania. The iconic and now extinct Tasmanian Tiger (*Thylacinus cynocephalus*) is the classic example of biogeographical connectivity across the land-bridge. The species was once abundant across all of Australia but became extinct on the mainland

* Corresponding author. School of Geography, Earth and Atmospheric Sciences, The University of Melbourne, Parkville, Vic, 3010, Australia.
E-mail address: davidmk@unimelb.edu.au (D.M. Kennedy).

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following the introduction of the Dingo c. 3,500 years ago (Balme and O'Connor, 2024). The flooded Bass Strait provided a barrier to the Dingo and the Tasmanian Tiger remained in Lutruwita/Tasmania until it was hunted to extinction during colonial times in the early 20th century (Letnic et al., 2012). The importance of the Late Pleistocene land-bridge in previous expansions of now-relict species across Bass Strait and beyond is also observed in the distribution and genetic diversity of a variety of species including gastropods (*Nerita* spp.) (Waters, 2008), freshwater crayfish (Schultz et al., 2008) trees (*Eucalyptus regnans*) (Kirkpatrick, 2023), seagrass (*Posidonia australis*) (Sinclair et al., 2016), mammals (*Dasyurus viverrinus*, *Sarcophailus harrisii*, *Thylacinus cynocephalus*, *Bettongia gaimardi*, *Thylogale billardierii*, *Pseudomys higginsi*) (McDowell et al., 2022, 2023), and birds (*Dromaius novaehollandiae diemenensis*, *Gallinula mortierii*) (Derham et al., 2023).

The land-bridge of Bass Strait is also critical Sea Country for the Gunai/Kurnai of southeastern Victoria (Birkett-Rees et al., 2023) and Tasmanian Aboriginal peoples (palawa), as well as the inferred Bassian Nation(s) that occupied Bass Strait during low-stand climate periods (Bowdler, 2015; Hamacher et al., 2023). People certainly inhabited the exposed landscape, with the oldest known archaeological evidence from Bass Strait currently dating to 27,740–26,599 cal BP (Bowdler, 2015; Brown, 1993). A shift in lacustrine charcoal concentrations and palynology has shown a change in fire regimes occurred in Lutruwita/Tasmania due to human habitation c. 41,600 years ago (Adeleye et al., 2024). This indicates that people traversed the Bassian Plain from the Australian mainland earlier than the currently available archaeological evidence from the island itself.

While the existence of the land-bridge, and its inferred vegetation cover during cooler climatic periods than present when sea levels were lower, is now well known (Adeleye et al., 2021), our knowledge of the landscape's precise morphology especially in the shallow sea regions is poor beyond that of the continental scale (Hamacher et al., 2023; James and Bone, 2011). This has complicated interpretations of past histories of the landscape, as the land-bridge is often viewed as a binary 'exposed' or 'drowned' feature rather than as a complex geomorphic environment with a range of landforms that behave differently when inundated by the sea. Yet the latter is crucial for understanding not only the configuration of landforms and their biogeography through time, including relict species and plant and animal communities, but also, and perhaps most critically, for the people who experienced the inundation of Sea Country. In this study, we use the latest high resolution bathymetry combined with the glacio isostatic adjustment (GIA) sea-level modelling for the region to unravel the complex nature of the land-bridge and quantify its exposure over the past 100,000 years. This analysis provides a benchmark for understanding flooding of land-bridges worldwide and in turn its impact on human mobility.

2. Regional setting

Bass Strait is situated within a carbonate-dominated cool-temperate marine realm, forming the southeastern continental margin of Australia (James and Bone, 2011). The geological history of the region is complex, initially relating to the continental break-up of Gondwana during the Cretaceous, with various extensive and compressive stress regimes occurring into the Tertiary period (Niyazi et al., 2021; Young et al., 1991). Deposition during this time has led to kilometre-thick sequences of sandstone to siltstone, with marls, limestone and coal also occurring (Weeks and Hopkins, 1967).

Uplift along the southern coast of Victoria and northern Lutruwita/Tasmania dates to since the Late Miocene and Pliocene with coastal strandlines found up to 100 km inland in Victoria and at elevations of up to 250 m above mean sea level (Wallace et al., 2005). The position of the Last Interglacial shoreline (Marine Isotope Stage 5e), however, provides more relevant information on more recent tectonic activity as it is closer to the maximum age of human settlement of Lutruwita/Tasmania, at just over 41,000 years ago (Adeleye et al., 2024). Last Interglacial shorelines have been qualitatively investigated across coastal Victoria, at the northern boundary of the study area and within Bass Strait, on 90-Mile Beach (Oliver et al., 2018), Flinders and King Islands (Murray-Wallace and Goede, 1995), Port Campbell (Reeckman and Gill, 1981) and Warrnambool (Carey et al., 2019). At all these locations, the Last Interglacial shoreline occurred within the globally accepted elevations of eustatic sea level implies no vertical land movement. At Cape Liptrap, quartz sand overlying a marine platform was dated to 122±9 ka at around 2 m above sea level, also representing a Last Interglacial shoreline (Gardner et al., 2006). At this same location, dating of offset terraces along a local fault system (Waratah Fault) suggests some more recent vertical movement, with the last event dated between 70,000–80,000 years ago (Gardner et al., 2009). At the southern end of Bass Strait, the neotectonic story is more complicated. Murray-Wallace and Goede (1995) described raised terraces of Last Interglacial (LIG) age in northern Lutruwita/Tasmania being the highest in Australia at an elevation of 11–23 m above MSL. They also inferred sloping LIG deposits on Robbins Island at +16 m, but the recent work of Goodwin et al. (2023) at this site conclusively showed LIG shorelines at lower elevations (+7 to +2 m above MSL) that align with global eustatic estimates. It is therefore very likely that Bass Strait and its northern edge have been largely neotectonically stable for the past 60,000 years, but there remains uncertainty regarding its southern edge.

The contemporary morphology of Bass Strait is characterised by a central basin (centred over the geological Bass Basin) with two elongate plateaux on the eastern and western sides (Heap and Harris, 2008): the Peninsula Basement Rise (PBR) and Bassian Rise (BR) respectively (Fig. 1a) (Blom and Alsop, 1988). Surface sediments over the central part of the shelf are fine-grained, with mean grain sizes of <4 ϕ (0.063 mm) coarsening to 2–3 ϕ (0.125–0.250 mm) around the edge of the Bass Basin, and to gravel size over the Bassian Rise (Blom and Alsop, 1988). The seafloor is dominated by carbonate , with the sand-size fraction dominated by foraminifera and fragmented bryozoan and molluscan remains (Blom and Alsop, 1988). Around the edge of the Bass Basin, facies of Bryozoan-dominated gravel and sand are found (James et al., 2008).

The wave climate of Bass Strait is strongly affected by the Southern Ocean, with long period deep-ocean swell dominating (McSweeney, 2020). There is a spatial and temporal variation in wave characteristics across the Strait. Wave shadow areas occur on the lee of King Island and Lutruwita/Tasmania, with the Strait between these two landmasses being the area of highest wave energy and longest period (up to 14 s). Wave heights are greater in winter than summer (Liu et al., 2022). Extreme wave events (99th percentile) exhibit significant wave heights (H_s) of 7.5 m, with the 1 % annual exceedance storms having an H_s of 11 m (Liu et al., 2022). The Strait is microtidal, with the M2 tidal constituent amplifying from <0.4 m at the edges of the shelf to 1.1 m in the central region near Lutruwita/Tasmania (Wijeratne et al., 2012). Waves and tide-induced currents lead to large mobile bedforms composed of coarse-grained sediment on the shelf adjacent to the islands on either side of the Strait (Malikides et al., 1989). In summary, Bass Strait is a high-energy shelf exposed to long-period swell from the Southern Ocean.

As part of an investigation of Last Interglacial (Marine Isotope Stage 5e; 130–115 ka) relative sea level at Robbins Island (northwest Luturuwita/Tasmania; Fig. 1a), Goodwin et al. (2023) produced relative sea-level predictions for the past 140,000 years for the Bass Strait using a glacio-isostatic adjustment (GIA) model (see Methods). These calculations indicate the Bass Strait sea-level minimum over the past glacial-interglacial cycle occurred c. 26,000 years ago when sea level was approximately 114 m below present elevation (Fig. 1b), which is slightly shallower and earlier than other proxy-derived estimates of −120 to −130 m from around Australia (Lewis et al., 2013; Webster et al., 2018; Yokoyama et al., 2001).

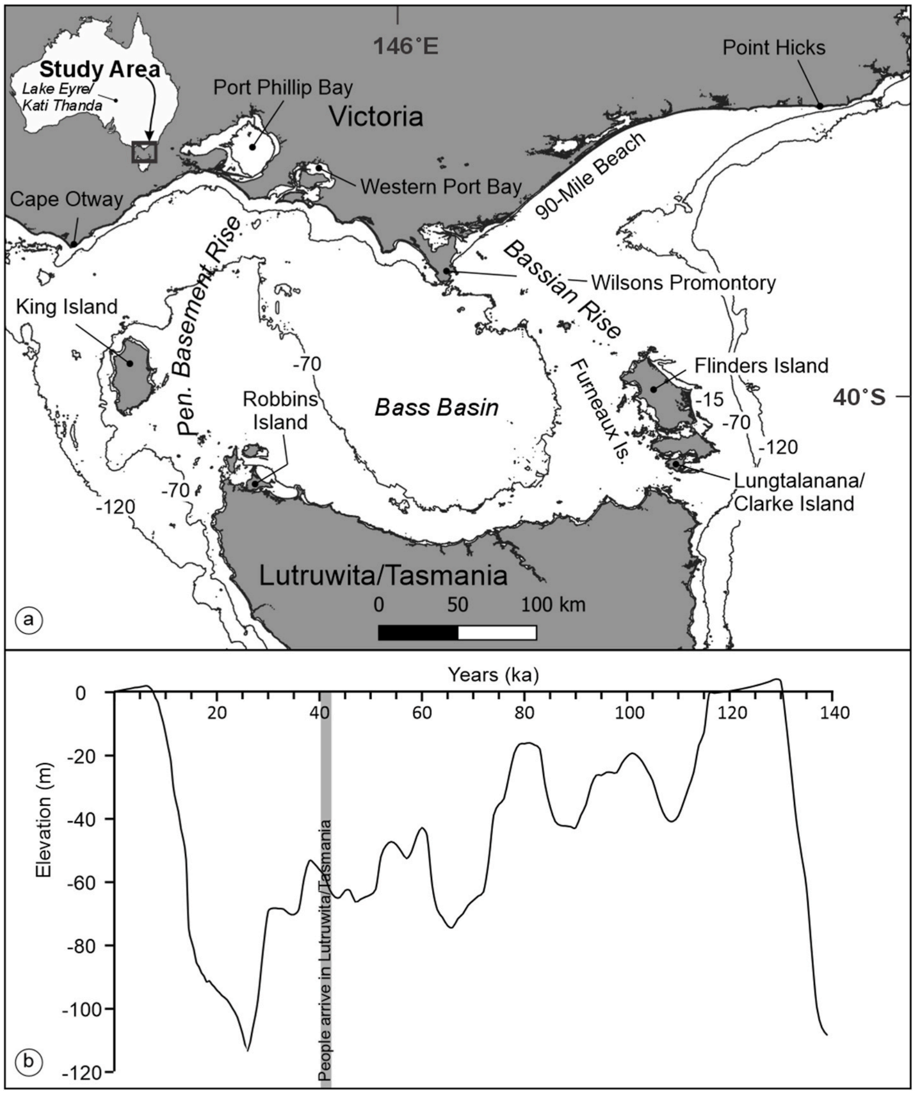

Fig. 1. Bass Strait geography and regional sea level curve. (A) Location of Bass Strait at the southeastern margins of Australia. Bathymetric contours are in metres below mean sea level. The Pen. (Peninsula) Basement Rise (western edge of Bass Strait) and Bassian Rise (eastern edge of Bass Strait) are the key land-bridges during cool climates. (B) Relative sea-level predictions for the past 140,000 years based on Goodwin et al. (2023).

3. Materials and methods

The bathymetric data used in this study are the AusBathyTopo (Bass Strait) 30 m 2022 Digital Elevation Model (DEM) (Beaman, 2022), which is a compilation of the most recent data obtained from various sources including ship-based multi- and single-beam echo sounder surveys, Electronic Nautical Chart spot depths, airborne LiDAR bathymetry, satellite-derived bathymetric data, coastline and near-surface feature data. This dataset offers comprehensive coverage of the seabed between the coastlines of Victoria and northern Lutruwita/Tasmania, extending approximately 460 km from west of King Island to east of Flinders Island. A combined raster dataset was generated, resulting in an interpolated digital elevation model as a continuous representation of the seabed surface in grid format at a spatial resolution of 30 m referenced to approximate mean sea level (Beaman, 2022). For this study, various secondary data layers including slope, shaded relief and depth contour layers were then generated using ArcGIS software (ESRI). A river network was also generated using spatial analyst and hydrology tools in ArcGIS.

Present-day bathymetric depth contours were used as proxies to reconstruct previous shorelines at specific intervals over the past 100,000 years. Estimates of the amount of time above or below relative sea level were based on the Bass Strait relative sea level predictions produced by Goodwin et al. (2023) and cumulative areas of exposure, enabling the calculation of inland shoreline movement (transgression) in m/yr. The GIA model used to produce the relative sea level predictions is a one-dimensional Maxwell viscoelastic Earth model that assumes a lithospheric thickness of ~50 km under Bass Strait (see Goodwin et al. (2023) for further details) and adopts the ice history defined in Clark et al. (2020) and Lambeck et al. (2006) and (2014). While this modelling approach was intended for examining peak Last Interglacial relative sea level, the Goodwin et al. (2023; pers. comm) predictions used here are appropriate for this study given they are geographically specific and because there are no other published modelling, or proxy-based time series of relative sea-level change available for (and specific to) Bass Strait. Similar analyses from other parts of Australia for pre-Holocene periods (Morrison et al., 2023; Norman et al., 2024; Williams et al., 2018) use global mean sea-level estimates (Grant et al., 2014; Lambeck et al., 2002) combined with bathymetric data to produce shoreline and land-area change estimates, whereas this study goes a step further to use regionally-resolved model predictions.

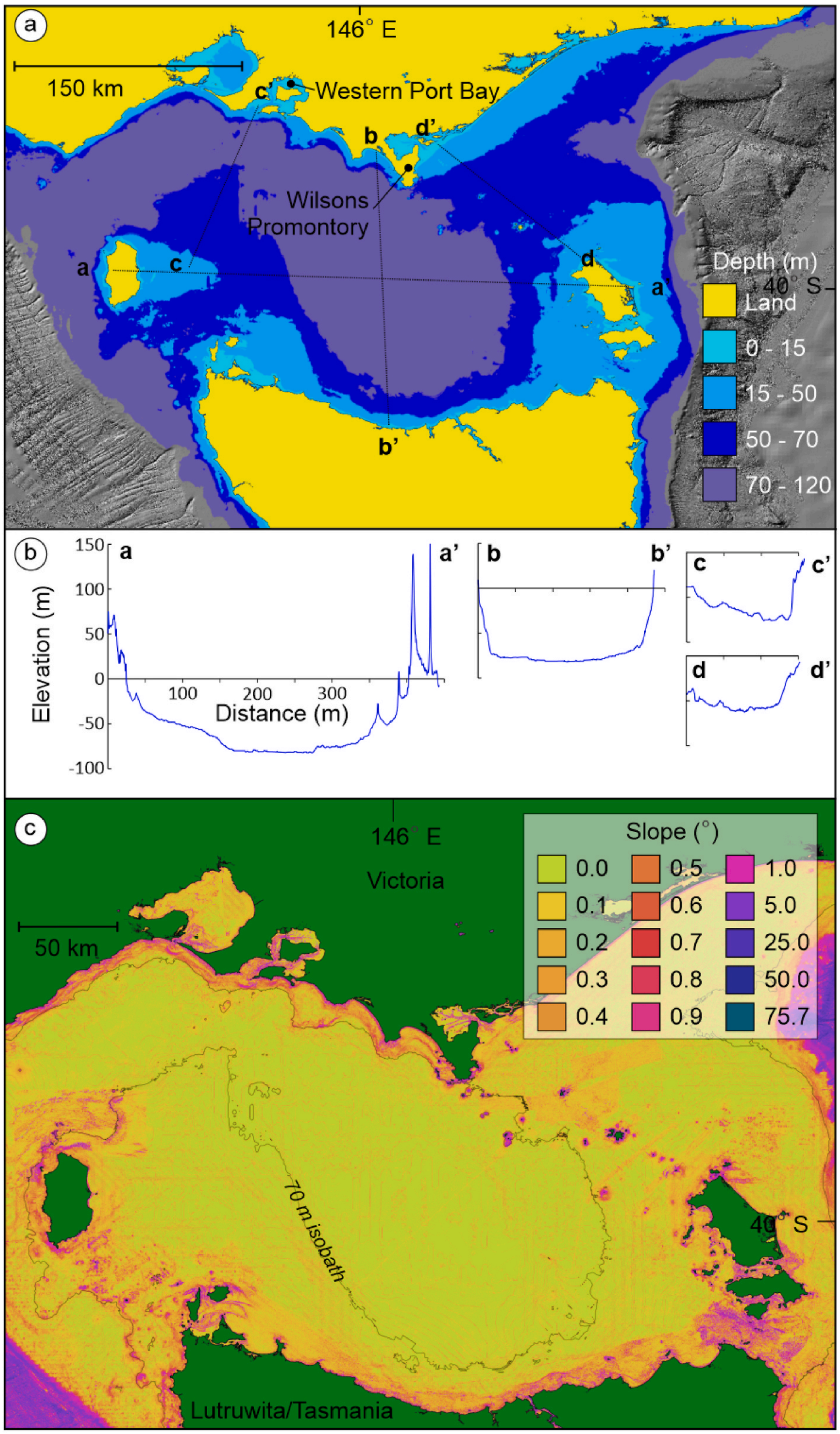

Fig. 2. Bass Strait shelf bathymetry and slope. (A) Broad depth characteristics of Bass Strait, highlighting (B) broad geometry of the basin (a-a' and b-b') in comparison with the extent of the two-principle land bridges that existed at low sea level (c-c' and d-d'). (C) Slope model of Bass Strait showing broad slope classifications. The Strait is characterised by very low slope, with steeper areas being found along the shelf's edges and along the modern shorelines and inland areas surrounding the Strait.

4. Results

4.1. Broad morphology

The Bass Basin is broadly U-shaped in cross-section, with a flat basin floor at around 79–80 m water depth, with the deeper areas greater than −70 m depth extending as a 43 km wide sill at its narrowest in the northwest towards Western Port Bay, from where it changes orientation to the southwest and exits towards the shelf edge (Fig. 2a). The Peninsula Basement Rise is 186 km long and 136 km wide at its minimum (at 70 m depth), with King Island located on its western edge. The Bassian Rise (246 km long, up to 129 km wide) connects to the mainland at the 70 m depth line along 90-Mile Beach in the north, with Wilsons Promontory marking its northwestern edge. The southern half of the Bassian Rise is characterised by a shallower shelf < −50 m depth, on which the Furneaux Island Group, including Flinders Island, rest. The connection between both land-bridges and mainland Australia is defined by a trough, the edges of which are both steeper at the northern edge, with the Peninsula Basement Rise trough being −75 m depth and the Bassian Rise trough being −59 m depth at their deepest (Fig. 2a and b).

The slope of Bass Strait is exceptionally low; gradients of <0.2° occur on 71 % of the area above the continental shelf edge, with 62 % being <0.1° (Fig. 2c). The areas of greatest slope on the shelf surface occur over relatively shallow plateaux adjacent to the islands and the channels that dissect them. In these areas, such as between the Furneaux Island Group and Lutruwita/Tasmania, the slope can reach up to 6°, associated with rhythmic bedforms (sand waves (Heap and Harris, 2008)). Such higher slope angles associated with active sea floor bedforms are also prominent up to 40 km north of King Island. The near-horizontal nature of almost the entire shelf contrasts with the steeper continental slope and canyons, and as the sea floor rises to the present-day coastlines of Victoria and Lutruwita/Tasmania or to abyssal depths respectively (Fig. 2c).

4.2. Maximum extent of the land-bridge

The maximum extent of the Bass Strait land-bridge (i.e., the Bass Plain) is defined by the −84 and −114 m bathymetric contours. At the lower elevation, all of Bass Strait was exposed as dry land (i.e., it was subaerial), with the shoreline then positioned at or close to the shelf edge in the east (Fig. 3). In the west, the main difference between the two bathymetric positions is the presence of a marine embayment between the present-day King Island and Cape Otway. When sea level was at its low-stand position (i.e. at what is now around −120 m), it would have been possible to cross the land-bridge from Point Hicks in the east to Cape Otway in the west (Fig. 3). Compared to the relative sea level curve (Fig. 1b), at the maximum lowest position of the sea, the land would only have been exposed 4 % of the time in the past 26,000 years and 1 % of the time in the past 100,000 years. However, at a slightly higher elevation of −84 m depth, when the land-bridge was fully exposed, the length of time of subaerial exposure increases substantially, to 42 % for 26,000 years and 14 % for the past 100,000 years (Table 1).

While the entirety of Bass Strait may be exposed due to its elevation with respect to sea level, the topography of the centre of the land-bridge has long been hypothesised to have been a large lake (Bass Lake) during low-stand conditions (Blom and Alsop, 1988), during periods when there was sufficient freshwater inflow. The maximum extent of the lake can be defined by the −75 m bathymetric contour, above which the Peninsula Basement Rise is inundated and would have become Sea Country. The low gradient of the shelf means that at its maximum

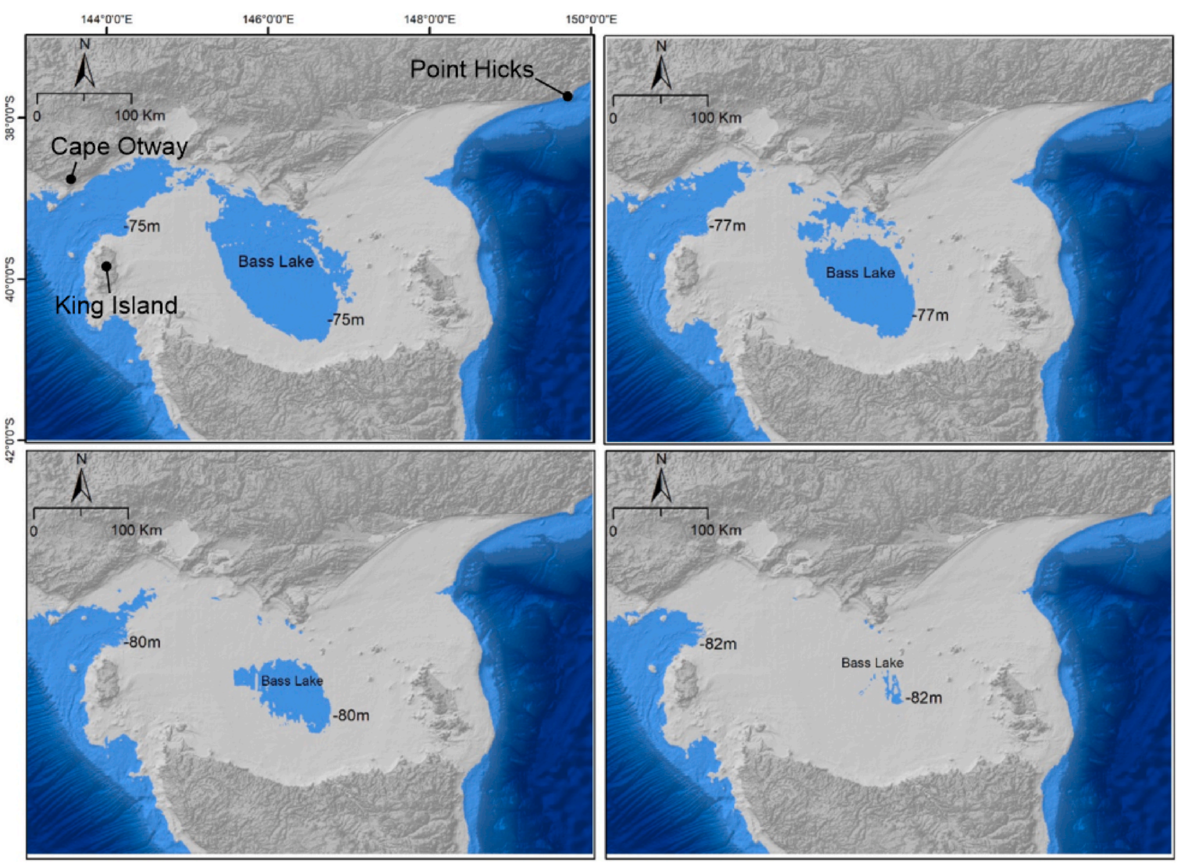

Fig. 3. Model of the extent of Bass Lake. The maximum extent of Bass Lake, located in the centre of the land-bridge as defined by the −75, −77, −80 and −82 m bathymetric contours. When sea levels are higher than −75 m, the lake becomes connected to the open ocean. The dark grey area shows the present-day land/coastline; the light grey area shows the surrounding exposed land by depth contour. Refer to Fig. 1 for all the locations mentioned in this study.

Table 1
Subaerial exposure times. The length of time of exposure of the Bass Strait land-bridge relative to relative sea level predictions (Fig. 1b).

Past 26,000 years				Past 100,000 years	
Sea-level position (m below present)	Years duration	Length of exposure over past 26,000 years (%)	Approx. years ago when the land-bridge became inundated[a]	Years duration	Length of exposure over past 100,000 years (%)
−120	1000	4	26,000	1000	1
−84	11,000	42	15,000	14,000	14
−70	12,000	46	14,000	25,000	25
−50	13,000	50	13,000	54,000	54
−15	16,000	62	10,000	90,000	90

[a] The rate of sea-level rise during the fastest period of deglaciation, and limitations on modelled position of sea level, mean that the date of flooding is approximate.

extent, the lake was only 13 m deep but is estimated to have had a surface area of 16,000 km^2 (c. 175 km NW–SE, 100 km NE–SW). At its maximum extent (following the −75m contour), Bass Lake is estimated to have been equivalent in area to the modern Kati Thanda/Lake Eyre North, but twice as deep during the latter's maximum recorded floods. Lake Eyre being the largest lake system in Australia when it is full.

4.3. Exposure and drowning of the land-bridge

While the area covered by the land-bridge was greatest when sea level was lower than −84 m below present, the land-bridge likely persisted as a narrower feature during periods of higher sea level. At the −70 m bathymetry line, the connection between Lutruwita/Tasmania and Victoria extended along the Bassian Rise, with the northern edge of the Peninsula Basement Rise being an open waterway into the former Bass Lake. This bathymetric interval, where there was a subaerial (dry land) connection across Bass Strait, occurred for a quarter of the past 100,000 years and just under half (46 %) of the past 26,000 years. At −50 m, however, a land-bridge was no longer present, with flooding occurring across the northern end of the Bassian Rise. At this elevation, a subaerial ridge extended north from the tip of Lutruwita/Tasmania, maintaining a land link to the Furneaux Island Group. King Island was nevertheless separated from both the Victorian and Lutruwita/Tasmanian mainlands at this stage. The land exposure of the −50 m bathymetry contour is estimated to have occurred for around half of the past 26,000 (50 %) and 100,000 (54 %) years (Table 1).

As the land-bridge provided a vital connection between the high terrestrial areas of Lutruwita/Tasmania and Victoria, understanding the timing of flooding is critically important for understanding when the terrestrial biological connection was terminated, as well as when the marine zones on either side of the Strait became connected (severing the land-bridge between Lutruwita/Tasmania and Victoria). The first stage of bridge flooding occurred at the northern (Victorian) edge of both the Bassian Rise and Peninsula Basement Rise. Due to the low relief and slope of the land-bridge, the region was likely flooded within a 3000-year period between 14,000 and 11,000 years ago, based on the corresponding depth on the modelled position of relative sea level. The first transgression occurred 14,000 years ago on the Peninsula Basement Rise, when sea level was positioned at –74 m. After a further 1000 years, the Bassian Rise flooded as an elevation of −59 m was reached, and very soon afterwards King Island became separated from Lutruwita/

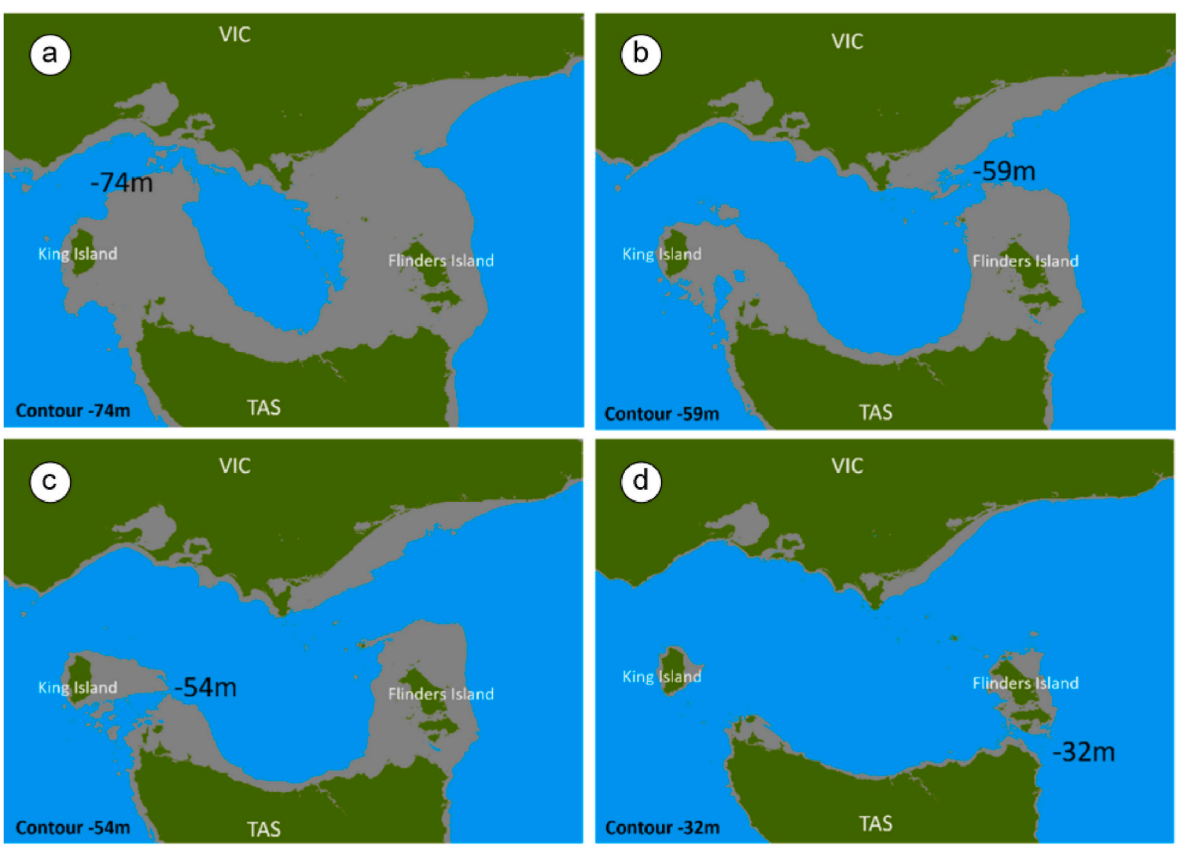

Fig. 4. Model of water depths of land-bridge flooding. Depth contours illustrating the depths at which the modern Bass Strait was formerly: (A) an interior seaway, connected to the Southern Ocean to the west, and when the Bassian Rise formed a land-bridge between mainland Australia and Lutruwita/Tasmania; (B) the land-bridge was submerged and the Bass Strait connected the Southern Ocean and the Tasman Sea; (C) King Island was disconnected from NW Tasmania; (D) the Furneaux Island Group became disconnected from NE Lutruwita/Tasmania. Further depth and age details are provided in Table 2.

Tasmania (Fig. 4). The islands of the Furneaux Group remained connected to the Lutruwita/Tasmanian mainland until 12,000 years ago, when sea levels rose to an elevation of −32 m (Fig. 4). Most importantly, based on the bathymetric and modelled sea-level data, it appears that the Bassian Rise land-bridge was exposed for 46 % of the last 26,000 years, with full cut-off of the main islands from Lutruwita/Tasmania occurring by 12,000 years ago. The final configuration of today's Bass Strait islands then occurred by 10,000 years ago, when the smaller islands of the Furneaux Group (such as Prime Seal, Badger and Hunter) formed as sea level rose above −15 m elevation (Table 2).

4.4. Geomorphology of the land-bridge during flooding

Present day Bass Strait is a highly energetic marine environment. This is reflected in the bathymetry, with complex associations of bedforms found around islands and promontories. These include scour holes, linear and transverse dune ridges, as well as accumulations of sediment banks on the leeside of islands and between Lutruwita/Tasmania and Lungtalanana/Clarke Island (Fig. 5). These dunes are up to kilometres in length and have relief of tens of metres above the seabed (Fig. 5). The orientation and scale of these bedforms and scours typify tide-dominated straits (Dalrymple and Rivers, 2023).

The relatively flat sea floor of Bass Strait and the resolution of the bathymetry mean that distinct palaeoshoreline features are rare across the now-drowned land-bridge. The high-energy reworking of the seafloor may also mask, or have removed, many features during the Holocene. The exception is a tell-tale shoreline feature found at −70 m along the western edge of the Peninsula Basement Ridge, 30 km northeast of King Island (Fig. 6). This feature is well defined; it has a smooth, cuspate-shaped arc that faces due west and is bounded at its northern end by a rocky promontory. The feature is 23.6 km long, with the 'seaward' (western) 700 m appearing to contain at least four ridges that are parallel to the −70 m isobath (Fig. 6). In cross section, the profile rises from −74.1 to −66.7 m depth, with a trough of around 2 m deep forming in its rear (Fig. 6). The feature then extends as a plateau towards the east, where it eventually becomes mantled by sediment, as inferred from the smooth appearance of the sea floor. Linear ridges, 6–12 km long and up to 1 km wide cross the entire area, appear to expose bedrock 14 km west of the −70 m shoreline.

Table 2
Landbridge inundation times. Estimated timing (in years) when the land-bridge was inundated and formed the islands we know today. The three largest islands (Lutruwita/Tasmania, Flinders Island and King Island) from the mainland of Australia and estimates of land-bridge exposure time are based on changes in sea levels (m) for the past 26,000 years. The islands in brackets represent smaller islands where archaeological records of human settlement have been recorded.

Island		Sea level relative to present (m)	Approx. timing of start of cut off from mainland Australia (years ago)	Land-bridge exposure time (years)	Land-bridge exposure time (%)
Tasmania	Peninsula Basement Ridge	−74	15,000	11,000	42
	Bassian Rise (Erith Island)	−59 (−57)	14,000 (14,000)	12,000	46
Flinders Island	(Prime Sea Island) (Badger Island)	−32 (−18) (-18)	12,000 (10,500) (10,500)	14,000	54
King Island		−54	14,000	12,000	46
	(Hunter Island)	(-15)	(10,000)		

5. Discussion

The Bass Strait land-bridge was exposed as dry land for thousands of years during the period of human habitation of Australia. Since the Last Glacial Maximum, people were able to live on and walk across the plains connecting mainland Australia with Lutruwita/Tasmania. During this time, the Bassian land-bridge was exposed as dry land for 46 % of the time along the eastern side of what is now Bass Strait, and 42 % of the time on the western side (the Peninsula Basement Rise). The inundation of the land-bridges on both sides of the strait starts when the position of sea level was at −74 m on the western side (Peninsula Basement Rise) and −59 m in the east (Bassian Rise). When comparing these depths to sea-level reconstructions for the region, the most recent period of inundation (i.e. completely severing all land connection between mainland Australia and Lutruwita/Tasmania) occurs in a narrow window of time between 15,000 and 14,000 years ago. The timing of initial flooding of both land-bridges coincides within the estimated time of rapid sea-level rise following ice-sheet collapse in the Northern Hemisphere. Melt Water Pulse (MWP) 1a peaked at around 13,800 years ago, when sea level rose at an average rate of 26–53 mm/year (Coonin et al., 2025; Lin et al., 2021; Stanford et al., 2011). Liu and Milliman (2004), considered the start of this period of rapid sea level rise to occur from a depth of −96 to −76 m (from 14,300 to 14,000 years ago) based on data from the Yellow Sea (between mainland China and South Korea) and Sunda Shelf. In Bass Strait, this depth corresponds to the deepest part of the Peninsula Basement Rise. MWP 1b occurred several thousand years later and is estimated to have peaked c. 11,300 years ago. This age-depth relationship has been inferred from contrasting environments of drowned reefs in Barbados (initiated at −53 m depth) (Blanchon et al., 2021) and palaeoshorelines along the South African Shelf (initiated at −58 m depth) (Green et al., 2014). The depth of the South African examples is within 1 m of the maximum depth of the Bassian Rise. The coincidence between the maximum depths of the land-bridge arms and the vertical positioning of the global MWP drowning events means these areas would have flooded very rapidly as part of a global-scale pattern of continental shelf flooding.

While the vertical rates of global sea-level rise and the depth ranges from which they initiated and ended provide the timing of land-bridge flooding, for human occupation and travel and animal movements it is important to understand the *horizontal* rates of change. Using a simple trigonometric approach, areas that are flatter will see greater horizontal shoreline displacement than those that are steeper; that is, the flatter areas will become inundated faster than the steeper areas (Fig. 7). At a slope of 0.50°, a rate of sea level rise of 44 mm/year (which occurred during a period of 250 years starting around 11,300 years ago, based on MWP 1b of Blanchon et al. (2021)) will see the shoreline shifting horizontally by 5.04 m/year. This increases to 25.21 m/year at 0.10°, and 126.05 m/year at 0.02°. A slower rate of sea-level rise of 10 mm/year (the average of the post-glacial marine transgression from 17,000 to 7,000 years ago (Lewis et al., 2013; Thom and Roy, 1985) results in horizontal shoreline transgression of 1.15 (0.50°) to 28.65 m/year (0.02°). Across the deepest (northern) ends of the land-bridge's western and eastern arms, both of which are near-horizontally flat, a 15 km-long stretch of coast would therefore have experienced complete inundation within a period of 60 years during MWP 1a. In other words, an Aboriginal Elder would have witnessed the inundation of some 15 km of Country within their lifetime.

An important source of uncertainty in the nature of the demise of the land-bridge is our incomplete understanding of the relative sea-level history of Bass Strait. The existing sea-level history published for Australia (Lewis et al., 2013) incorporates very limited paleo-data from the Bass Strait region, and limited pre-Holocene data outside of the Great Barrier Reef and Bonaparte Gulf (Webster et al., 2018; Yokoyama et al., 2018). Even sparser are data that constrain Bass Strait relative sea

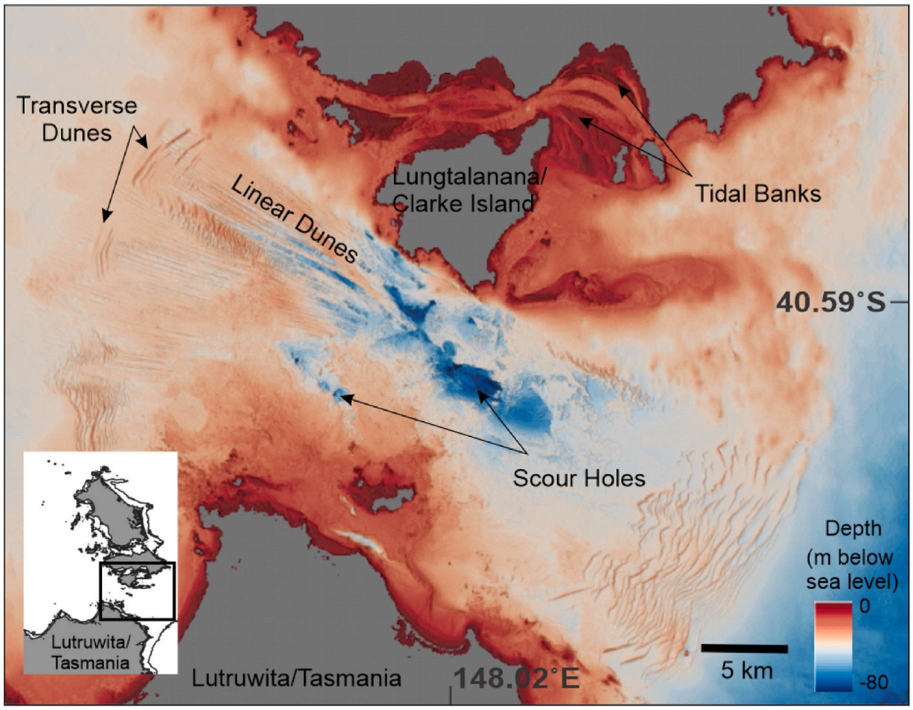

Fig. 5. Wave and tidal current induced sea floor features. A typical example of the complex bedforms found around islands in Bass Strait. The imagery is the combined data product derived from airborne LiDAR and sonar mapping (Beaman, 2022).

level during Marine Isotope Stages (MIS) 2–4. In this analysis we use relative sea-level model predictions that incorporate broad global ice volume changes and solid-Earth feedbacks that are specific to the Bass Strait (Goodwin et al., 2023; Goodwin pers. comm.). Models with different parameters (e.g., Earth viscosity, ice sheet geometries) predict different sea-level histories, which would alter the timing of flooding and the rate of shoreline change reported in this study. There is still uncertainty on global ice volume during the LGM (Gowan et al., 2021; Simms et al., 2019; Yokoyama et al., 2022) and even greater uncertainty into MIS 3 (Dalton et al., 2019; Gowan et al., 2021)), meaning our knowledge of relative sea level when the land-bridge existed is highly uncertain. Our approach here uses a realistic and regionally-specific sea-level history (which contrasts with other studies of Australian land-bridges that use global models (Morrison et al., 2023)) which has provided a first quantitative estimate of the evolution of the land-bridge, and sets the foundation for future studies to better constrain the regional sea-level history.

Sea-level rise and shoreline transgression would have occurred at rapid rates across the whole of Bass Strait. The subsequent behaviour of the geomorphic systems then becomes important for assessing the impact of flooding on people and other parts of the ecosystem. This is because landforms are not simply static features that are passively flooded during periods of rising sea levels (Kennedy et al., 2023). Based on comparable coastal depositional systems in areas of low relief across the region, two primary geomorphologies can be expected: beach-dune sequences (Kennedy et al., 2020) and tidal flats and salt marshes (Rogers et al., 2005; Saintilan et al., 2013). The prevalence of these landforms during periods of lower sea level in Bass Strait is unknown, so it is difficult to infer a starting point of coastal form when understanding landscape responses to sea-level rise. Beach-dune sequences under rapid sea-level rise would likely have been rapidly reworked inland through overwash (Fruergaard et al., 2015, 2018). However, this assumes an absence of diagenesis, which is a likely possibility in the region as the sediments are carbonate-dominated on the current sea floor. *In situ* drowning is also a possibility (Mellett and Plater, 2018), given the rates inferred to have occurred during the MWPs. Drowned beach-barrier sequences have previously been identified at −70 m water depth offshore of the northern end of 90-Mile Beach (Beaman et al., 2005; Brooke et al., 2017) and 30 km ESE of Wilsons Promontory at −67 m water depth (Nanson et al., 2023), and these match the morphology of the embayed shoreline found in this paper at the same depth just northeast of King Island (Fig. 5). For such landforms, it appears that the shorelines composed of beaches and dunes were unable to keep pace with sea-level rise and were thus drowned *in situ*. The limited extent of such landforms suggests that sediment supply for their formation was low. Examples of preserved barchan dunes atop the land-bridge (Brooke et al; Nanson et al., 2023) attest to low sediment supply rates in the region at that time. However, contemporary energetic currents may have removed evidence of additional barriers, albeit much of the 30 m bathymetry grid for Bass Strait is interpolated with high-resolution surveys required to confirm the precise nature of the seabed in some areas. Drowned rocky shorelines at −70 m depth are also found further to the west along the southern Victorian coast, providing additional support for the interpretation of a period of rapid coastal change (Bezore et al., 2016, 2019). This sea-level change is certainly global in extent, with other palaeoshorelines being found at similar depths in South Africa (Green et al., 2014).

Marshes are forecast to migrate progressively inland as sea levels rise (Saintilan et al., 2023). Salt marshes can keep up with sea-level rise if sediment rates are high enough FitzGerald and Hughes, 2019; Kirwan and Temmerman, 2009; Saintilan et al., 2022, though none have been described as being capable of adjusting to the rapid rates of sea-level rise inferred for the Early Holocene transgression. Marsh-dominated systems are expected to rapidly backstep across the shelf. Importantly for the strait's geomorphology, rather than being a distinct land-sea boundary, it is likely that an extensive wet marshy system was created as post-glacial sea-level rose (such as the Big Swamp in Northern Australia (Woodroffe et al., 1993)). This has implications for patterns of human occupation and movement, as well as for spatial shifts in animal migrations. The development of extensive marshlands would have restricted passage across the land-bridge to a greater degree than if the changes in habitats were based solely on sea level related water

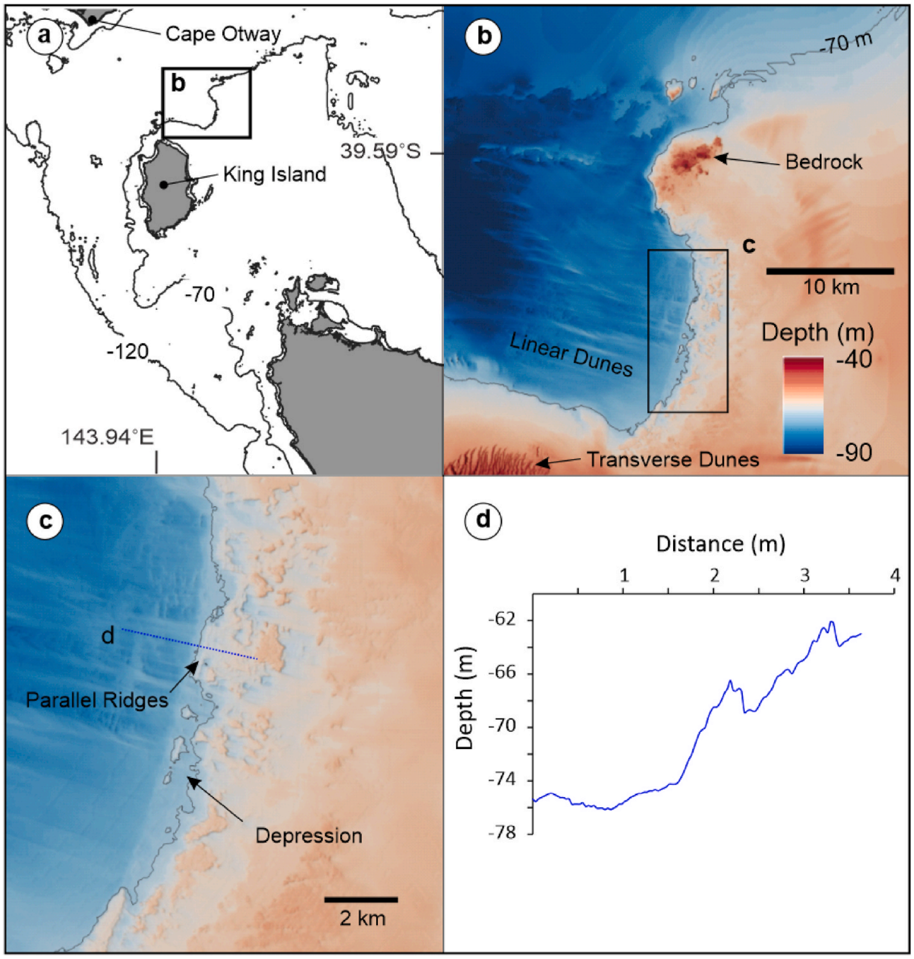

Fig. 6. Drowned shoreline at 70 m water depth. (A) A visually distinctive palaeoshoreline is found northeast of King Island at −70 m water depth. (B) The palaeoshoreline forms in a bay-like feature between inferred rocky outcrops. (C) The morphology of a series of parallel ridges similar to modern-day barrier dune sequences in Bass Strait suggests a common geomorphic environment. (D) A cross-section across the inferred drowned barrier. Bathymetry for parts b and c derived from Beaman (2022).

elevations (as much of the archaeological literature on 'sea-level rise' has so far focused on). A lack of data on the detailed geomorphology and marine geology of Bass Strait limits our interpretation of the physical nature of the coastline during periods of sea-level rise across the region.

Based on the sea-level modelling presented above, the contemporary island configuration in Bass Strait would have manifested rapidly. Such inundation of previously terrestrial landforms to form the islands of Bass Strait occurred at decadal timescales. For people, this change would have been noticeable and extraordinary (Morrison et al., 2023). The rates of sea-level rise during periods of ice sheet collapse mean that hills on the exposed coastal plain would have become islands within a person's lifespan. The rates of flooding laterally across the landscape, at almost 130 m/year, mean that people would have seen rapid change as they resided, moved and returned across the landscape seasonally. Nineteenth-century accounts and current oral histories document that Gunai/Kurnai Traditional Owners travelled dozens of kilometres annually between the current Victorian highlands and the coast in the 1800s (Bulmer, 1888; Howitt, 1904), as well as on the lakes and, to a lesser degree, along the coastline in bark canoes (Howitt, 1904; Van Waarden, 1989). Such mainly seasonal movements would also have occurred in the deeper past across the land-bridge, which means that some people may have had difficulty returning to their homelands due to coastal flooding when returning from, or to, more distant parts of Country (e.g., to visit kin, for trade or ceremony, or a myriad potential reasons). As sea levels rose rapidly, the changes to the landscape across the Bass Strait land-bridge would have been very fast, impacting individuals, families and more extended communities to an extent not seen before. Such rapid environmental change is almost certain to have occurred across other land-bridges globally where the continental shelf is relative shallow and flat (Voris, 2000).

While flooding is the focus of this work, comment can also be made on the first exposure of the land-bridge in relation to human migration. The earliest archaeological evidence is 38,800–41,050 cal BP (34,790 ± 510 BP, Beta-42122B/ETH-7665B) for Warreen Cave in the interior southwest of Lutruwita/Tasmania, and in the north-central area at Parmerpar Meethaner between 37,310 and 39,790 cal BP (33,850 ± 450 BP, Beta-68159 CAMS-10270) (Allen, 1996; Cosgrove, 1995; Holdaway and Porch, 1996). The earliest human habitation of Lutruwita/Tasmania inferred from landscape burning records within sediment cores occurs at c. 41,600 years ago (Adeleye et al., 2024). Based on our modelling sea level needs to be below −59 m for the land-bridge to be exposed. The GIA modelling (Fig. 1b) indicates that this elevation was reached between 42,000 and 41,000 years ago. A paucity of understanding of sea-level fluctuations around this time significantly hinders our ability for a more precise determination of the timing of settlement of Lutruwita/Tasmania, but the available evidence strongly suggests people crossed the land-bridge as soon as it was exposed.

6. Conclusions

The Bass Strait land-bridge has been exposed above sea level for the majority of the Quaternary. Its morphology is characterised by two

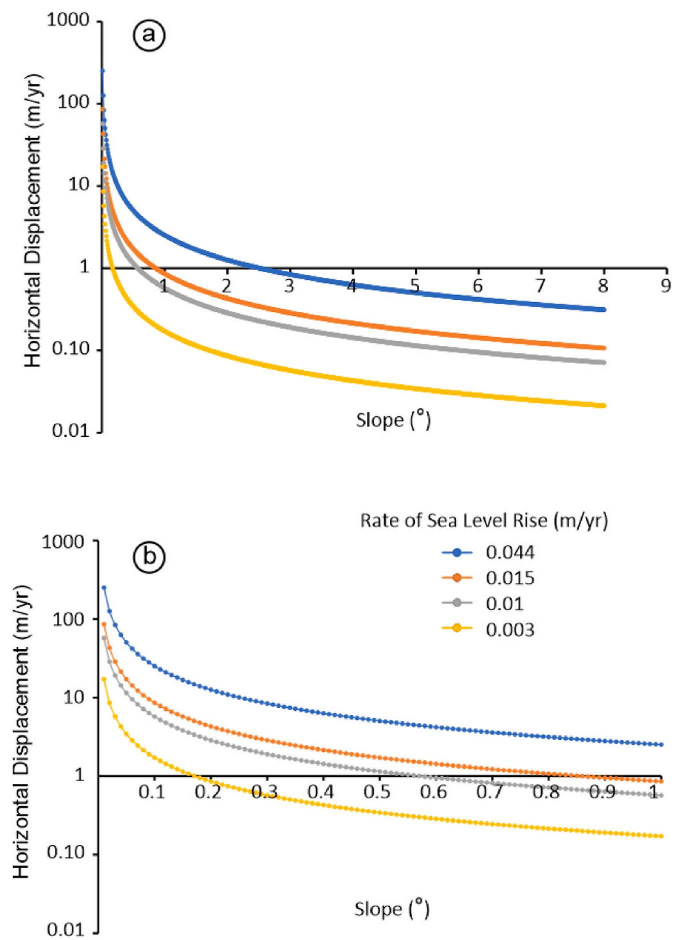

Fig. 7. Model of slope determined shoreline transgression. The rate of horizontal shoreline displacement associated with different rates of sea-level rise (in m/year) over a shelf which (a) slopes between 1° and 9°. (b) A more detailed representation of slopes of <1°, which are most common in Bass Strait.

separate ridges that flank the modern-day Bass Strait continental shelf. Strong wave and tidal currents today cause major reworking of sediments over the shelf surface. Yet despite this sediment mobility, beach-barrier sequences remain preserved on the sea floor today. These submerged geomorphological features occur at −70 m water depth, and this shoreline is certainly regionally extensive, with examples being described across Victoria; it also corresponds with shorelines of similar depth internationally.

A critical depth limit of around −59 m occurs in the region. This marks the vertical position where the land-bridges along both northern arms of the Bass Plain became submerged by sea-level rise. This depth is similar to that of other identified shorelines in South Africa and is coincident with the position of sea level where rates of rise increased dramatically during the MWPs associated with ice sheet collapse. Modelling rates of 44 mm/year sea-level rise during this period across near-horizontal land surfaces reveals rates of inland shoreline movement (transgression) of up to 126 m/year. At these times, the land-bridge would have ceased to be a land-bridge within a period of 60 years, as a 15 km-wide trough flooded. This rapid rate of change is within a person's life-span and certainly would have profound impacts on the Indigenous peoples on and around the Bass Plain, who until this time would have lived on and travelled across land-bridge Country on foot.

Data and materials availability

The full bathymetry is available athttps://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/147043.

Author contributions/CRediT author statement

David M. Kennedy: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Visualization, Project administration, Ali Jalali: Methodology, Formal analysis, Writing - Review & Editing, Visualization, Bruno David: Conceptualization, Writing - Review & Editing, Matthew C. McDowell: Validation, Writing - Review & Editing, Rachel A. Nanson: Methodology, Validation, Writing - Review & Editing, Ashleigh J. Rogers: Validation, Writing - Review & Editing, Russell Mullett: Methodology, Validation, Writing - Review & Editing, Joanna Fresløv: Validation, Writing - Review & Editing, Jessie Birkett-Rees: Validation, Writing - Review & Editing, Juliet Sefton: Validation, Writing - Review & Editing, Daniel Ierodiaconou: Conceptualization, Methodology, Resources, Writing - Review & Editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

A link to the data and/or code is provided as part of this submission.

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