Report Prepared for Cardno

The Geomorphology of the open coast of Corner Inlet and Southern 90-Mile Beach

Prepared by:
[redacted]

School of Geography, Earth & Atmospheric Sciences, The University of Melbourne, Parkville Vic 3010.

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Executive Summary

The shorelines of the southern 90-Mile Beach and the mouth of Corner Inlet are very dynamic environments composed of sandy beaches and backing dune systems. There are three primary subaerial landforms: (1) prograded beach-barrier plain, (2) shore attached beach-barrier spit, and (3) barrier islands. Their present and past dynamics are all closely linked to the Corner Inlet sediment system, in particular the large ebb-tide deltas that form adjacent and within the entrances to this large structural estuary. The behaviour of the barriers during their evolution has been driven entirely by natural processes due to the lack of human development in the region. The only exception being the narrow coastal-plain north of McGaurans Beach where the single foredune is a product of the introduction of exotic marram grass (*Ammophila* sp.). The shorelines of the region are broadly stable to accreting through time and this is driven by the abundant sediment supply from Corner Inlet and Wilsons Promontory. Isolated areas of erosion have occurred related to inlet breaching and associated shoreline-orientation change. These changes can be considered part of the natural sediment-dynamics of the region driven by waves and tidal currents. The high sediment-supply means the landform systems have a degree of resilience to climate change. Reorientation of the shoreline by several degrees can be expected in association with a changing in direction of deep-water wave approach, while the on the centennial scale the barrier islands may transgress landward as higher sea levels shift the equilibrium beach-profile inland.

1.0 Scope of Review

This review aims to summarise the current understanding of the geomorphology of the southern Gippsland-region. It covers area from northern tip of Wilsons Promontory, marking the southern boundary of Corner Inlet, to McLoughlin's Beach. The review is focussed on the open-coast landforms, their formation and projected future evolutionary-trajectory. This includes the southern parts of 90-Mile Beach, the islands of Corner Inlet and the coastal plain at the northern tip of Wilsons Promontory

The study area therefore includes portions of the Wilsons Promontory National Park, Corner Inlet Marine and Coastal Park, Nooramunga Marine and Coastal Park and McLoughlins Beach – Seaspray Coastal Reserve (Fig. 1).

The temporal frame of the review is focussed on those processes that determine the character and drive evolution of the landforms that form the contemporary open-ocean coast. These are primarily Holocene features having formed as a result of sea-level changes over the past 10,000 years. The locations and form of these landforms also bears the imprint of geological processes over longer timescales which have determined the sediment supply for the region as well as the available accommodation-space for landform development.

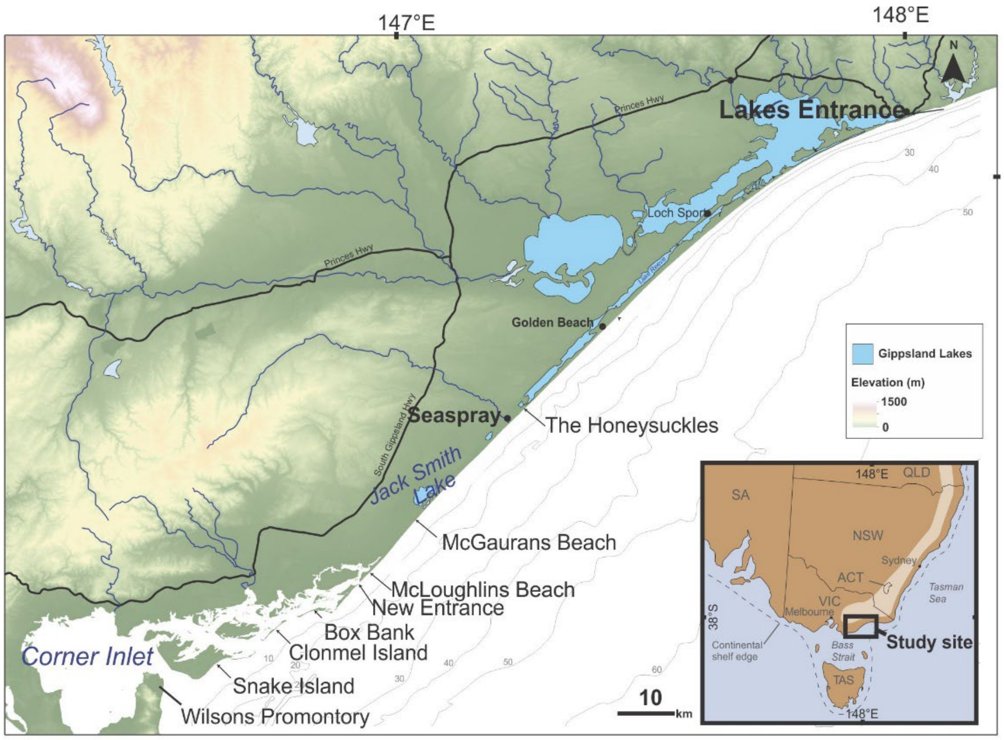


Figure 1: Location of southern 90-Mile Beach in SE Australia and study area of this review from Wilsons Promontory to Seaspray.

2.0 Geological History of the Gippsland Basin

The Gippsland Basin underlies the entire study-area forming the continental-shelf basement of eastern Victoria and extending into the La Trobe Valley onshore. The basin was formed during the Mesozoic period as a result of rifting associated with the breakup of the eastern Gondwana and creation of the Tasman Sea. It is infilled with up to 7.5 km of sediments (Baillie et al., 2019; James and Evans, 1971) and the basin is most well-known for its petroleum resources. Sediments of the Seaspray Group, a cool-water carbonate shelf depositional environment, form a seal for the oil and gas resources (Holdgate et al., 2003) and in places this unit is exposed at the surface.

The southern end of the basin is defined by the Darriman and Foster Fault systems which marks the Southern Terrace zone (Fig. 2). The study area is framed within this zone with the Foster Fault system extending into the middle of Corner Inlet (Baillie et al., 2019; James and Evans, 1971). Vertical movement on these fault systems has led to the creation of vertical space in which sediments can accumulate on the coast as well as the large depositional basin of Corner Inlet (Bird, 1993).

These major fault systems within the basement geology, while providing the geological boundaries for landform development, can be considered inactive during the Holocene (Cupper et al., 2003) and therefore can be assumed not to affect present day sediment transport.

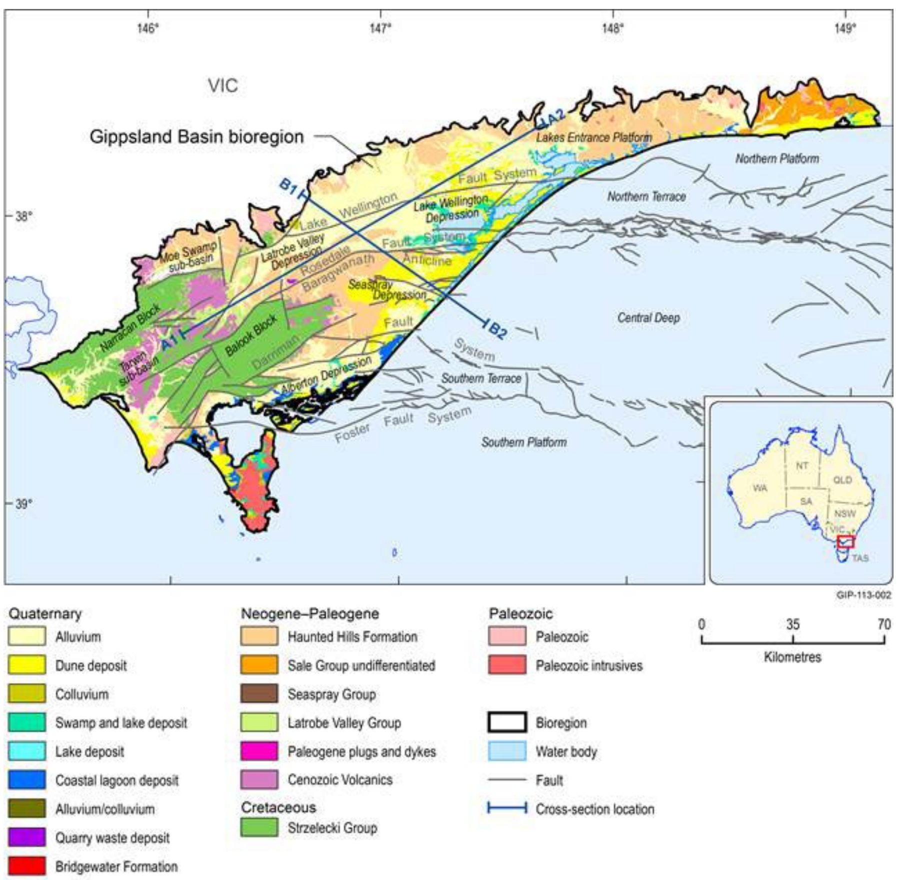


Figure 2: Geological of the Gippsland Basin (source: Bioregional Assessment Programme (2015) Geology 250k -. Viewed 29 September 2017, http://data.bioregionalassessments.gov.au/dataset/e248f087-ed0e-4b92-9c66-2fc239f94f58.)

3.0 Surface Geology

3.1 Contemporary Shoreline

The oldest units found exposed on the modern coast are Middle Devonian age (380 Ma) Mount Singapore Granite on Wilsons Promontory. These lithologies are an S-type monzogranite (Rossiter, 2003) which are relatively high in Rb and low in Ba and Sr with occasional concentrations of garnet (Chappell et al., 1988). Weathering of the granite during the Mesozoic occurred to depths of over 300 m with much of this regolith being subsequently eroded, especially at the coast (Hill and Joyce, 1995; Hill et al., 1995). The topography of Wilsons Promontory is strongly influenced by tectonic activity dating after the early-Cretaceous with vertical fault-movement contributing to the elevation of paleoerosion surfaces (Hill et al., 1995).

The next oldest sediments to be exposed are older limestones observed to outcrop on the beachface and surf zone at McGaurans Beach following storms (Rosengren, 2013). This represents the uppermost and younger parts of the Seaspray Group of carbonates described by Holgate et al (2003) elsewhere in the basin.

The remaining units, which account for the nearly all of the coast, are composed of Holocene age beach and dune deposits which form a coastal plain up to 10's of kilometres wide, behind which low energy swamp deposits are found. The width of the Holocene sequences is determined by the presence of Tertiary-age terraces which are closest to the modern-day coast at McGaurans Beach. Where the coastal plain is wider, from approximately McLoughlins Beach north to Lakes Entrance, the lakes of the Gippsland Lakes region are formed where beach-barrier sequences of Last Interglacial and Penultimate Interglacial age are also found (Bird, 1961, 1965; Kennedy et al., 2020; Oliver et al., 2018)

3.2 Shelf Environment

The southern extent of the contemporary offshore sedimentary environment is the Bassian Rise which extends from Wilsons Promontory to Flinders Island in Bass Strait. This rise separates the Gippsland from Bass Basins and forms a morphological divide between the study area and the contemporary sedimentary environments further south. The sea floor of the inner shelf, adjacent to the study area, is broadly composed of gravelly sand with isolated patches of sand and gravelly muddy sand (James et al., 2008) with a mean grain-size of 1 – 2 ϕ coarsening to greater than -1 ϕ offshore in an easterly direction (Blom and Alsop, 1988)(Fig. 3) (diameter of particle in mm: $d(mm) = 2^{-\Phi}$.) The sediments of the inner shelf are broadly Holocene in age composed of biogenic gravel sand and mud (James et al., 2008), with a mineralogy of over 70% carbonate (Blom and Alsop, 1988). Closer to shore in the upper shoreface, in the zone of principle sediment-transport, the carbonate content is lower (<50%) (Blom and Alsop, 1988). In some locations, such as the bedrock defined bays of Wilsons Promontory the sandy sediments (Ierodiaconou et al., 2018) are observed to be entirely quartoze representing a local source of sand from the surrounding granitic hills. On the inner shelf, bryozoan-derived sediment dominates the carbonate fraction with this relict biogenic material becoming dominant at the shoreface at the northern end of the study area (James et al., 2008) and also coinciding with the observed outcrops of carbonate rocks of the Seaspray Group in the surf zone.

The contemporary inner-shelf environment is not a major sediment source for the shorelines of 90-Mile Beach north of Corner Inlet. It is considered to be a ravinement surface (Holdgate et al., 2003) and therefore having little connection to the inshore sediment-transport systems. During the early to mid Holocene, as sea level stabilized at modern elevations after rising from its low stand during the last Glacial Maximum, the beach barriers of the contemporary coast were initially built from sediment transported from the inner shelf (Bird, 1961, 1965, 1971; Kennedy et al., 2020; Thom, 1984), however by the late Holocene this source was exhausted with sediment supply being primarily sourced longshore from Corner Inlet in the south (Kennedy et al., 2020).

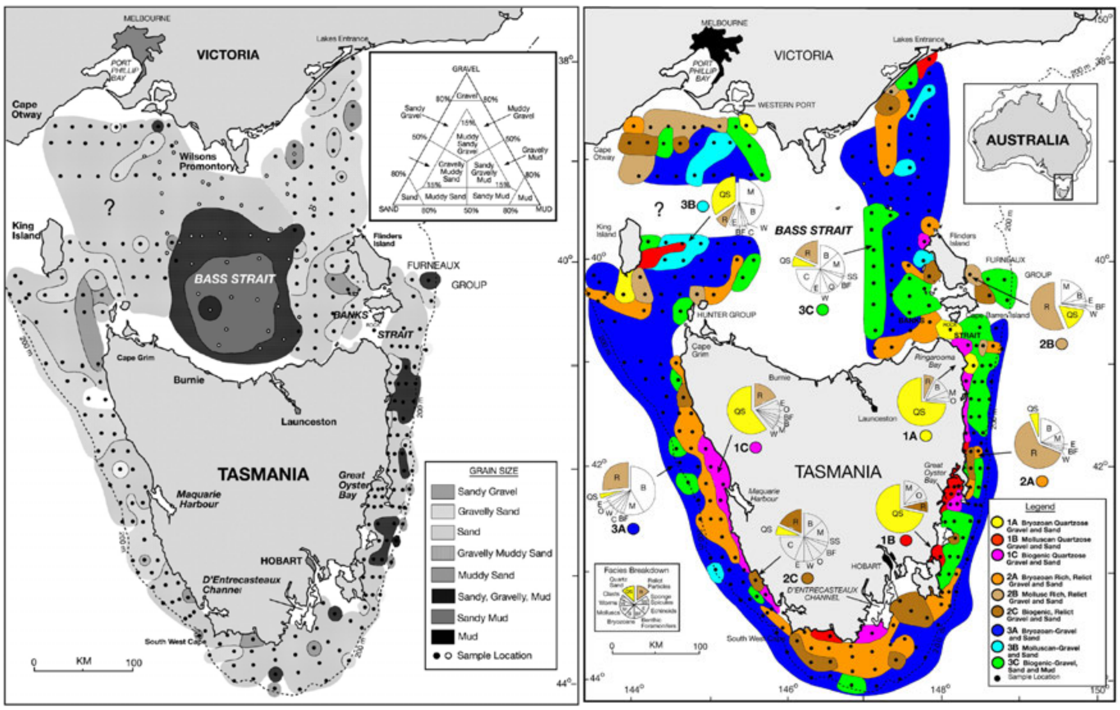


Figure 3: (a) The different grain sizes of surface sediment on the continental shelf and in Bass Strait. (b) Distribution of surface sediment facies, based on study of samples indicated, on the continental shelf off Tasmania and in Bass Strait. (source: James et al., 2008).

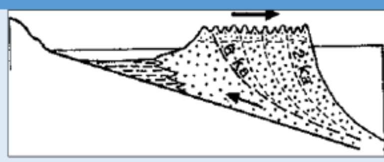
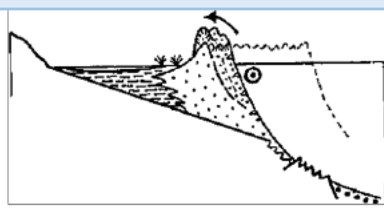
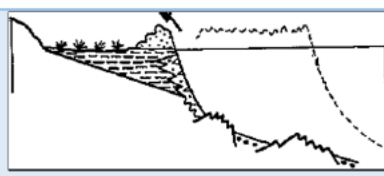
4.0 Geomorphology

4.1 Beach Barrier Systems

The study area is dominated by beach-barrier sequences (Bird, 1993; Kennedy et al., 2020; Oliver et al., 2018). Broadly, the evolution of these landforms systems is determined by the available sediment supply and sea level (Otvos, 2000; Otvos, 2012). For a beach-barrier to form, the slope of the continental shelf must be less than 1° during a period of rising sea-level to ensure that the migration of sediment is inland. Where the shelf is steeper, sediment movement is offshore and the shoreline tends to be rocky in character (Roy et al., 1994).

There are three types of barrier systems (1) Barrier Island, (2) Shore-attached barrier and (3) inner shelf sand bodies. Their position is broadly related to shelf slope with barrier islands being in locations of shallowest slope and shelf sand bodies being in areas of highest slope. Once sea level has stabilised a further three types of barrier are recognised, namely (1) prograded (regressive), (2) stationary, and (3) receded (transgressive barriers) (Roy et al., 1994) (Table 1). Sediment supply is the primary determinate of the evolutionary form of a barrier under a period of relatively stable sea-level (Otvos, 2000; Otvos, 2012).

Table 1: Common beach-barrier morphologies found during periods of sea level stability (information based on (Roy et al., 1994)).

Barrier Type	Morphology	Common Characteristics	Sediment Supply	Examples
Prograded		• Multiple dune ridges • Ridge morphology often parallel to the coast	High	McLoughlins Beach Entrance Point
Stationary		• No evidence of progradation • Complex foredune structure • Narrow	Low	Woodside Beach
Receded		• Outcrops of estuarine muds of peat on beachface • Less than 10 m thick	Very low – negative (erosional)	McGauran Beach

4.2 Barrier Response to Rising Sea Levels

Beach-barrier systems often form during periods of rising sea-level as sediment is reworked landward as the shoreline rises as climate warms. In the Gippsland region, this has led to the formation of three sets of beach-dune sequences dating back over 200,000 years. They are termed the Prior, Inner and Outer Barrier (Bird, 1961, 1965, 1971), with recent dating confirming their age to be related to periods of higher sea-level around 200,000, 80,000 -125,000 and 8,000 – 0 years ago, respectively (Bryant and Price, 1997; Kennedy et al., 2020; Oliver et al., 2018).

Barriers under rising sea-level move landward through a process known as washover. This occurs through waves breaching and overtopping the foredunes behind the beach with sediment then moved in the low-lying areas behind the dunes. As more sand is transferred from the beach to the back-barrier environments the profile progressively moves landward (Fig. 4).

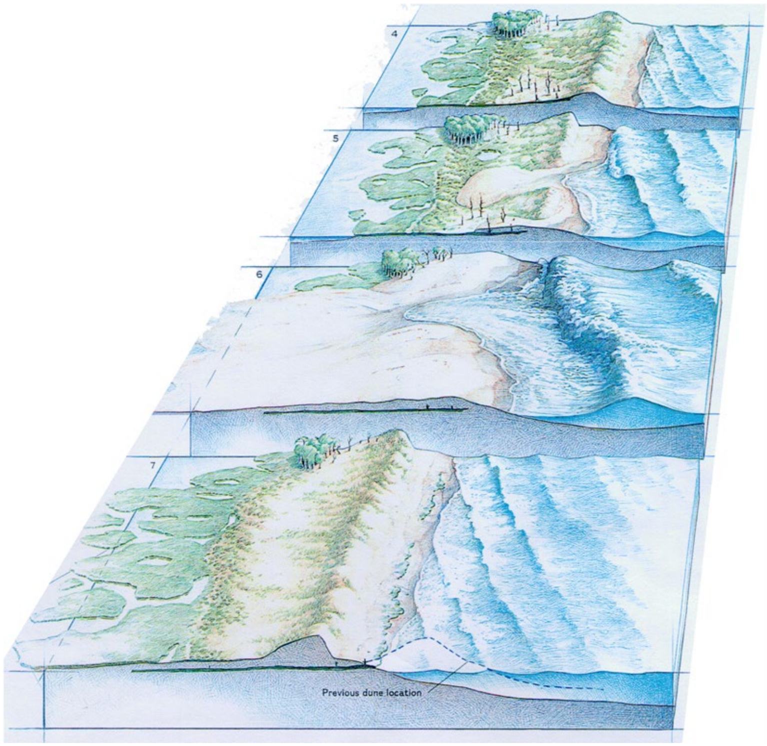


Figure 4: Schematic diagram showing the process of overwash of a barrier transferring sand from the beach to back-barrier leading to shoreline retreat during a period of sea-level rise. (Source Unknown)

Barrier systems can be drowned *in situ*, or persist in the same location, however, the latter response requires a significant active sediment supply to maintain the beach profile. In the Gippsland region significant overwash is observed today in the areas with the narrowest and lowest dune- ridges, particularly along the northern part of the study area north of McGauran's Beach to Seaspray (Rosengren, 2013).

4.3 Barrier types in southern 90-Mile Beach

4.3.1 Northern Wilsons Promontory (shore-attached foredune ridge plain)

The 2.5 km wide coastal plain at the northern tip of Wilsons Promontory forms the southern boundary of the study area. It is composed of 70 distinct ridges forming a shore-attached foredune barrier sequence. The plain rises to 6-7 m elevation at its rear, decreasing to around 4 m average round 400 – 700 m from its landward end, with the rest of the 1.8 km length being between 2 and 3 m above mean sea-level (Fig. 5). The evolution of this plain is closely linked to sea level as it is most likely, based on the geomorphology, that this system has been prograding seaward consistently throughout the Holocene. The rear of the plain likely formed soon after sea level stabilisation at 7,000 years ago with the decrease in elevation being related to coastal progradation during a period of sea level fall of 1 – 2 m since the mid Holocene. The ebb-tide deltas from Corner Inlet are the likely source of the majority of sediment supplemented by northerly longshore drift from Wilsons Promontory.

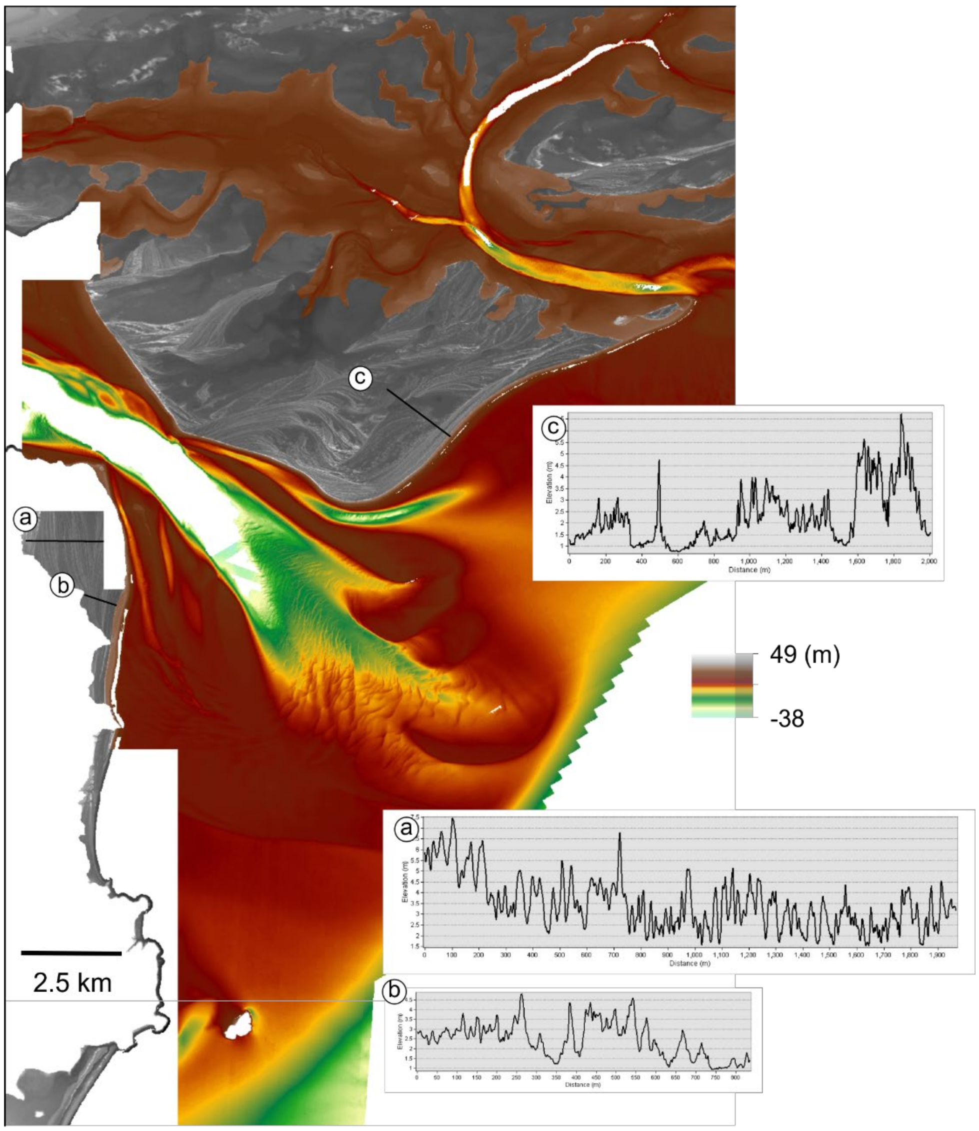


Figure 5: Terrestrial (grey scale) and bathymetric (colour) LiDAR surveying of the southern entrance to Corner Inlet showing cross sections of the coastal plains that have developed as sand has accumulated above mean sea-level.

4.3.2 Nooramunga Marine and Coastal Park (Barrier Islands)

The sandy islands of Nooramunga represent offshore barrier-islands and these form the seaward boundary of Corner Inlet. The barrier islands are composed of a series of curved spits and prograded foredune ridges, the latter dominating the current modern beach which range up to 500 m in width on Sand Island. Wave overwash is a natural process on these islands and is particularly apparent in locations where the barrier is thin, especially the southern end of Clonmel Island in the region of the Clonmel Sands. The tidal channels which separate the islands are dynamic and are migrating on an annual basis north and south as observed in the rates of shoreline change for the past 30 years (section 5). In extreme events, new channels may be created when tidal currents are able to exploit erosional lowering of the dunes after storm overwash events. This is observed in the creation of New Entrance opposite Saint Margaret Island in 1961 (Rosengren, 2013). The elevation of the foredune ridge plain is similar to that of northern Wilsons Promontory at around 4 m on average, suggesting they formed within a similar time period, likely the mid to late Holocene (Fig. 5). The ridges associated with spits formation in the centre of Sand Island likely formed in association with migrating tidal channels, however without age control their relation to the foredune ridges is unknown.

The sand lobes associated with the ebb-tide deltas of Corner Inlet with abundant mega-bedforms (Fig. 5) implies a high sediment supply and strong evolutionary relationship between the evolution of the islands and hydrodynamics of the nearshore. Corner Inlet is the main source of sediment supply to the islands.

4.3.3 New Entrance to Reeves Beach (Barrier Spit)

The 4.5 km long barrier spit starting at New Entrance is a series of prograded foredune ridges that are shore attached at their northern extremity but are separated from the mainland by an arm of Corner Inlet to the south (Fig. 6 and 7). The barrier is at a maximum of 650 m wide (300+ m of ridges and 200+ m of beach) at its southern end and composed of around 15 foredune ridges, and thins to c. 60 m and composed of only a few ridges at Reeves Beach. The plain is 6 - 8m high with dating by Kennedy et al (2020) indicating it prograded in a short < 500 year time period between 2,000 and 2500 years ago (Fig. 7). The orientation of the ridges is 6.3° from the modern coast suggests a long-term shift in beach alignment at present.

A series of large scale (500 – 1000 m) bedforms from the shoreline to 30 m water depth occur, superimposed on which are smaller sand waves 10 to 100 m meters in width (Fig. 6). The orientation of these bedforms suggests northerly sediment transport and an abundance of sand and gravel being sourced from Corner Inlet and then transported northwards by a combination of wave and tidal currents.

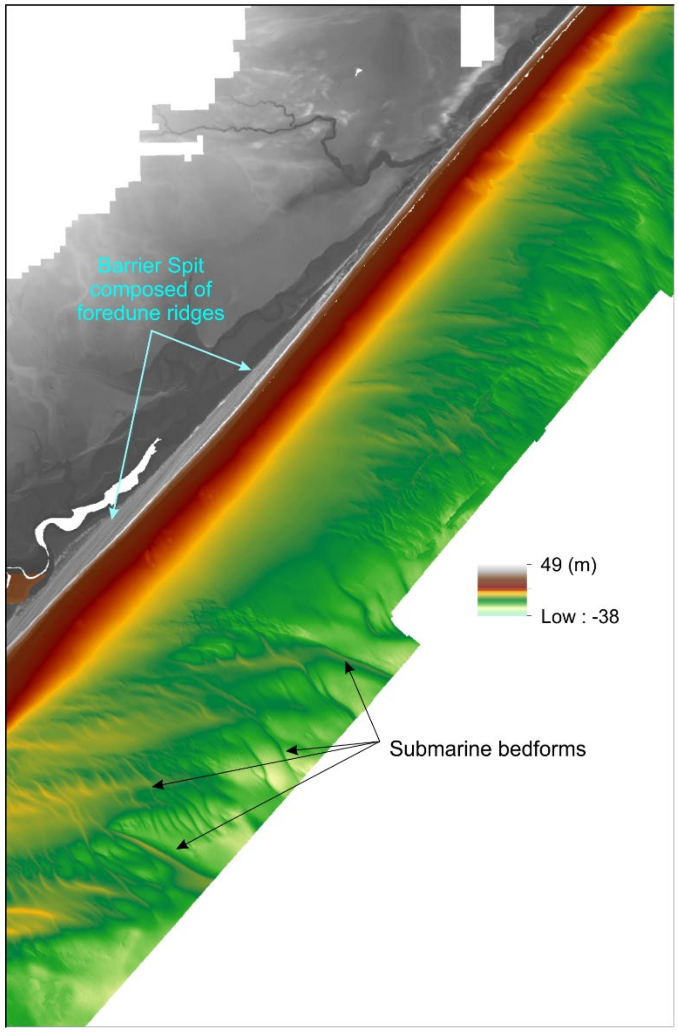


Figure 6: Terrestrial (grey scale) and bathymetric (colour) LiDAR surveying of the barrier spit of MacGaurans Beach. Substantial sediment transport appears to be occurring as evidenced by the subtidal bedforms.

4.3.4 Reeves to McGaurans Beach (single shore-attached barrier ridge)

The barrier north of Reeves Beach is generally composed of a single dune ridge. This ridge is generally dominated by exotic Marram Grass (*Ammophila* sp) and its morphology can be attributed to the growth habit of this species. The dunes are modern, having developed in the past 100 years in association with the introduction of Marram. The young age is supported by luminescence age dating of the sand at around 100 years old (Kennedy et al., 2020). The narrowness of this dune makes it highly susceptible to overwash which has occurred at several locations in the past 50 years (Rosengren, 2013). The offshore environment to 30 m water depth is dominated by similar bedforms to the previous zone, further indicating significant northerly drift of sediment (Fig. 6).

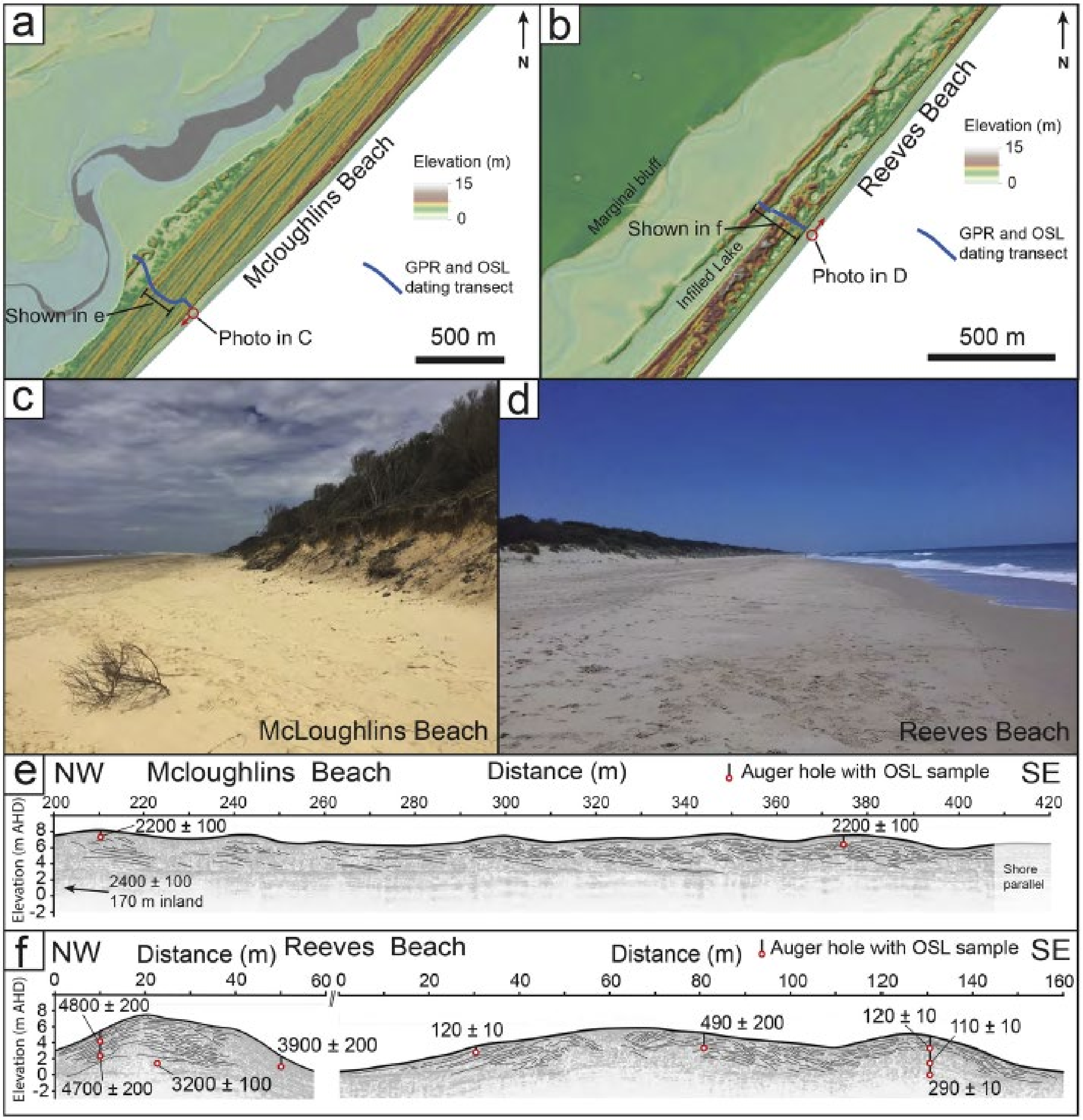


Figure 7: Surface morphology of the southern section of 90 Mile Beach in Zone 1 at (a) McLoughlins Beach and (b) Reeves Beach. The dunes are scarped at their seaward margins at McLoughlins (c), while at Reeves beach (d) foredunes are accreting today. Ground Penetrating Radar traces for (e) Reeves and (f) McLoughlins Beach shown seaward dipping reflections. (Kennedy et al., 2020).

5.0 Decadal-Scale Shoreline Change

The shoreline from the mouth of Corner Inlet to McLoughlins Beach are some of the most dynamic in Victoria (Konlechner et al., 2020). This has been determined through the analysis of 30 years of satellite data sets, primarily from Landsat 5, 7 and 8 platforms as well as Sentinel -2 imagery. The analysis of shorelines is based on a wetted-line or mean sea-level proxy and therefore represents long term adjustment of the beach position rather than that of the dune face (see (Bishop-Taylor et al., 2021; Luijendijk et al., 2018) for full methodology).

The barrier islands that mark the seaward boundary of Corner Inlet have both accreted and eroded at rates of over 2.4 m/yr in the past 30 years (Fig. 8). These rates are the highest magnitude of shoreline change in Victoria (Konlechner et al., 2020). The juxtaposition of both recession and accretion locations, termed hotspots, indicates significant sediment transport in these locations and a highly dynamic landscape (Fig. 9).

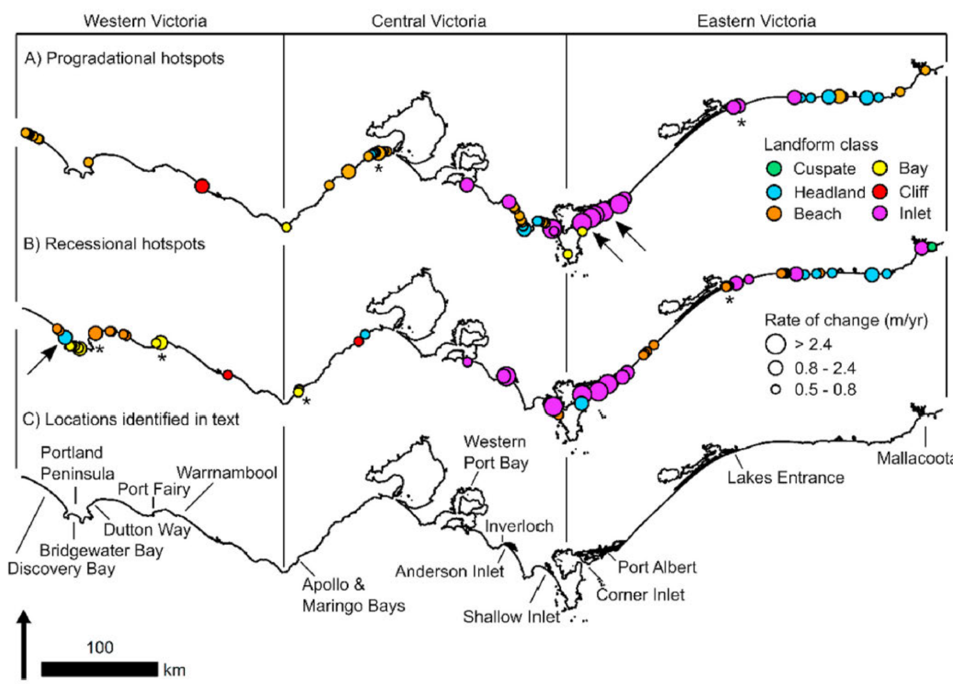


Figure 8: Shoreline change analysis for Victoria for 1986–2017; showing A) hotspots of significant seaward advance (progradation) in shoreline position; B) hotspots of significant landward retreat (recession) in shoreline position based on linear regression rates (LRR) at P > 0.05; and C) locations referred to in text. Bins for rates of change equate to 50 and 90 percentiles of hotspots. Arrows identify the longest hotspots in alongshore length (Konlechner et al., 2020).

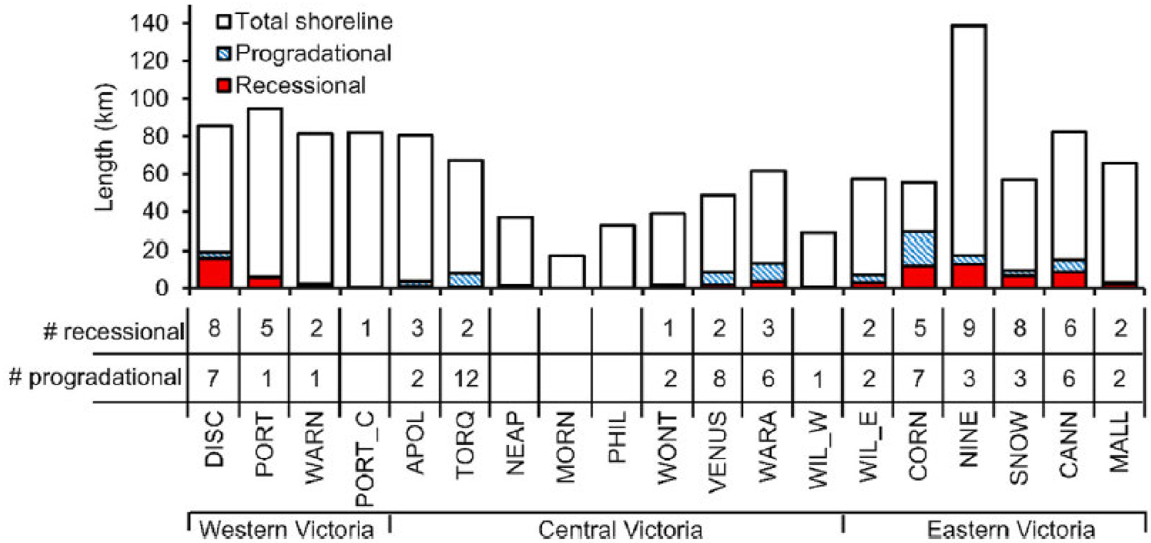


Figure 9: Length and number of recessional and progradational hotspots per secondary sediment compartment. CORN represents the Corner Inlet compartment while NINE is the 90-Mile Beach compartment. (Konlechner et al., 2020).

The overall trend for the past 30 years is one of accretion for the majority of the islands, with the most recession occurring at the northern tip of Wilsons Promontory where the sandy plain is adjacent to the main channel of Corner Inlet. The shoreline is generally stable where the beach and dune systems are shore attached with areas of recession occurring at Jack Smith Lake and the town of Seaspray. Recession is also observed at McLoughlins Beach (Fig. 10).

Figure 10: Net shoreline change since 1988 from Corner Inlet to Golden Beach. The barrier islands show significant accretion with minor erosion occurring where the beach-barrier sequence is thin. Source (DEA, 2021)

The individual shoreline positions between Box Bank and Clonmel Island highlight the dynamic nature of this coast. The channel separating these two islands has progressively migrated northwards leading to erosion on its northern end and accretion of the southern side of the channel. The net position of the shoreline to the north has retreated by just over 170 m, however the position of the island has remained relatively static away from the immediate vicinity of the channel. Overall, the coast in this area has significantly advanced, and this is well illustrated along Snake Island where the shoreline has prograded by 160 m leading to the development of a new series of shore parallel foredunes.

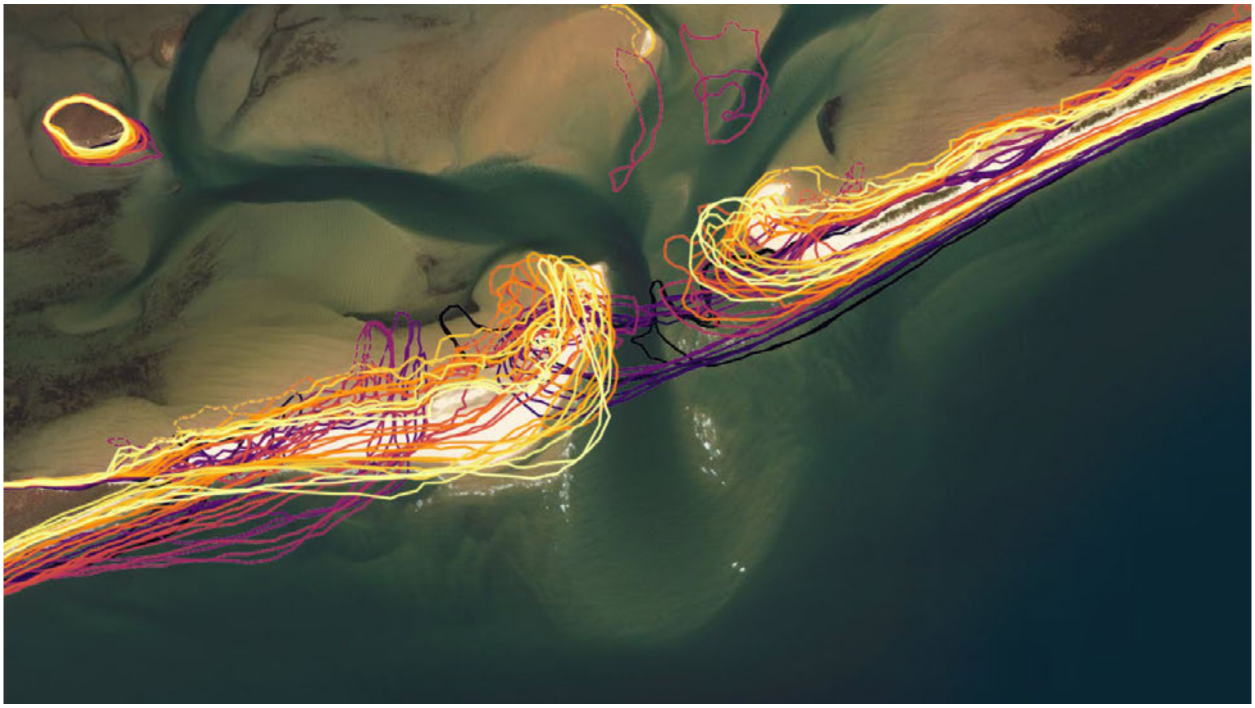


Figure 11: The channel between Box Bank (left) and Clonmel Island (right) has progressively migrated north since 1988 leading to shoreline accretion and erosion as sediment has been redistributed. See Figure 10 for legend (source: DEA 2021).

Figure 12: Continuous shoreline progradation is observed on Snake Island during the past 30 years. See Figure 10 for legend (Source: DEA 2021).

The isolated areas of shoreline recession observed on the barrier islands is most likely a cycling of sediments around the dynamic entrances and not a long-term trend of shoreline recession. The area of erosion at McLoughlins Beach however is exposing dunes of mid Holocene sage (c. 2 ka) and that 3.3 km long section of beach appears to have moved into a net erosional phase (Kennedy et al., 2020). Similarly, the shoreline at Jack Smith Lake Wildlife Reserve and Seaspray is also undergoing net recession, due to the lack of accommodation space for dune development at these locations. It is likely that this section has been naturally sediment starved during the Holocene with the current dunes formed as a result of recent human management through the introduction of Marram grass (Kennedy et al., 2020).

6.0 Future Evolution

The dynamics of the beaches and dunes of the region are driven by the marine and estuarine hydrodynamic processes combined with the abundant sediment supply. The high sediment supply, in particular, ensures a relative resilience of these systems to environmental change.

For the study area, southerly movement of the subtropical ridge and intensification of Southern Ocean swells (Meucci et al., 2020; O'Grady et al., 2015) will be the biggest driver of future sediment movement. The natural state of the coastal system enables it to adjust to these changing boundary conditions as evidenced by hotspots of both erosion and accretion in the past 30 years. A future changed wave-climate and higher sea-levels will likely lead to a reorientation of the islands and parts of the mainland connected barrier systems; however, the broad geomorphology will likely remain similar. The abundant sediment supply in the system and connection between the beaches and dunes and the ebb-tidal delta systems of Corner Inlet ensures this ample sediment supply.

The most significant change in the future will likely be the continued erosion of the barrier spit near the southern end of 90-Mile Beach as the sand is redistributed northwards. This will likely continue until the position of New Entrance stabilises and reworking adjacent to the mouth slows as the ebb-tidal delta of this new channel reaches an equilibrium morphology. In the next century some landward transgression of the barrier islands may occur as they adjust to higher sea-levels.

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