Holocene beaches, bedforms and sediment dynamics of Geographe Bay, southwestern Australia

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Abstract

Geographe Bay is a large near-symmetrical north-facing bay in southwest Australia, characterised by a continuous arcuate sandy beach extending over 50 km, and a wide microtidal shallow inner continental shelf devoid of significant currents. It displays shoreline features in dynamic equilibrium with present metocean conditions, superimposed on relict bed-forms dating from the end of the Last Glacial Maximum. Records of historic shorelines, in places going back to 1941, show that about 90% of the bay's beachline is accreting, whereas only about 10% is subject to natural erosion. Accretion is progressive, but not cyclic—estimates indicate the beach accumulates sand at about 100,000 m^3/yr. Total long-shore littoral sand fluxes on both western and eastern arms of the bay are about 42,000 m^3/yr, implying a remarkable addition of 142,000 m^3/yr to the system. It is unlikely that such a volume was generated by coastal erosion, rivers draining into the bay, or erosion of offshore sandbars and ridges.

Large, linear, stationary, sand ridges oriented at about 60° to the beachline are a distinctive bathymetric feature of Geographe Bay and extend to the 10 m isobath. These ridges are largely stabilized by seagrass meadows and are interpreted as relics from sometime in the last 7,000 years as their size, asymmetry and orientation are incompatible with present metocean conditions. They possibly formed due to intense high-pressure continental systems at the conclusion of the last Pleistocene glacial event after which a strong clockwise gyre may have operated in the bay. Small shore-attached sandbars, about 30° oblique to the beach, overprint the larger ridges to form a complex network bare of seagrass. Although locally reworked, they have been stationary for the past 80 years, and do not contribute to the sediment budget. The large Dunn Bay bars at the western end of the bay commenced building soon after sea-level recession from the Holocene highstand reached its present stillstand at about 3,770 yrs BP.

A field of small, northeastly ripples, between the 6 m and 9 m isobaths, are evident on LIDAR bathymetry as fine lineaments that bulge shoreward into the seaward limits of the larger bedforms. They relate to refracted Southern Ocean swells that pass around Cape Naturaliste but are not actively importing sediment into the bay. The sand influx probably comes from seaward of seagrass meadows at depths of 10–15 m on the inner continental shelf. There is an inexhaustible supply of sandy sediment on the now-inundated post-glacial plain, derived from erosion of the Cretaceous Leederville Formation during the protracted sea-level falls from much higher levels through the Cenozoic. At present, northwesterly winter storm waves feed sediment into the bay where it is dispersed by seasonal wind-generated waves. Southwesterly winter fronts and summer sea breezes drive the major dispersal of ~35,000 m^3/yr along the eastern arm of the bay, whereas a minor pathway of ~7,000 m^3/yr along the western arm is driven by easterly winds. Under this regime, coastal erosion is not a major threat to Geographe Bay.

Keywords: Geographe Bay, Holocene, sediment cells, beach accretion, oblique sand ridges, palaeorivers, sand budget, gyre, relict bedforms, palaeoclimate

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INTRODUCTION

Potential threats of erosion and inundation in Geographe Bay have been assessed as products of coastal processes (Shore Coastal 2018; Eliot 2013), mostly by engineering and research consultancies jointly commissioned by the City of Busselton and the Western Australia Department of Transport (DoT). Their focus has been on localized erosion, loss of amenity and infrastructure protection, rather than a quantitative, whole-of-bay, sediment-budget approach that takes the geological evolution of the bay into account. Previous studies demonstrated quantifiable sediment transport by littoral drift relating to seasonal winds, but also invoked migration of the offshore sandbars. These studies underpin many proposals in coastal hazard risk management and adaptation plans (City of Busselton 2022).

Coastal engineering investigations have identified two leading features in Geographe Bay. Firstly, significant beach accretion for which Damara (2011) provided a qualitative estimate with no explanation of the source of the sediment nor a discussion of the implications of this phenomenon. Secondly, the origin of the atypical shore-oblique sandbars is poorly understood, as pointed out by Pattiaratchi *et al.* (2017).

There is a general perception that historic records show cycles of accretion and erosion influenced by sediment fed from migrating offshore sandbars (Damara 2011; Shore Coastal 2018). However, neither the historic records nor the seabed forms in the bay substantiate this claim. Importantly, many of the coastal and seabed features are incompatible with current meteorological and oceanic (metocean) conditions. Moreover, no definite quantitative sediment budget has been developed despite the abundance of historic beachline data dating back 80 years and available on the Shared Location Information Platform (SLIP) website maintained by DoT. (https://maps.slip.wa.gov.au/Marine/app/).

The consultant reports referenced here are in the open domain and provide valuable background information on present-day metocean parameters and some commentary on sediment dynamics. Most studies attempt to link observed shoreline and seabed features with present-day coastal parameters, sometimes with numerical models. This can yield inconclusive interpretations for sediment sources, pathways and sinks. Coastal engineering studies have mostly overlooked geological processes and palaeoclimates that have shaped the beaches and seabed forms we see today. This imposes constraints on previous sediment-dynamic models and the effectiveness of proposed geo-engineered remedial actions.

Recently Bufarale *et al*. (2019) presented a realistic geological framework as a basis for interpreting bathymetric features in Geographe Bay. However, their study did not explain the significance of some seabed features, or the sediment dynamics in terms of sources, sinks and pathways. This paper reinterprets some of the bedforms of the bay, and provides a model for sediment dynamics, in terms of sources, sinks and processes throughout the Holocene.

GEOLOGICAL EVOLUTION OF GEOGRAPHE BAY

Geographe Bay is a broad, shallow, northwest-facing sand-enriched bay formed over the last 40 million years by marine erosion of poorly consolidated sedimentary rocks of the Perth Basin, which is flanked by hard metamorphic rocks of the Naturaliste Ridge to the west and granitic rocks of the Yilgarn Craton to the east. The hinterland is characterised by a series of ancestral coastal plains and scarps carved into the 150 m-thick Lower Cretaceous Leederville Formation, which postdates the break-up unconformity created by the separation of India from Australia (Thomas 2018; Gee 2022).

Cenozoic Evolution

The J-shape of the bay evolved by marine erosion during a protracted but episodic fall in sea level from the highstand at about 90–110 m above sea level (ASL) of the Eocene Climatic Optimum, through the glacio-eustatic sea-level oscillations of the Pleistocene to the present (Gee 2022). Episodic sea-level falls formed a progressive series of concentric strand lines that mimic the present-day outline of the bay (Fig. 1). Onshore erosion extended through the late Eocene and Miocene, when the Leederville Formation was eroded locally to form the Whicher Scarp. This process moved a large volume of sand onto the continental shelf offshore from Geographe Bay.

The Ambergate Plain at the foot of the Whicher Scarp is a marine-cut platform with a veneer of paralic strand-line sand and estuarine mud, formed during the Pliocene marine regression (Gee 2022). The plain slopes gently seaward from 41 m ASL at the toe of the Whicher Scarp to the marine-cut Cemetery Scarp at 9–21 m ASL at the seaward edge of the Ambergate Plain. The scarp corresponds to one or more of the Pleistocene Marine Isotope Stage (MIS) highstands such as MIS 5e, MIS 7 or even MIS 9. Its formation corresponds to the end of lateritisation in the Cenozoic warm periods, and the end of substantial hinterland erosion, as well as the beginning of the geologically benign processes that prevail today.

Seaward of Cemetery Scarp is the near-coastal Ludlow Plain, at 3–5 m ASL, which is underlain by a 6 m-thick sheet of shelly coralline Tamala-type calcarenite. This unit was deposited against the Cemetery Scarp and a marine erosional surface cut into the Leederville Formation at 1 to 3 m below sea level. Correlation with similar deposits in the southwest suggests the coralline calcarenite accumulated during MIS 5e at 124 ka BP (McCulloch & Mortimer 2008). The seaward edge of the Ludlow Plain at 2–3m ASL records the Holocene highstand at about 7 ka BP.

Water bores and geotechnical probes near the present shoreline indicate the base of the Pleistocene and Holocene deposits is erosional on the Leederville Formation or the overlying Osborne Formation. Subsurface data also suggests erosion of the now buried calcarenite segmented this unit to form discrete bars parallel to the present coast. Bufarale *et al.* (2019) demonstrate similar calcarenite segments or ‘ridges’ in water depths of <10 and ~20 m.

The seabed of Geographe Bay shelves gently northwest for 75 km across the continental shelf to the continental slope, which starts at around 170 m below present sea level. Bufarale *et al.* (2019) investigated the nearshore seabed and substrate of the bay using acoustic seismic profiling, augmented by seabed sampling. Their study identified a thin unconsolidated Holocene mixed carbonate-silicate sediment, and an ‘acoustic basement’ around 15 m below the seabed, postulated to be Leederville Formation, but which also could include younger strata.

Rivers from the hinterland, principally the Carbunup, Vasse, Sabina, Abba and Capel rivers (Fig. 1), developed soon after formation of the Whicher Scarp in the Eocene-Miocene (Gee 2022). Stranded alluvial fans at the foot of the Whicher Scarp, and micro-deltas where the rivers (especially Sabina River) debouch onto the coastal wetlands behind the present beach dunes, demonstrate a progressive decline in sediment load to a now insignificant volume.

The nature of the substrate near the shore in the bay is unclear as there has been no drilling. In a review of the Southern Perth Basin, Thomas (2017, plate 6), used exploration seismic-reflection data to infer a post break-up sedimentary section at least 200 m thick about 5 km

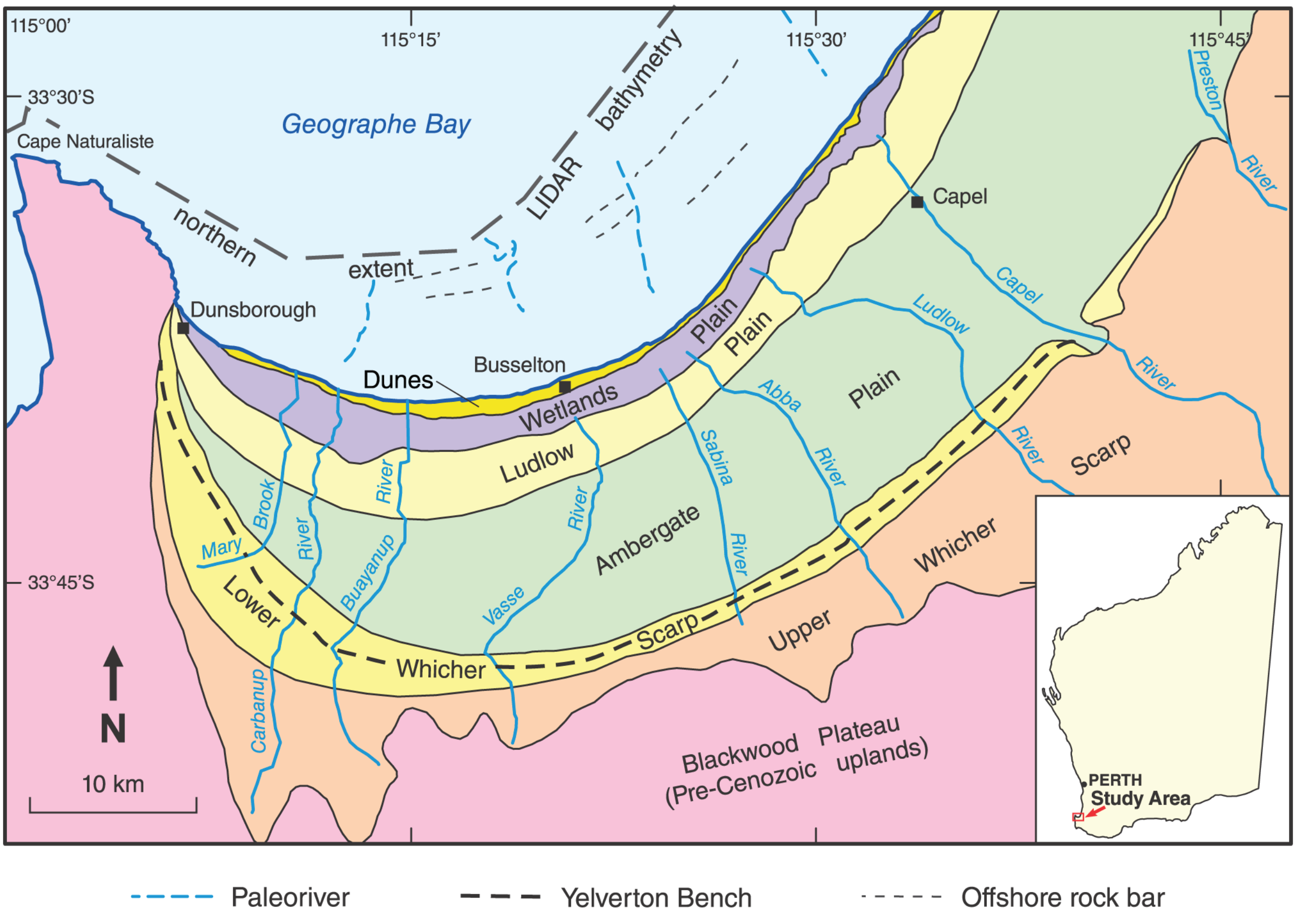

Figure 1. Onshore geomorphic elements (after Gee 2022) of Geographe Bay, showing the extent of LIDAR bathymetric coverage, offshore palaeo-shorelines and palaeorivers.

offshore, thickening considerably to the northwest. This section could include Leederville Formation and offshore facies of the overlying Upper Cretaceous Coolyena Group, such as Osborne Formation, together with a large amount of sand eroded from onshore sections of the Leederville Formation during the Eocene–Miocene evolution of the Whicher Scarp.

Pleistocene–Holocene Evolution

Sea level changes during Pleistocene glacial–interglacial events were important in the development of shoreline and seabed features of the bay. Coastal aeolianite deposits and now-drowned shorelines provide records of these events along much of the western coast of the State (Brooke *et al*. 2014) but not in and around Geographe Bay because of the long-standing protection provided by the Naturaliste Ridge.

At about 17,000 years BP, global sea levels were approximately 130 m below their present level (Miller *et al*. 2020) thereby exposing the present continental shelf for about 75 km northwestward of Busselton. At that time a cool arid plain formed, on which veneers of stranded beach sands, shell and coral debris, wind-blown dunes, alluvial channels and sheetwash material presumably accumulated. Based on the sea-level curve of Twiggs & Collins (2010) for the Abrolhos coast, 700 km to the north of Geographe Bay, the marine transgression prior to the present interglacial passed the present position of the coast at 7,500 yr BP, and reached the Holocene highstand 2–3 m above present sea level at 7,000 yr BP. Since then, the sea level has slowly receded to its present position.

The entire beach around the bay is backed by twin-ridge aeolian dunes (Quindalup Dunes; McArthur & Bettenay 1960), which have a low profile at the head of the bay and progressively increase in size to the east (Gee 2022). The landward dune first developed at about 6,580 yr BP as the sea level fell from the Holocene highstand to the present, and the seaward foredune developed on a layer of seagrass with a carbon age of about 3,770 yr BP (Hamilton & Collins 1997). These dunes are largely built by wind-blown sand from the beaches, a process that continues today.

METOCEAN CONDITIONS OF GEOGRAPHE BAY

The seabed of Geographe Bay gently slopes to the northwest with a gradient of 1:275 between the coast and the 30 m isobath, which is the effective wave base for sediment disturbance on the inner shelf during storms. The bay is subject to diurnal tides with an average range of 0.5 m, and lowest to highest astronomical tides of 1.2 m (Fahrner & Pattiaratchi 1994). This is at the lower end a micro-tide classification (<2 m). As such, tidal currents play no significant part in sediment movement within the bay.

The Leeuwin Current (Smith *et al*. 1991; Pattiaratchi & Woo 2009) flows southwards near the 200 m isobath, on the upper continental slope, well to the west of the coast and does not enter the bay. Neither does the counter Capes Current (Pearce & Pattiarachi 1999), near the 50 m isobath, although it has the potential to augment any current exiting the bay via the Naturaliste headland.

In summer, the bay is subject to prevailing easterly winds, associated with high-pressure systems generated within the Great Australian Bight, and to southwesterly sea breezes. In winter, strong winds of storm intensity blow from the north-west quadrant, during the passage of low-pressure systems (Fahrner & Pattiaratchi 1994); however, these winds are insufficient to establish wind-shear currents within the bay.

Seasonal winds can generate nearshore currents capable of moving sand in shallow waters. Thus Gallop *et al*. (2010) and Gallop *et al.* (2012) note sea breeze induced currents of 0.3 – 0.7 m/sec restricted to the top 5 m of the water column. Such currents are insignificant in terms of sediment movements discussed in this paper. Sand movement in the bay is principally by wind-driven waves that impinge obliquely onto the beach face (Farhner & Pattiaratchi 1994) and thereby generate long-shore drift in the surf and swash zones immediately adjacent to the beaches.

SEABED FEATURES

LIDAR bathymetry reveals several seabed features that do not relate to present metocean conditions. These are described below in order of oldest to youngest, as deduced from interactive and superpositional relationships.

Palaeo-shorelines

Low-relief ridges around the 20–28 m isobaths, with arcuate geometries that mimic the current shoreline (Fig. 1), are interpreted as cemented Tamala-type calcarenite. They probably represent palaeo-shorelines formed during still stands related to various sub-stages of MIS 5, coinciding with the marine regression that led into the Last Glacial Maximum (Bufarale *et al.* 2019).

Submarine Palaeochannels

Low-relief palaeochannels on the seafloor extend west to at least the 28 m isobath (Eliot 2015). These align with the seaward extensions of the present-day Carbunup, Vasse and Capel rivers prior to their deflection by Holocene beach dunes (Fig. 1). They represent river channels that flowed across a wind plain during the Last Glacial Maximum. Modern sediment infill in the nearshore zone obscures parts of the palaeochannels (Bufarale *et al.* 2019).

Large oblique offshore sand ridges

Large linear sand ridges oblique to the shoreline are a characteristic feature of Geographe Bay (Fig. 2). On LIDAR bathymetric imagery, they extend as much as 6 km to water depths of 12 m, where they gradually diminish. The ridges have wavelengths of 1 to 1.5 km, and amplitudes of up to 5 m. Their axes trend WNW–ESE along the eastern arm of the bay, swinging to NNW–SSE in the western arm, thereby maintaining a constant 50° obliquity to the shore. LIDAR bathymetry indicates steeper side to the south, which implies growth by southward migration. Seemingly, the sand ridges formed from clockwise currents along the coast. However, the large sand ridges are now stationary. Geo-referenced ortho-rectified aerial photo mosaics (provided by DoT), dating back to 1959, show no lateral movement in the ridge axes and that current nearshore processes only disturb their nearshore tips.

Large sand ridges are out of place in the present microtidal, minimal-current coastal environment of Geographe Bay. Elsewhere in the world, strong tidal currents form similar large linear or curvilinear sand ridges, typically on inner-shelf platforms at depths of 20–40 m (Dronkers 2016). Their origin in Geographe Bay is enigmatic. Possibly, they formed by active bottom currents, seemingly initiated under surface currents associated with marine transgression after the Last Glacial Maximum and then re-shaped by bottom currents, in a similar manner to ridges on the Spitzbergen Shelf of the Barents Sea (Bellec *et al*. 2019). Off the Atlantic coast of the USA large oblique sand ridges formed as parallel offshore ridges during lower sea levels and grew shoreward at their down-current tips in response to southwest-directed storm currents during rising sea levels (Swift & Field 1981; Trowbridge 1995; Garnier 2006; Nnaffie 2014). The ridges exhibit landward-flank erosion where the current deviates seaward, allowing seaward-flank deposition when the current turns landward. The resulting toroidal current causes landward migration of the down-current tip, leaving an up-current trailing moribund ridge. Numerical modelling requires constant nearshore wave stirring and strong longshore currents of about 0.8 m/sec (Nnafie 2014). This process may have acted in Geographe Bay on the smaller, shore-attached oblique sandbars, in the nearshore zone, but is unlikely to apply to the large oblique ridges.

In terms of seabed morphology, the most likely analogue is the oblique linear sand ridges off the KwaZulu coast of South Africa, which are related to the southwest-directed Agulhas geostrophic current (Green *et al*. 2022). These ridges splay seaward off the coast, are asymmetric, possess internal cross-stratification, have rounded crests, and display evidence of down-current-over-riding of smaller bars by larger ones. Ridges migrate down current and grow in height due to amalgamation of smaller ridges. In Geographe Bay a constant supply of locally available sediment is needed to build such large ridges, so they possibly developed soon after the retreat from the Holocene highstand during a climatic phase dominated by strong northerly or north-northeasterly winds.

Small nearshore oblique sandbars

Pattiaratchi *et al*. (2017) have drawn attention to enigmatic nearshore, apparently shore-attached oblique sandbars between Busselton Jetty and Port Geographe. In contrast to the large ridges described above, these bars are restricted to the eastern arm of the bay, where they extend no more than 1.5 km seaward, are 200–400 m apart, have irregular wavelengths, amplitudes of 3–4 m and no seagrass. They lie at 30° to the beachline and swing gently

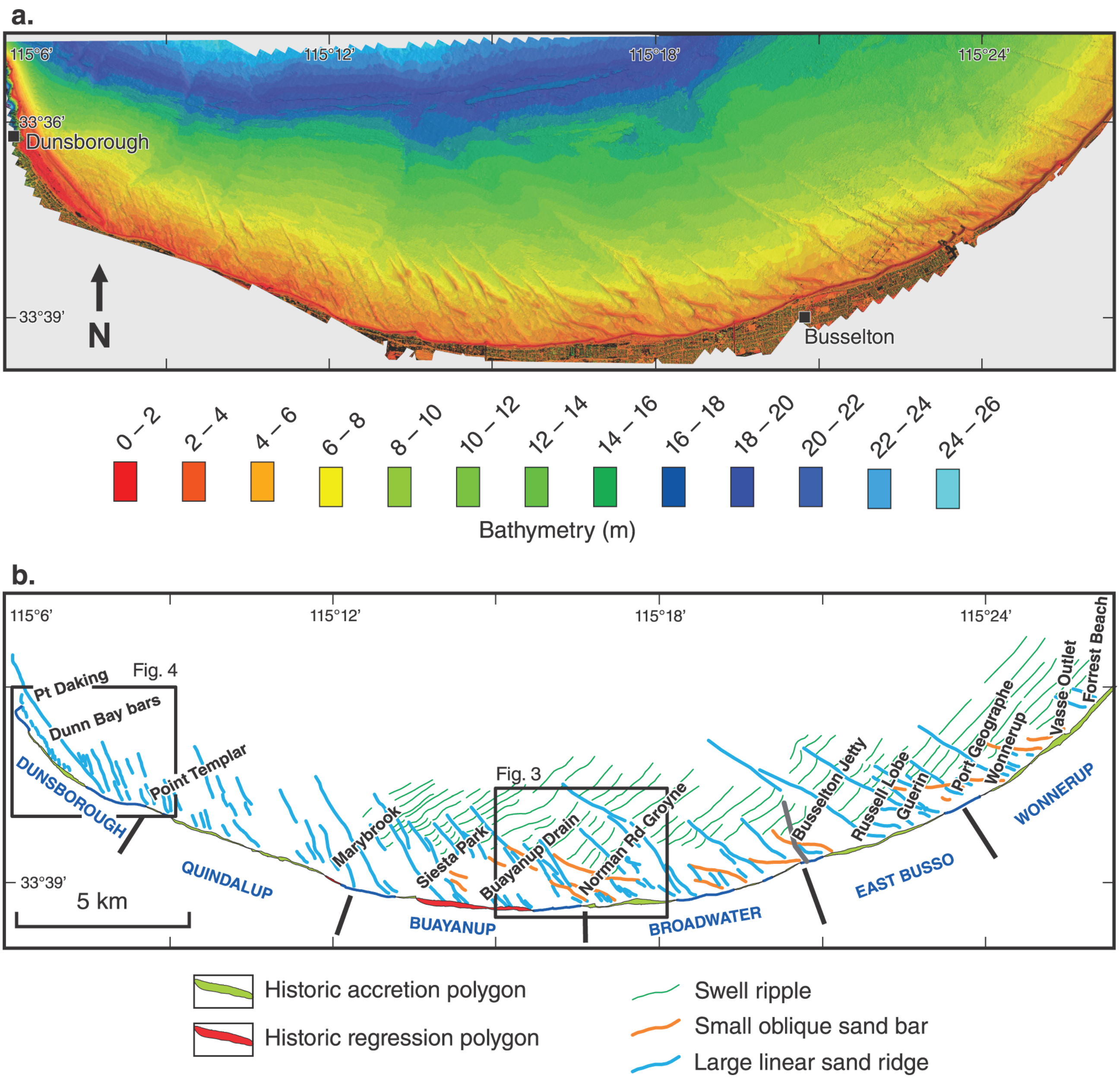

Figure 2. **a)** LIDAR image of area of study; **b)** Main morpho-dynamic seabed features of Geographe Bay; large linear sand ridges, (pink), small shore-attached oblique sandbars (orange), seafloor swell ripples (green), accretion polygons (green) and regression (red), showing beach sectors and localities mentioned in text, and the location of Figures 3 and 4.

with the curvature of the eastern arm of the bay. Thus, they point northeasterly in the direction of the littoral drift. Sense of asymmetry is equivocal, and difficult to determine from the bathymetry. Seismic profiles (Bufarale *et al*. 2019) suggest some may have northward asymmetry. Although they closely approach the shore, there is invariably a runnel between their nearshore tip and the shore. They overprint and modify the shoreward tips of the large linear ridges to form a complex interlaced network of bedforms (Figs 2b, 3). LIDAR bathymetry shows no evidence of lunate scours, or shore-parallel sandbars, reported by Searle & Logan (1978) and Riedel & Byrne Ltd (1989). Such supposed scours are better interpreted as part of a complex network of ridges and bars of different generations.

Historical aerial photographs and satellite imagery (dating back to 1941 and 1984, respectively) indicate no measurable change in the overall position of the sandbars although there is evidence that their shoreward tips have grown slightly. Thus, Rogers (2015, fig. 3.6) shows the immediate shoreward tip of a bar at Broadwater has grown down-current and turned shoreward in response to the development of a 1 km-long regression pocket following the construction of the Holgate groyne in 1999. Importantly, in Rogers (2015), the same figure shows no measurable movement on this specific sandbar. Thus, his often-quoted metric of down-current migration at 8.5 m/yr cannot be used to assert that these small oblique sandbars are still active.

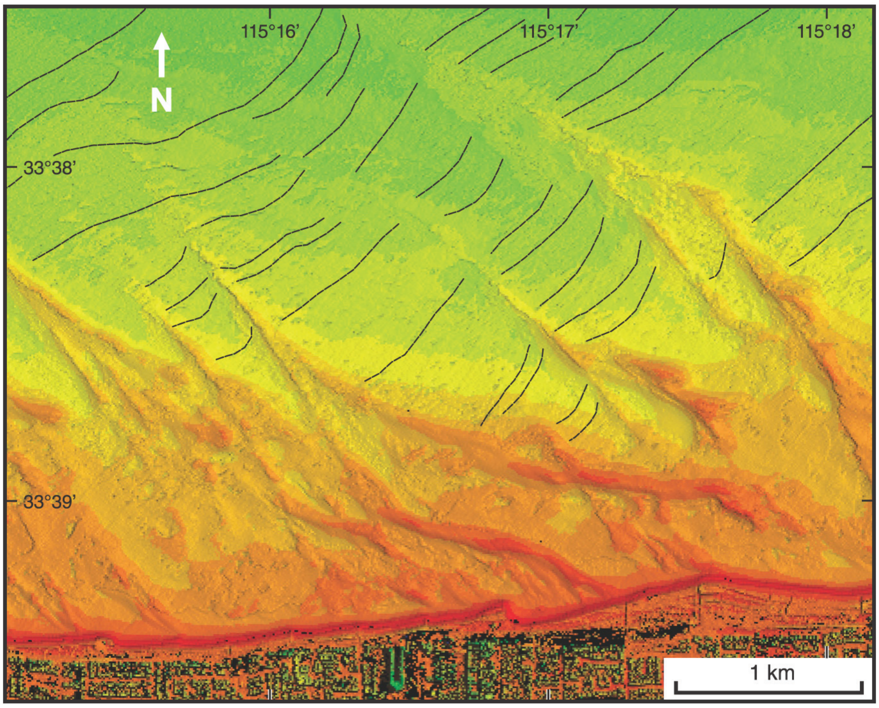

Figure 3. Bathymetric detail of small oblique sandbars superimposed on older sand ridges at boundary of eroding Buayanup (left) and accreting Broadwater (right) sectors at head of the bay. Note the asymmetry of linear ridges, and swell ripples (black) pushing shoreward between ridges. Location shown on Figure 2.

The toroidal dynamic model proposed by Trowbridge (1995) and numerically modelled by Garnier *et al*. (2006), may well apply to the modifications on the shoreward tips of the sandbars, but not to their original construction. Such small apparent shore-attached oblique sandbars in the bay appear to be inactive and not substantially eroding.

Seafloor swell ripples

An area of seabed ripples forms an arcuate field extending from the Carbunup palaeochannel, eastward to the Wonnerup palaeochannel (Fig. 2b and 3). The field is constrained between the 9 m and 6 m isobaths where it interacts with the nearshore sandbars. These features are evident as fine striations with spacing of 30–50 m, and amplitude of about 1 m on LIDAR bathymetry images. Shoreward, they refract at the leading tips of the large linear sand ridges (described above), and bulge into the swales between the ridges (Fig. 3). The general orientation of the axes and the restriction to a specific depth zone indicate these are oscillatory ripples related to refracted Southern Ocean swells as they pass around Cape Naturaliste and turn into Geographe Bay. Whereas Searle & Logan (1978), and several subsequent authors, propose this mechanism for the formation of sandbars in Geographe Bay, it is more likely that the sandbars and ridges are pre-existing features bearing no relationship to the theoretical or observational orientation of the swell-generated seafloor ripples.

Dunn Bay Sandbars

The most striking feature of the far-western part of Geographe Bay is the large composite sandbar in Dunn Bay (Fig. 2b and 4). Damara (2011) noted this is different to the other sandbars within the bay but provided no explanation of its origin. The bar contains two adjacent bare sandbars, separated by a 6 m deep swale covered by seagrass. Together they extend for over 4.6 km and are 0.7 km across. They shoal at low tide where they lie in waters of 6 m or shallower.

The outer bar is narrow and asymmetrical with a shallow seaward face and a steep landward face, implying the bar was built from the northeast. The seaward face possesses small lunate ripples, probably due to present-day storm currents. The inner bar is 'locked' within the curvature of Dunn Bay. It is broader and more irregular in shape, and its surface takes the form of a series of small, en echelon, curvilinear, nearshore oblique sandbars similar to those farther east. Offshore sandstone bars at Quindalup, just to the east of Dunn Bay, are probably composed of the Leederville Formation (Justin Parker, pers comm. 2020). Thus, the NW–SE banding, marked in Figure 4, is probably a sandstone pavement of that formation.

The Dunn Bay bars cover 2.5 km^2. Considering the bar and swale profiles, the average thickness is conservatively estimated at 5 m, giving a volume of over 12 million m^3 of sand in 'storage'. Although the oldest aerial photos for this area only go back to 1975 and cover only the southeastern half of the Dunn Bay bars, they are sufficient to show that the outer bar did not have measurable movement in the past four to five decades, either longitudinally or transversely. In contrast, the inner bar has moved seaward by over 100 m, along with an equivalent amount of beach accretion behind it, partially closing the swale.

Beach morphology

Geographe Bay possesses a typical wave-dominated, low-angle sandy beach with an average width of 40 m, as measured between mean sea level and the vegetation line at the base of the foredune system. It is dominantly

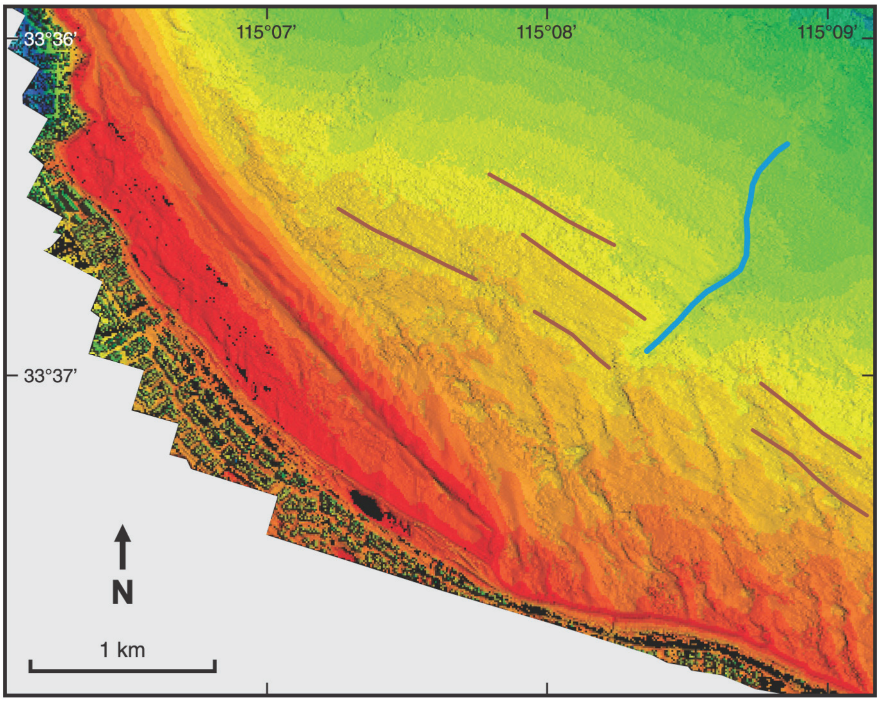

Figure 4. Detail of relict Dunn Bay sandbars at western end of Geographe Bay, showing stacking of relict sand ridges against bar; northwesterly features, interpreted to be Leederville Formation rock bars (brown), are cut by palaeochannel. Location shown on Figure 2.

composed of fine-grained spherical quartz grains, with lesser contribution from biogenic carbonate grains.

The beachline is characterised by lobes that bulge seaward for about 100 m from the adjacent smoothly scalloped embayments, with wavelengths of about 5 km (Fig. 6d). In this respect, they are not the common rhythmic cusps of wave-dominated beaches, nor do they relate to any natural or artificial hard feature. The spatial relationship between the lobes and the shoreward projection of the larger oblique offshore sand ridges points to the lobes accreting where they are protected from wave action by offshore sandbars, whereas the embayments are less protected. Wider tracts of beach, particularly the areas behind the lobes, have a wide berm (the flat surface above the beach face), which displays incipient lines of foredunes, indicative of an overall beach accretion. Thus, the position of the offshore bars and ridges determines that of the lobes, not the reverse.

HISTORIC BEACH CHANGES OF GEOGRAPHE BAY

The Coastal Infrastructure Section of DoT provides data that enables the tracking of coastal movement by way of a series of ortho-rectified aerial photos for the years: 1941, 1964, 1965, 1974, 1975, 1980, 1982, 1985, 1986, 1993, 1996, 2009, 2014, 2016. Some of this imagery is available via the Shared Location Information Platform. From these data the following lines of various ages have been extracted into MapInfo GIS:

- Vegetation line - essentially marking the back of the beach berm.
- Australian Height Datum (AHD) 0 m line – mean sea level for all years, except 1941.
- Natural water line – water line at time of photograph.

Historic changes in beach aspect were analysed using the concept of sediment cells, i.e. spatially discrete areas of the coast within which marine and terrestrial landforms are likely to be connected through processes of sediment exchange (Stul *et al*. 2012). These processes require sediment supply (source), sediment loss (sink), and linking transport pathways, which can include both along-shore and cross-shore processes. Cells provide the framework for a sediment budget.

The usefulness of sediments cells is somewhat limited as they do not account for long-term changes in sediment behaviour related to palaeoclimate, effects of which are evident in Geographe Bay. Nevertheless, they provide a convenient framework for analysis and description. Accordingly, the bay was analyzed along six shoreline sectors (Fig. 2b), which correspond closely to the tertiary sediment cells of Gozzard (2011). To provide relevance to local issues relating to Port Geographe, his Busselton to Wonnerup Cell is divided into two sectors. From west to east the cells are:

1. **Dunsborough** – Point Darkling (rocky headland) to Point Templar.
2. **Quindalup** – Templar lobe to Marybrook (Carbunup River Drain).
3. **Buayanup** – Marybrook to Norman Road groyne.
4. **Broadwater** – Norman Road groyne to Busselton Jetty.
5. **East Busso** Busselton Jetty to Port Geographe.
6. **Wonnerup** – Port Geographe to Forrest Beach.

Historical beach areas

Historical changes in beach areas, defined as lying between the edge of vegetation and the 0 m AHD datum, were examined from images spanning 51 years. The oldest dataset is for 1965, which can be compared directly with equivalent imagery for 2016. Whereas there is a 1941 vegetation line, there is no AHD for 1941. Although a 1941 waterline is mappable from the aerial photos, the tide elevation at the time of their acquisition is unknown. The respective beach boundaries for 1965 and 2016 were digitized across the six sectors, from Point Darkling in the west, to the northern extent of the Wonnerup lagoons, 10 km north of the Vasse River outlet.

No significant change in beach area is evident for the last 51 years. The small reduction in the Dunsborough sector (0.07 km^2; Table 1) is due to installed revetments, seawalls and boat ramps, plus accelerated dune rehabilitation. This preservation indicates the beaches are in dynamic equilibrium with the current geomorphic and metocean elements. Such equilibrium does not imply that beaches are stationary—they have moved significantly in most areas.

Beach accretion

Beach movement is analysed by comparing 1941 vegetation lines (from the earliest available rectified aerial photographs) and 2018 vegetation lines (from Google Earth) in the complete arc from Point Daking to Wonnerup Lagoons (Fig. 2b). Where the 2018 vegetation line is seaward of the 1941 line there has been accretion, and where landward of the 1941 line, there has been regression/erosion.

The two timelines mostly track together and sinuously interweave. Their interconnection defines the deviation polygons shown in Figure 2b. The green polygons indicate accretion and the red polygons regression. Polygons smaller than 20 × 400 m are considered insignificant and therefore not displayed in Fig. 2b).

The greatest accretion is in the east, notably along the Broadwater, East Busso and Wonnerup sectors, which total 863,360 m^2. There is also substantial accretion in the Dunsborough and Quindalup sectors in the west, totaling 388,070 m^2. The only significant regression is within Buayanup sector east of Siesta Park groyne where the main polygon indicates the loss of 350,600 m^2. The estimate for net accretion across Geographe Bay over 77 years is 866,210 m^2 (Table 2). In detail, the largest accretion is in lobes of new sand, but significant accretion is also evident on the intervening scalloped embayments. Lobes show growth lines marked by incipient vegetation, which become the next generation of foredunes along the coast.

Table 2. Mass accretions and losses Geographe Bay Beaches in 77 years. Note: GIS derived values are not rounded, stated precision not implied.

	m^3	Thickness	m^3	m^3/year
Western sectors	388,070	6.5	2,522,455	32,759
Buayanup central	-350,600	3.5	-1,227,100	-15,936
Eastern sectors	863,360	7.5	6,475,200	84,094
Net Totals	866,210		7,544,517	100,096

The accretionary lobes and beach berms in the eastern sectors reach 3.5 m ASL, and are assumed (Damara 2011) to lie on a 4-m thick mobile substrate, giving an accretionary prism 7.5 m thick (volumes estimates in Table 2). For the western sectors, a marginally thinner prism seemingly reflects lower energy accretion. The eroded prism at Buayanup is assumed to be similarly thin, or thinner. Net sand accumulation for Geographe Bay is about 7,545,000 m^3 over 77 years, implying a net annual addition of around 100,000 m^3 (Table 2). This accords with the estimate by Damara (2011) using a non-polygonal method.

Rates of Accretion

Linear measures of seaward accretion for representative sections (Table 3) include the Buayanup regression polygon for reference. Growth curves (Fig. 5) show accretion is progressive, quasi-linear, with no evidence of cyclic accretion and regression. Cyclone Alby in 1978 left ephemeral dips in the Guerin and Russell sections. Small sections of artificial recession related to engineered structures are not included in this analysis. An example is a small pocket of starvation immediately east of Port Geographe revetment in an otherwise accreting coast. The shoreline in this pocket is still seaward of the 1941 position.

Table 3. Seaward movement of accretionary lobes

Sector	Feature	Distance m
Dunnsborough	Dunnn Bay Beach	120
Quindalup	Templar Point lobe	72
Buayanup	**Siesta Park regression**	**-150**
Broadwater	Maryilla lobe	120
East Busso	Russell St lobe	82
Wonnerup	Baudin lobe	107
	Vasse River lobe	170

Table 1. Comparison of beach areas (in m^2) between 1965 and 2016.

Sector	From	To	1965 Beach Area M^2	2016 Beach area M^2
Dunsborough	Point Daking	Pt Templar	116,100	185,600
Quindalup	Pt Templar	Marybrook	224,100	221,000
Buayanup	Marybrook	Norman Rd groyne	215,840	171,330
Broadwater	Norman Rd groyne	Busselton Jetty	357,760	270,350
East Busso	Busselton Jetty	Port Geographe	157,800	235,100
Wonnerup	Port Geographe	Wonnerup Lagoons	245,890	163,850
Totals (m^2)			**1,317,490**	**1,247,230**

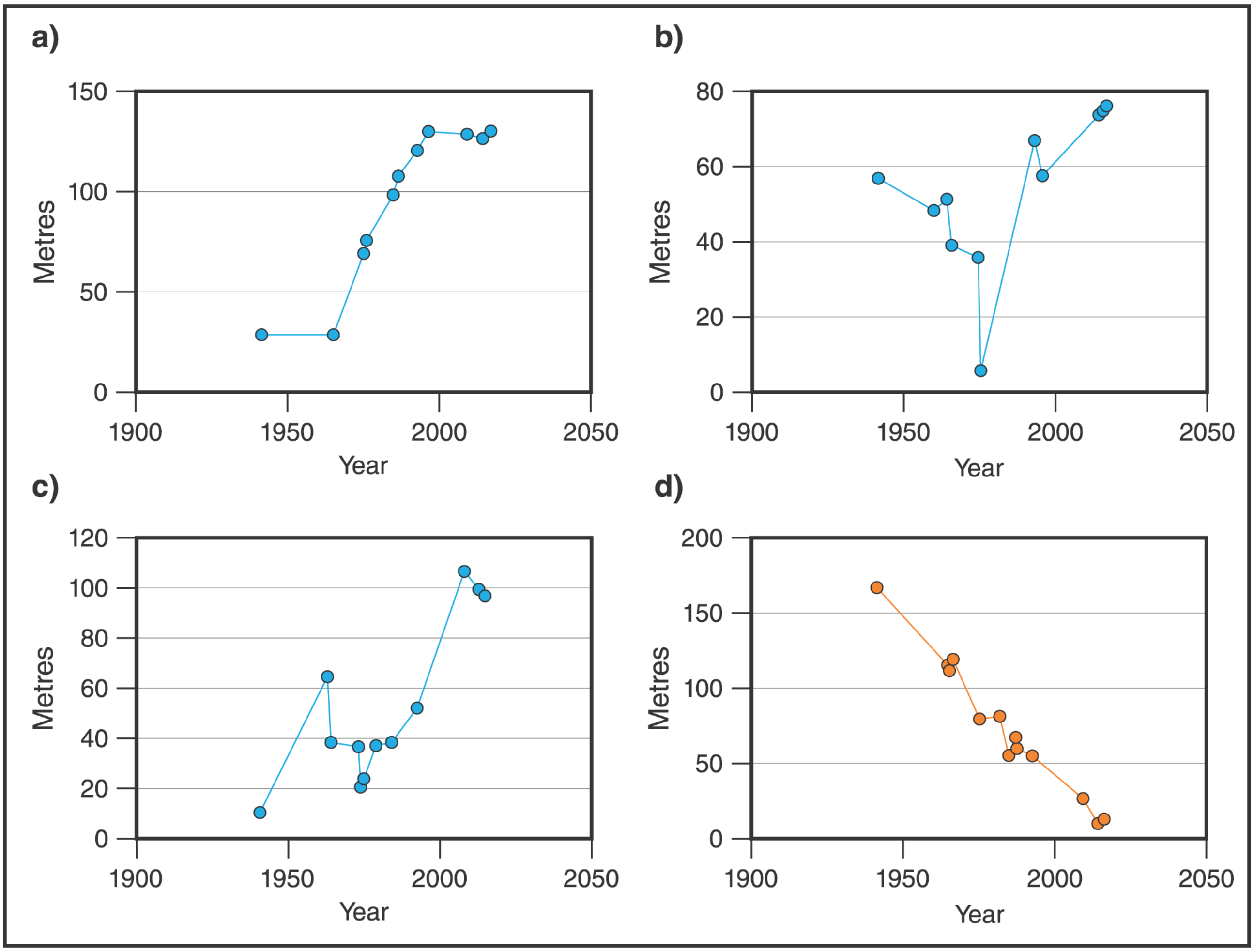

Figure 5. Time series graphs of historic vegetated beachlines extracted from the SLIP Website, showing rates of progressive accretion at representative sites: **a)** Wonnerup at Vasse River outlet; **b)** Guerin Street; **c)** Russell Street lobe; and **d)** Buayanup.

Buayanup regression

The Buayanup sector contains the only natural regression polygon along the entire bay. It covers 350,600 m^2 along 3.3 km, and records a landward retreat of 150 m since 1941. Although this erosion is locally significant, it has only made a minor contribution to the sediment budget (Table 2). The regression polygon starts at the 130 m-long Siesta Park groyne, which was installed in 1960, ostensibly to prevent erosion. West of the groyne an accretion wedge contributes to localized sediment starvation immediately down-drift of the groyne. The Buayanup recession curve (Fig. 5d), 1 km east of the groyne, shows a remarkable linear regression of 1.8 m/yr, and presumably is ongoing.

A popular belief is that the Siesta groyne is responsible for erosion. This can only apply to the small pocket against the groyne, but not the regression polygon. Erosion at this location is likely related to present metocean conditions. Offshore bathymetric features (Fig. 3) are no different in this sector to any other part of the bay. Damara (2011) observed that this sector, being at the head of the bay, receives full frontal amplification of northwesterly storms. Regression in this part of the bay is a natural part of its progressive evolution.

LITTORAL DRIFT IN GEOGRAPHE BAY

Wind-driven waves provide the principal mechanism of sand movement around the bay. Individual grains move obliquely up the beach face by obliquely impinging waves, and rill orthogonally down the beach face. Thus, sand migrates down-wind. Littoral drift adds no sediment to the total system and may lose material if blown into the foredunes. Asymmetry of accretionary lobes and intertidal micro-deltas at drain outlets provide vectors and quantitative measurement of flux where they build against artificial groynes.

Drift indicators along the western arm of the bay are subtle. Micro-deltas at the outlets of river drains, together with sand built up against the old wooden groynes in the Buayanup and Quindalup sectors indicate east-to-west movement. Asymmetry of the Templar accretionary lobe in the Quindalup sector indicates a similar sustained movement. Westerly littoral drift in the western arm relates to the easterly component of the present-day bimodal wind pattern.

East of the Buayanup sector, vectors are consistently to the east. The elbow against the western groyne of Port Geographe has accreted 110 m since its reconfiguration in 2015. Asymmetry of the Russell Street accretionary lobe, which shows seaward growth of 82 m, indicates sustained easterly movement. Easterly littoral drift relates to the southwest component of the present-day bimodal wind pattern.

SEDIMENT BUDGET

Using sand built up against artificial structures, Damara (2011) estimated a sediment flux of 25,000 – 35,000 km^3/yr at west Busselton. Reidel & Byrne (1989) estimated 40,000 m^3/yr at Busselton Jetty and 50,000 m^3/yr at Port Geographe, which suggests that the sand-flux increases down drift. In constructing a sediment budget, the annual eastern-arm flux is taken as 35,000 m^3/yr.

The western-arm flux is not easily quantified, but a reasonable assumption can be made by comparing the dimensions of the two arms, and the strengths of the respective driving winds. Thus, a western flux of 20% of the eastern flux, i.e. about 7,000 m^3/yr is assumed. The combined flux is therefore 42,000 m^3/yr, which together with the net amount of annual accretion (100,000 m^3/yr) infers that 142,000 m^3 is being added to the entire system each year. This large volume raises the question of where this sediment is coming from.

Input from rivers that drain into the bay is miniscule. Constructed polygons (summarized in Table 2) show that natural erosion at the head of the bay can only provide about 15% of the required amount. Searle & Logan (1978) suggested that wave fronts from Southern Ocean swells refracting around Cape Naturaliste to reach the beaches align with nearshore scour-and-fill structures within the bay and are responsible for sediment input. However, that study pre-dated modern bathymetric data and lacked estimates of the magnitude of the required sediment. It is now evident that the sediment movement by refracted ocean waves is limited to seabed micro-ripples.

Sand distribution patterns and stability of nearshore bars are evidence against the contribution of sand around Cape Naturaliste to accumulate in Dunn Bay. Moreover, waters off Cape Naturaliste are too deep (>40 m) to

Figure 6. Aerial images along Geographe Bay: **a)** accreting beach encroaching onto relict sand ridges, Russel Street lobe. Thinly vegetated strip behind beach marks accretionary growth; **b)** relict linear sand ridge at Busselton Jetty; historic records show no migration. Dark area is seagrass meadow; **c)** sand starvation at Broadwater groyne has returned the beachline back to its 1960s position; oblique sandbar has not migrated in historic time; and **d)** lobes and sand-ridges on western arm of Geographe Bay looking east; back-beach lagoon is in the swale between dual ridges of Quindalup Dunes (Photographs by Ron Jensen, Dec 2021).

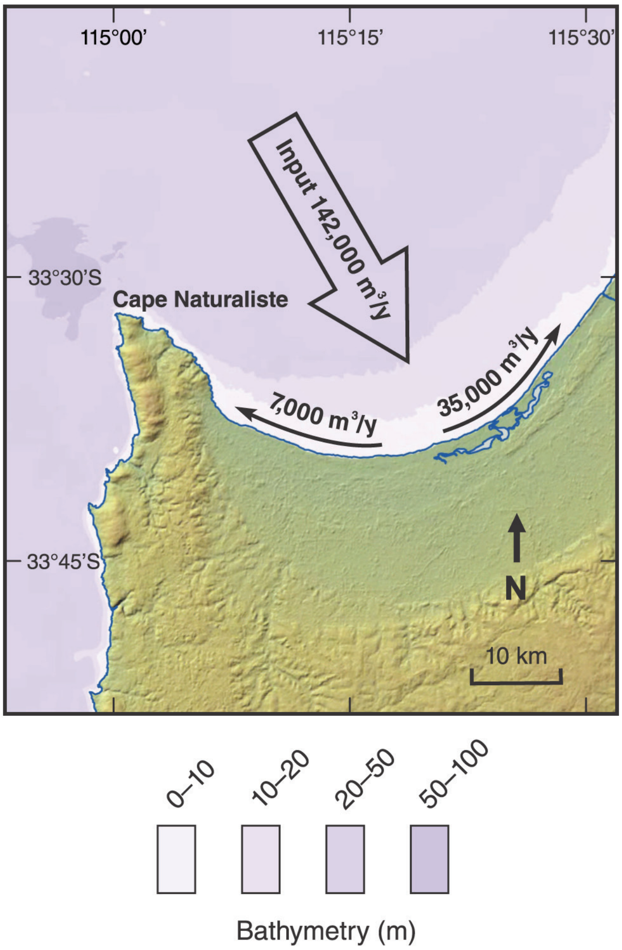

Figure 7. Model of sediment sources, pathways and sinks. The difference between input and dispersal is the amount sequestered by accretion (100,000 m^3/y).

allow seabed sand transport. Dunn Bay bars presumably were built up by sediment overwash within the bay, but present-day metocean conditions are insufficient to do this. Dunn Bay is a sediment sink, and not a source for contemporary accretion, as proposed by Barr & Eliot (2011). Thus, the Dunn Bay bars represent relicts of a past climate. The volume in storage (12×10^6 m^3) and the assumed flux (7,000 m^3/y) suggest Dun Bay bars took about 2,000 years to accumulate, commencing soon after 3770 yrs BP, when sea-level recession from the Holocene highstand reached its present position.

Damara (2011) recognised an onshore sand flux, albeit understated, and assumed offshore sandbars were the source. In the absence of detailed bathymetric data over many decades, his assumption is difficult to susteain, but the stationary nature of the ridges and bars indicates this is unlikely. The large oblique sand ridges are stationary as they are now stabilized by sea grass, and so are interpreted as relics of a past climate. They are active only at their innermost tips, where consumed by the accreting shoreline. Similarly, small oblique sandbars show no sense of movement, and they have maintained their positions and gross morphology over many decades. In the surf zone, they are remolded rather than migrated. Their remarkable persistence for over 60 years indicates they cannot be a source of accretionary sand.

Seabed data within Geographe Bay, collected as part of the post-glacial sampling program of the southern Rottnest platform, does not include detailed mineralogy, which could help determine the provenance of this sediment. Data from samples collected by Collins (1983) and Carrigny (1956) has been collated in the Geoscience Australia Marine Sediments (MARS) Database (http://dbforms.ga.gov.au/pls/www/npm.mars.search). Samples from depths down to 30 m are predominantly well-sorted quartz sand (with <30% $CaCO_3$) of 0.45 mm to 0.8 mm diameter, with an average of 0.64 mm. Similarly, the 'loose Holocene layer' Bufarale (2019) encountered at depths around 10 m contains 60–90% medium-grained quartz of medium sphericity. Significantly, some sampling sites failed as they encountered hard surfaces indicating local stripping of the loose sand from the seabed.

DISCUSSION

In terms of geomorphological evolution, the formation of large oblique linear ridges marked the beginning of a substantial ingress of sand into the bay, after it had achieved its present shape and position, some 7,000 years ago. It is notable that the larger ridges form clusters around the positions of the palaeo-outlets of the ancestral Capel and Vasse rivers. Alluvial fans and marine deltas related to these rivers could be the source of the sediment in these ridges.

Considering their size, shape and position, the large ridges would have required strong prevailing northeast winds to form. For southwestern Australia, such wind direction is associated to anti-cyclonic high-pressure cells on the continental interior but, in the present-day climate, these winds are not strong enough to generate such significant features. However, at the termination of the Last Glacial Maximum, intense anti-cyclonic cells operated over western continental Australia, as shown by the quasi-circular pattern of longitudinal desert dunes, dated by optically stimulated luminescence methods at 45,000–17,000 yr BP (Rhodes *et al.* 2004). Such intense anticyclonic winds may have persisted through the Holocene when the marine transgression reached the position of the present coast at about 7,500 yr BP. At that time, the Leeuwin Current was operating (Collins *et al.* 1991) as probably also was the counter north-flowing Capes Current, closer to Cape Naturaliste. The Capes Current, combined with strong anti-cyclonic winds, could have generated a clockwise gyre of sufficient strength to form the large sand ridges around the bay, and to build the Dunn Bay bars.

The formation of the smaller nearshore oblique sandbars with east–west axes that overprint the large sand ridges probably signals a moderating shift to more northerly prevailing winds, and possibly the advent of direct storm influence. Thereafter, the bay became a sink for introduced sand. It is likely that seasonal storms brought in the bulk of present-day sand. The highest intensity modern storms are from the north-northwest, down the axis of the bay. Geographe Bay experiences 5 to 15 such events per year, with storm-wave amplitudes averaging 3.3 m and peaking at 5 m (Damara 2011). Waves of this magnitude have a wave base of 15–20m, sufficient to move sand landwards from beyond the seagrass meadows.

The large volumes of sand stripped from the Leederville Formation through the Cenozoic have provided an almost inexhaustible source of sand on the inner continental shelf off Geographe Bay. This process may have operated for at least the last 2,000 years. Seasonal winds then generated along-shore dispersal pathways. The major pathway is northeasterly along the eastern arm of the bay, driven by the southwesterly tails of winter storms and summer sea breezes. A minor pathway is northwesterly along the western arm, driven by easterly winds. The large volume of sediment entering the system is much more than long-shore littoral drift can disperse, thereby accounting for the extensive accretion around the bay.

CONCLUSIONS

The beachline along Geographe Bay is rapidly accreting due to the influx of large amounts of sand, estimated at 142,000 m^3/yr. Accretion is progressive and not cyclic. Some sectors of the coast have advanced as much as 170 m seawards since the 1940s. Only a small sector 3 km in length at the head of the bay is subject to natural erosion. Pockets of sand depletion adjacent to engineered groynes and revetments are of local concern, but do not signify a fragile coast, which overall is robust.

Accreting sediment comes from the mobile sand layer on the inner continental shelf that accumulated during lower sea levels associated with global Pleistocene glacial cycles, rather than from eroding offshore sandbars, as is commonly thought. The offshore ridges and bars show no evidence of migration over the last six to eight decades. The large offshore linear, oblique ridges pre-date present metocean conditions, and are interpreted as submarine migrating sand ridges formed by a clockwise gyre in the bay related to strong anti-cyclonic winds at the beginning of the present interglacial, about 7,000 years ago. Landward tips of the large ridges are being disturbed by the advancing beaches. This disturbance may provide minor sediment feed for the development of nearshore oblique sandbars that are effectively stationary.

Geographe Bay is a large sediment sink, and possibly has been so for the last 5,000 years. Sediment dynamics is best interpreted in terms of evolutionary sequences related to palaeoclimatic conditions, rather than attempting to fit bed forms into present-day metocean conditions. It is not an intention of this study to make recommendations on coastal management by geo-engineering actions; however, such actions need to take into account the geological interpretations of this study, which imply doubtful benefits in the installation of groynes and sunken seawalls in stable sectors of the beachline.

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