Landscape evolution and Cenozoic sea-levels of the Geographe Bay hinterland, southwestern Australia

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Abstract

The Busselton area in southwestern Australia is characterised by three distinct coastal plains along the foot of Whicher Range that formed mainly by marine attrition during progressive sea-level falls through the Cenozoic and, to a lesser extent, erosion by long-lived rivers. None of the geological and geomorphic units, all of which overlie the Lower Cretaceous Leederville Formation, show evidence of tectonic tilting so, in the absence of masking dune systems, this area offers a reference for Cenozoic global sea levels.

The oldest landform, a marine erosional surface at 112–166 m ASL on Whicher Range, is a remnant of the Blackwood Plateau capped by in situ laterite of likely Eocene age. The Whicher Scarp, with relief of about 120 m, formed by marine erosion removing much of the Leederville Formation during a progressive Eocene–Miocene sea-level fall (~43–13 Ma). At 72–83 m ASL, the Yelverton Bench represents a probable Miocene stillstand during this fall. The scarp below this bench is characterised by a piedmont laterite lithologically and spatially distinct from the older plateau laterite on Whicher Range. The toe-line at 41 m ASL marks the base of the Whicher Scarp and the beginning of the coastal plains—it represents the geomorphic expression of a buried Pliocene (~2.8 Ma) erosional surface at 29 m ASL.

At 21–41 m ASL, the Ambergate Plain is a terrestrially re-sedimented marine erosion surface covered by continuous strand facies of the upper Pliocene Yoganup Formation, which in turn is overlain by lateritized clay that may correlate with the Pliocene–Pleistocene Guildford Formation. The main heavy-mineral strands formed as ancestral shorelines and are embedded within the Yoganup Formation across the entire Ambergate Plain. The Cemetery Scarp, with a relief of 11 m and associated erosion surface at 5 m ASL, cuts into the Ambergate Plain and probably formed during an early Pleistocene interglacial highstand, possibly MIS 11 (~400 ka).

The Ludlow Plain at 3–5 m ASL is covered by low eolian swales and ridges of shelly calcareous sand up to 6 m thick containing coral fragments of possible MIS 5e (~124 ka) age attributed to the Tamala Limestone, which marks the beginning of marine platform carbonate production. The Busselton Wetland Plain was formed during a gentle recession after the Holocene highstand at 7.5 ka following the last glacial maximum and is recognised from a low scarp on the seaward edge of the Ludlow Plain. Although the Capel River has a history spanning the last 30–40 Ma, most rivers draining the scarp postdate the Pliocene. The build-up of barrier beach dunes during the last 7500 years next to the present coast has diverted rivers on the Wetland Plain and forced outlets to Geographe Bay to migrate laterally. Lateritization was episodic, principally in the Eocene, Miocene and Pliocene, but after the deposition of the Guildford Formation, did not extend through the Pleistocene or Holocene.

KEYWORDS: ancestral shorelines, Holocene highstand, laterite, Yoganup Formation, Guildford Formation, heavy-mineral strands, Tamala Limestone, Whicher Scarp, river diversion

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INTRODUCTION

The coastal plains and hinterland adjacent to Geographe Bay have long been known for their arcuate geomorphic features that mimic the present shape of the bay and are related to Cenozoic strandlines. However, their sedimentology and geospatial relationships have previously only been documented and interpreted in a perfunctory manner. This paper examines the evolution of these landforms between the Capel River and the western granitic shoreline beyond Dunsborough in relation to changing sea level, erosion, sedimentation, lateritization and drainage development based on new detailed geological mapping. The study area (Fig. 1) extends across the southern extension of the Swan Coastal Plain and over the Whicher Scarp to include remnants of the Blackwood Plateau. The southern boundary is the drainage divide between north-flowing rivers (Capel, Ludlow, Sabina, Abba, Vasse, Buayannup) and the south and west draining Blackwood and Margaret systems.

Although some high-latitude coastal areas around the globe show signs of uplift due to isostatic compensations

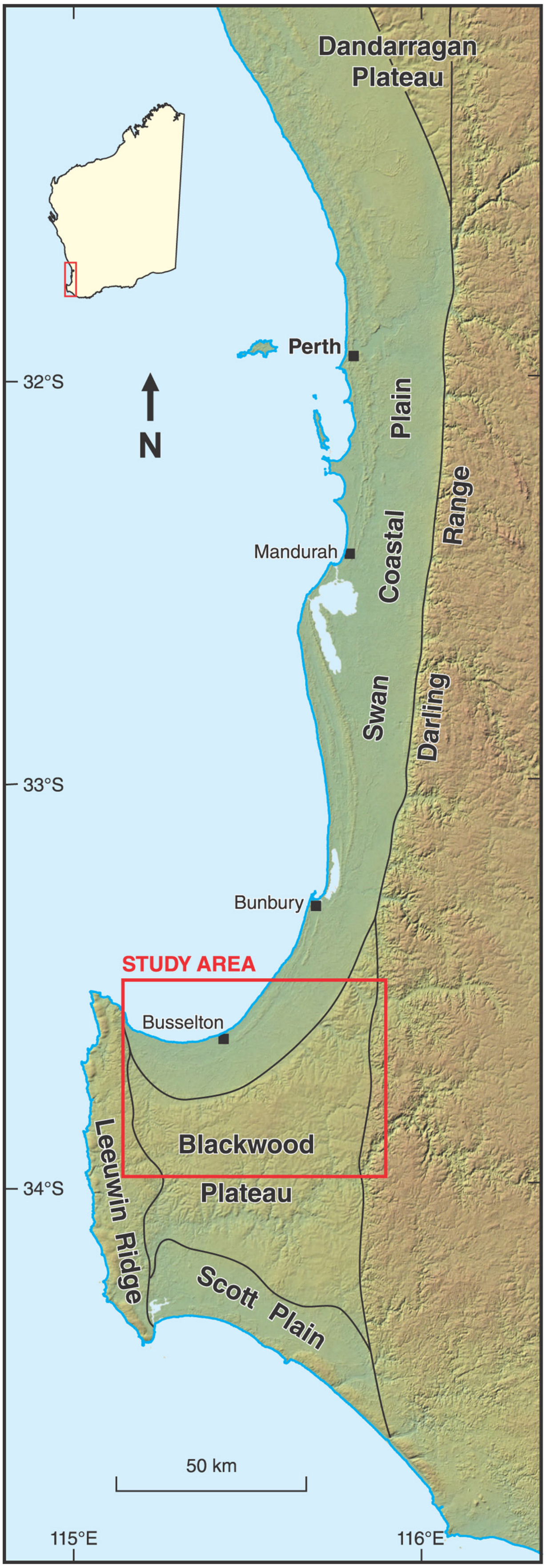


Figure 1. Location of study area in relation to major geomorphic elements of southwest Western Australia.

from Pleistocene ice sheets, the southwest of Western Australia has been relatively tectonically stable. Measurements of Whitney & Hengesh (2015) indicate this stability extends north along the coast for about 1000 km to Cape Cuvier and Cape Range where there is evidence of Cenozoic tectonism and uplift (Mylroie *et al*. 2017). This regional stability allows the southern onshore geomorphic features to be dated from global sea level curves, especially as these have become increasingly precise in terms of age and elevation over the last two decades, and forms the basis of the chronostratigraphic framework of this study (Fig. 2). These factors make the Geographe Bay hinterland, with its minimal dissection and absence of extensive inland dune systems, an ideal area to study Cenozoic geomorphic systems.

Some of the ancestral strandline deposits contain economic accumulations of heavy-mineral sands, predominantly ilmenite, which have been exploited for over 60 years. Although these buried deposits have minimal surface expression, they and other geomorphic features in the area have been related to Cenozoic sea levels (e.g. Fairbridge 1961; Baxter 1977, fig. 6). Such strands have colloquially been referred to as 'shorelines'. However, these geomorphic features are not simply residual surficial accumulations abandoned on a progressively receding marine erosional surface, and do not necessarily represent the true sea level at the time of deposition. It is therefore necessary to distinguish between the geomorphic expressions of ancestral shoreline features and erosional surfaces formed by sea-level changes.

Interpreting the landscape evolution of the region incorporated: a) detailed mapping compiled into MapInfo-Discover GIS with b) elevation information from a 30 m-pixel Shuttle Radar Topography Mission digital surface model (DSM), and c) voluminous open-file mineral exploration drilling data available via WAMEX (https://dmp.wa.gov.au/WAMEX-Minerals-Exploration-1476.aspx) of the Geological Survey of Western Australia. The revised geological map of the study area is shown in Figure 3.

REGIONAL GEOLOGICAL SETTING

The hinterland of Geographe Bay extends from the Archean Yilgarn Craton along the Darling Range, across the Darling Fault and its associated scarp, and westwards over Cretaceous strata of the southern Perth Basin to the Proterozoic granitic complex of the Leeuwin Ridge. The Cenozoic features of this study largely overlie the Lower Cretaceous Leederville Formation of the Perth Basin between the Proterozoic and Archean basement highs.

Throughout most of the Phanerozoic, Western Australia was a passive continental margin with rifting events in the Permian to Early Cretaceous. Following the final separation of Greater India from Australia in the Valanginian, siliciclastic and carbonate shelfs prograded across the erosional breakup unconformities to form the present continental shelf, whereas onshore the western part of the continent was largely subjected to fluvial and associated chemical processes apart from near the present coast.

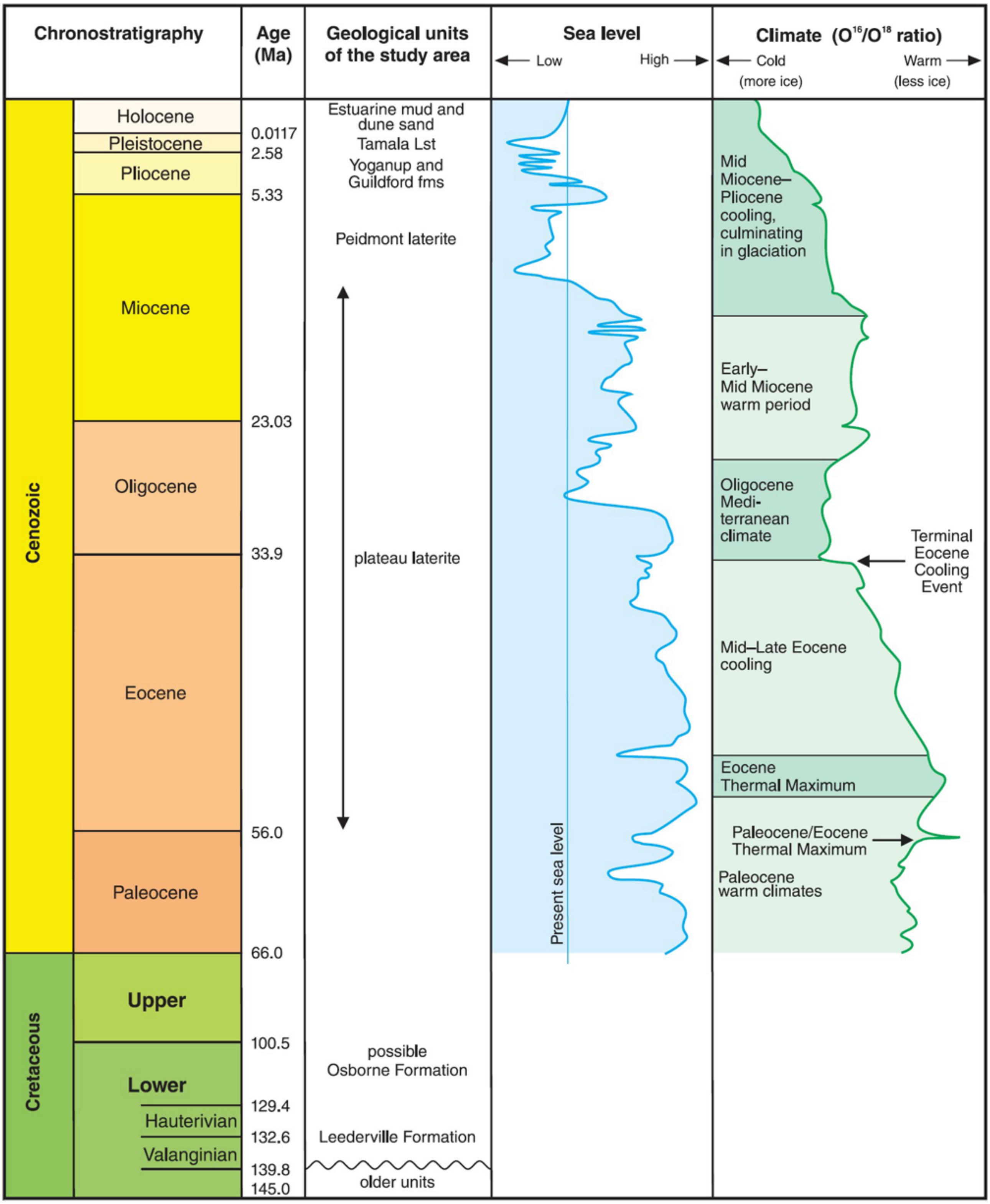


Figure 2. Chronostratigraphic framework for the study area; sea-level curve and climate intervals adapted from Słodkowski *et al*. (2013) and Miller *et al*. (2020).

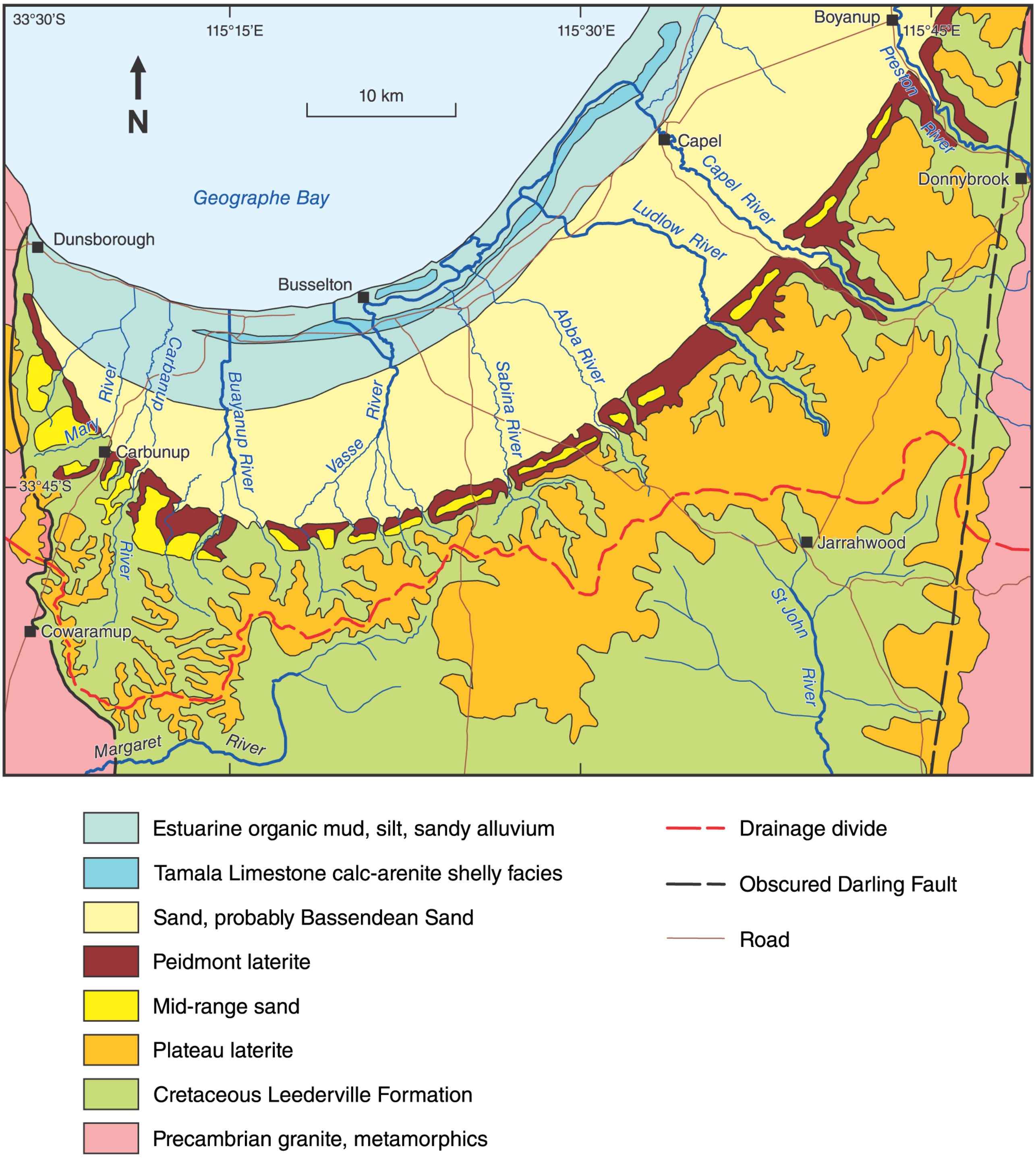


Figure 3. Revised geological map of the study area.

Leederville Formation

The Leederville Formation (Cockbain & Playford 1973) directly underlies all contemporary landforms from Geographe Bay to Whicher Range. This extensive sandstone-dominated unit is about 140 m thick (Thomas 2018), of Early Cretaceous (Hauterivian–Aptian; ~132–113 Ma) age and together with the overlying Osborne Formation, records the final fill of the southern Perth Basin. It was deposited in a shallow marine-to-fluvial environment, and unconformably onlaps Precambrian basement rocks along the Darling Scarp to the east and the Leeuwin Ridge to the west (Lowry 1967).

The base of the Leederville Formation onlaps the Valanginian (136 Ma) breakup unconformity at the onset of sag-phase tectonics followed by the separation of Australia from Antarctica along the western and southern margins of the continent (Norvick 2004; White *et al*. 2013). Mild post-breakup tilting due to uplift along the southern margin of the continent (Sandiford 2007; Dicaprio *et al*. 2009; Cockbain 2014) probably was the last significant tectonic event to affect the area and initiated the Cenozoic geomorphic evolution of the study area. Tilting can be measured from the relative levels of internal stratigraphic markers within the Leederville Formation. The Upper Mowen Member of the Leederville Formation (Schaffer *et al*. 2008, fig. 5) indicates a regional dip of 0.13° to the north. This interpretation is consistent with glauconitic siltstone at shallow depths in water bores in the Busselton area (Passmore 1962; Hirschberg 1989)—this likely to be the Osborne Formation, which lies stratigraphically above the Leederville Formation.

Despite being extensive, outcrop of the Leederville Formation is rare and typically consists of saprolitic grey clayey sand. In the subsurface the unit is a medium-grained sub-arkose with subangular to subrounded monocrystalline quartz grains, up to 40% of angular K-feldspar grains and up to 2% pyrite (Descourvieres *et al*. 2011). There is no quartz or carbonate cement and compaction is minimal. In a 5 m-thick section in the walls of a 'refuge' dug into the lower part of the Whicher Scarp off Palmer Road (115.5070°E 33.7257°S) the unit is thickly bedded, with internal gritty lenses and rip-up shale clasts between cross beds (Fig. 4).

The lithological features make it susceptible to weathering, lateritization and erosion, thus becoming a prime source of sand for post-Cretaceous sedimentation. It is the likely source of the ilmenite strands on the coastal plains (Collins & Baxter 1984), a proposition supported by ore-grade concentrations in the Leederville Formation in the Carbunup area (Johnson 2004).

GEOMORPHIC UNITS

Geomorphic elements of the study area (Fig. 5) are underpinned by the revised geology, and include several newly defined elements in this paper. As yet, there are few precise Cenozoic age determinations within the study area. Attribution of age depends on regional correlation with global sea-level curves and established climatic events through the Cenozoic based on chronometric benthic $\delta^{18}O$ temperature data, ice-volume calculations, adjustments for glacial isostatic uplift, back-stripping of paralic sediments and ocean-basin dynamic changes (Dutton *et al.* 2015, Miller *et al*. 2020). The Pleistocene glacial and interglacial events and associated sea-level models are increasingly tied to accurate elevations and precise age dating at well-studied geological sites (Rovere *et al*. 2014, Dutton *et al*. 2015, Miller *et al*. 2020). The traditional Exxon curve still has chronological value, albeit imprecise, for sea levels in older geological epochs, although amplitudes relative to present sea level may be overstated (Miller *et al*. 2020).

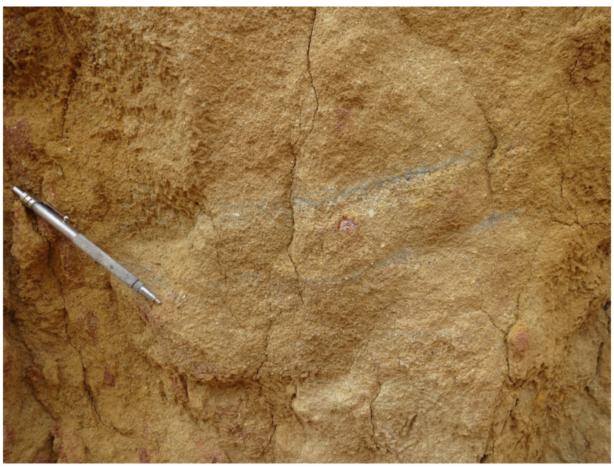


Figure 4. Leederville Formation exposed at Palmer Road 'refuge' (115.5070°E, 33.7257°S) showing diffuse coarse cross bedding, granule lenses and shale intraclasts.

Blackwood Plateau

The term Blackwood Plateau was invoked by Playford *et al*. (1976) for the uplands between indurated Archaean rocks of the Darling Plateau at 230 m above sea level (ASL) on the east and similarly resistant metamorphic rocks of the Leeuwin Ridge at 150 m ASL to the west. As the Blackwood Plateau is dissected by current drainage systems only remnants remain across Whicher Range, which now forms a major drainage divide. The DSM shows a gently sloping planar surface (gradient 0.02°) falling from 166 m ASL on the eastern plateau remnant to 142 m ASL where it abuts the Leeuwin Ridge. This may be a remnant of an old marine erosional surface, but there is no direct evidence for its age. It may be analogous to the Dandaragan Plateau 300 km to the north—an erosional surface capped by the Poison Hill Greensand, which is dated as latest Cretaceous (83–66 Ma) by Mory *et al.* (2005).

PLATEAU LATERITE

The Blackwood Plateau across Whicher Range is capped by a typical plateau lateritic duricrust akin to, and continuous with, that described by Anand & Paine (2002) across the Yilgarn Craton. The weathering profile consists of 3–5 m of duricrust which is topped by loose goethite and maghemite pisolites, and underlain by a mottled zone above a pallid saprolite of leached sandstone. The duricrust contains concentrically zoned goethite–hematite nodules, plus angular fragments of highly-ferruginized hematitic sandstone with goethite cutans and abundant small pellets of maghemite.

Morphologically, the laterite is a remnant of a once-extensive blanket on the pre-dissected Blackwood Plateau. It therefore preserves part of a flat erosion surface pre-dating regional lateritization. As described for the Darling Range by Wilde & Walker (1982), in situ lateritic duricrust extends part-way down spurs of contemporary valleys within the Whicher Range. This is especially so for the Preston and Capel rivers, which are the largest to cross the Whicher Scarp. This indicates plateau lateritization continued once dissection of the plateau commenced.

The regional geochronological framework of plateau laterite in southwest Western Australia is provided by paleomagnetic dating (Pillans 2005), which records the position of the pole of remnant magnetism on the trace of the Australian apparent polar wander path (Schmidt & Clark 2000). The phase change from goethite to hematite records the remnant magnetism. Pillans (2005) documents

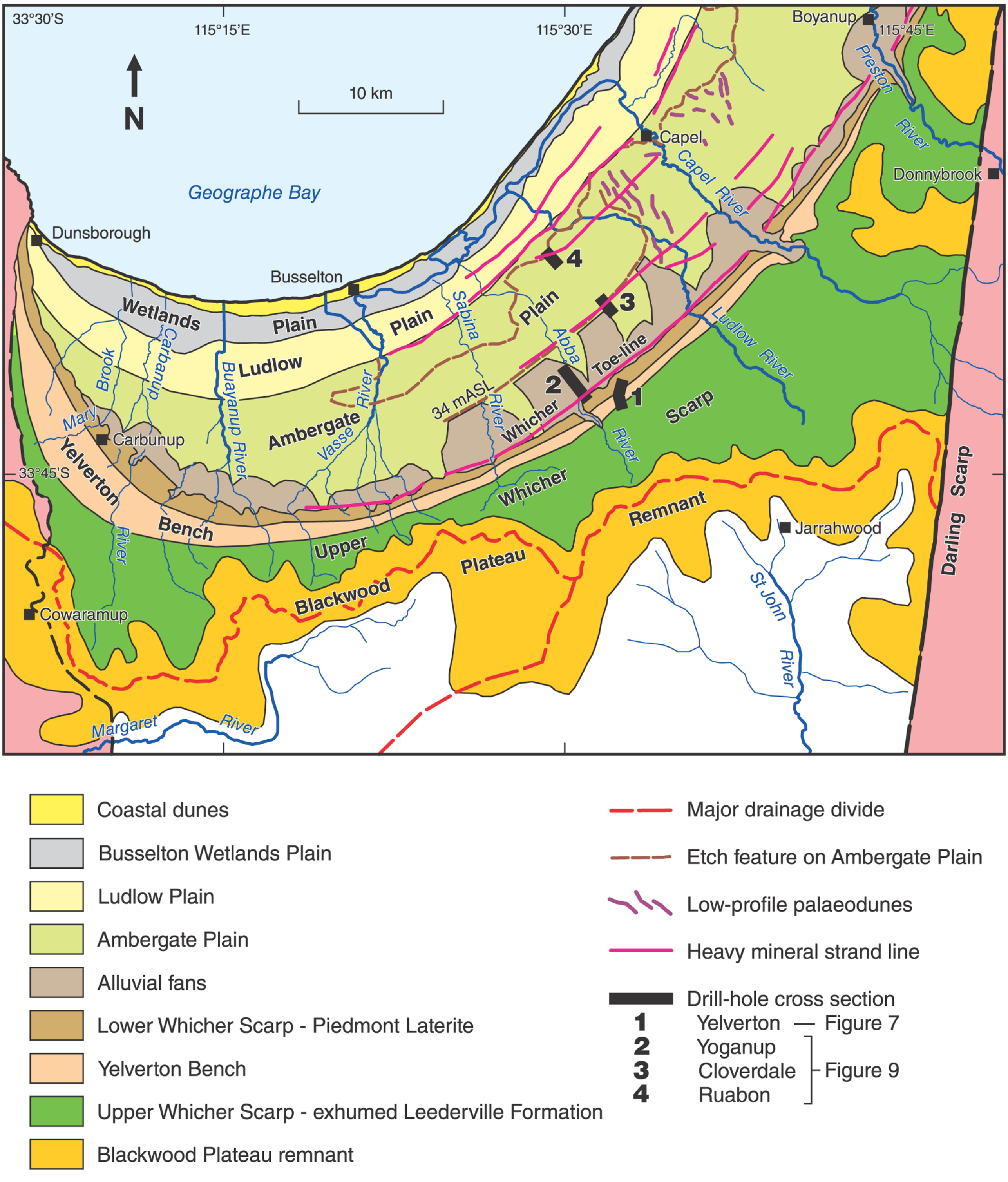


Figure 5. Geomorphic elements of the study area.

paleomagnetic determinations from many sites in the Yilgarn Craton, showing distinctly bi-modal distribution of ages in the Cenozoic with a major event at ~50–60 Ma (late Paleocene – early Eocene) and a younger one at ~10 Ma (late Miocene).

Also of relevance are ribbons of silcreted quartz sandstone, grit and conglomerate on some of the older drainages of the southwestern margin of the Yilgarn Craton (Wilde & Walker 1982) which are subject to lateritic duricrust. These include sediments at Kirup, Kojanup and Muradup—the latter contain Eocene plant fossils (Wilde & Backhouse 1976). Cockbain (2014) correlates these occurrences with the Plantagenet Group on the south coast which falls within the Eocene Climatic Optimum (~50–40 Ma; Miller *et al*. 2020), when there were ideal conditions for deep chemical weathering and laterite development.

Duricrust possibly forms during continuous alternations between desiccation and saturation near the top of the water table, whereby goethite transforms to hematite, and under some conditions of sub-aerial exposure reduces partially to maghemite (Anand & Gilkes 1987). Attempts to radiometrically date laterite using U/Th suggest that the process takes tens of millions of years. Thus, the relatively young ages in Darling Range laterite of 10.0 – 7.5 Ma determined by Pidgeon *et al.* (2004) and 5.7 – 3.9 Ma by Wells *et al*. (2018), may record the lock-in of daughter products and helium into maghemite during a prolonged period of maturation. Alternatively, these ages may be due to a separate episode of duricrust formation in accordance with the younger event at 10 Ma of Pillans (2005).

Whicher Scarp

The Whicher Scarp (Lowry 1967; Finkl 1971) rises to a maximum of 125 m above the coastal plain in the east. Where not affected by watercourses it is expressed as smooth slopes, preserving close to the original 2.9° erosional gradient. In the west near Yelverton and Yallingup, it is only 100 m above the plain, and forms rolling dissected hills and marshy creeks, with an overall gradient of less than 0.6°.

The scarp formed by marine erosion into soft sandstone of the Leederville Formation after the main period of Eocene plateau lateritization. As with the Gingin Scarp 300 km to the north (Harrison 1990), marine erosion could not have commenced until after the deposition of the Upper Cretaceous glauconite sands, chalk and marls at ~72 Ma (Ingram & Cockbain 1979). The initiation of this scarp seemingly coincides with global sea-level falls that commenced about 43 Ma after the Eocene Climatic Optimum (Miller *et al.* 2020).

YELVERTON BENCH

A distinctive feature within the Whicher Scarp is a bench, which corresponds to the 'mid-range sand' in Figure 3. Welch (1964) previously called this the 'Middle-Escarpment Shoreline' and indicated an altitude of about 76 m ASL. Wilde & Walker (1982, p. 27) recognised it as the 'Happy Valley Shoreline' at 'about 80 m above sea level' where the Capel River cuts the Whicher Scarp. South of Dunsborough in the far west of the study area, Marnham *et al.* (2000) identified a regolith-landform

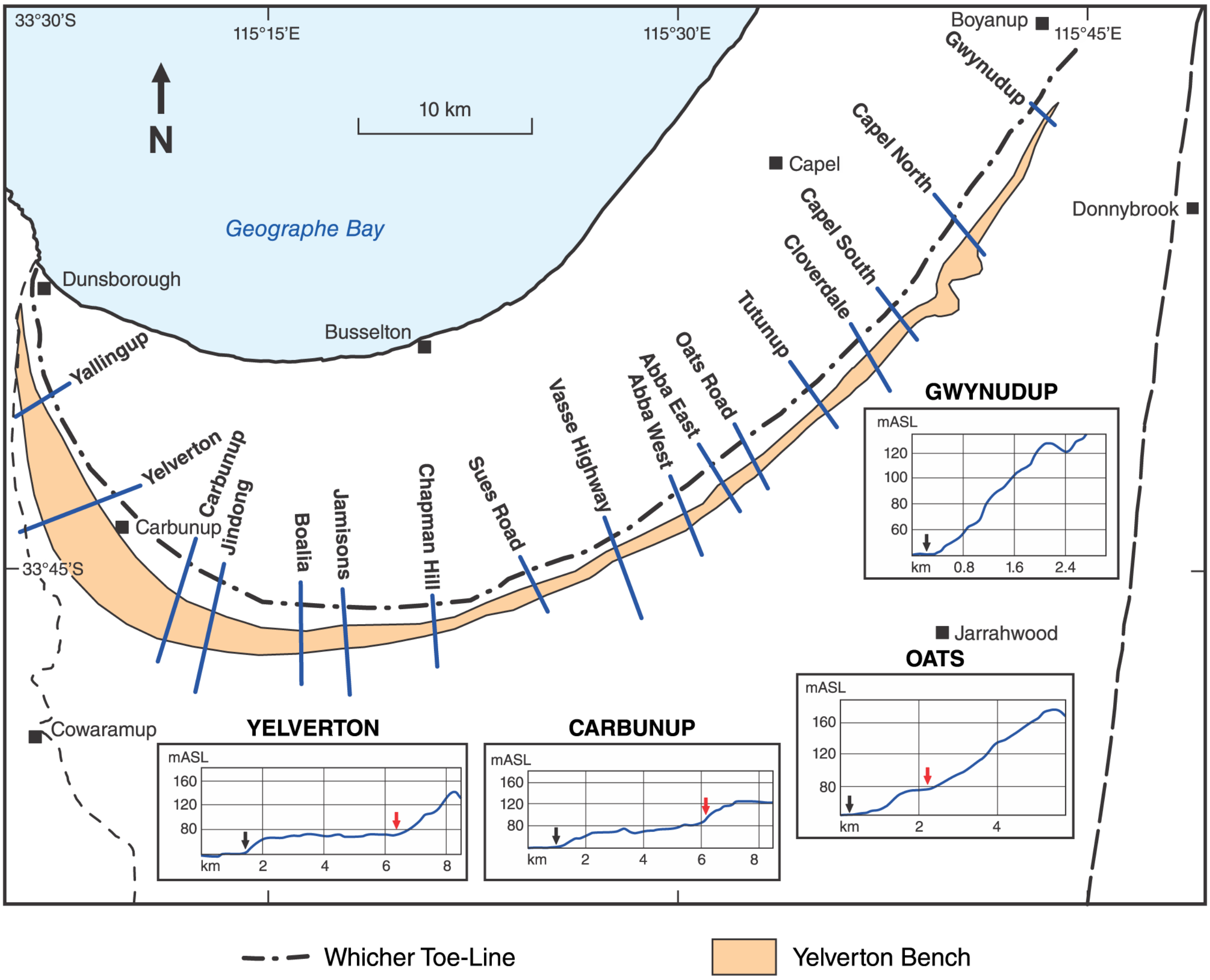


Figure 6. Transects of the Whicher Scarp and representative profiles; red arrows indicate head of Yelverton Bench, black arrows indicate base of Whicher Scarp.

of subdued rolling hills at some 60–90 m ASL which they called the 'Yelverton System'. Gozzard (2010, fig. 23) subsequently renamed it as the 'Yelverton Shelf'; however, the geomorphic term Yelverton Bench is preferred here.

Lowry (1965) relates this mid-scarp bench to the Ridge Hill Shelf along the Darling Scarp in the Perth hinterland, which Prider (1948) noted has 10 m of ferruginous cemented sandstone and detrital laterite, at 67–91 m ASL. Baxter (1977) gave a more precise elevation of 82 m, but it is not clear if this is the geomorphic expression of the bench, or erosional notch cut into the basement. Its age has not been determined by paleontology or radiometric dating.

The Yelverton Bench has not previously been documented in detail along the entire length of the Whicher Scarp. For this study, 17 regularly spaced profiles along its full extent, in transects avoiding watercourses, were constructed from the DSM using the raster functions in MapInfo. Parameters such as bench width, slope and height were then measured and assessed for regional tilting (Table 1) from sub-surface information to define the shoreline elevation. Representative topographic profiles (Fig. 6) show preservation of the flat bench and the talus wedge at the notch. The toe of the talus wedge is taken as the morphological elevation of the bench (Table 1). Because of the layer of stranded shoreline sediment on the bench, the morphological elevation is markedly higher than the marine erosional surface.

The Yelverton Bench is not developed north of Preston River whereas it is 390 m across on the Gwynudup Transect on the southern valley wall of the Preston River. It progressively widens westward to 4 km in the Carbunup and Yelverton localities, before abruptly terminating at the Leeuwin Ridge. In profile the bench has gentle seaward gradients. A linear regression line of the geomorphic elevation of the 17 transects indicates a fall from 83 m at Gwynudup to 72 m at Yallingup, giving a drop of 11 m over 60 km. Cloverdale at 90 m is the only transect that is anomalously high, being 5 m above the regression line. This is interpreted to represent thicker preserved sediment on the bench. Furthermore, information from heavy-mineral exploration indicates the apparent fall in elevation results from progressive loss of sediment from the western tracts of the bench.

Diagnostic information on the internal construction of the Yelverton Bench comes from exploration drilling by Cable Sands at the Whicher heavy-mineral deposit (Heptinstall 2003) which underlies the Oats Transect of this study. Available data includes drill-hole collar coordinates, RL (effectively metres ASL), lithology, heavy mineral layers and position of the erosional unconformity with the Leederville Formation. The cross section in Figure 7 is derived from that exploration report. The clastic wedge at the notch is 250 m wide and 18 m thick at its maximum point, and directly overlies Leederville Formation. The wedge consists of up to 9 m of reddish-brown, medium- to coarse-grained sand with abundant (3.5%) heavy mineral, overlain by 9 m of brownish-grey clayey sand, in turn capped by 2 m of lateritic duricrust. Two steps are evident in the erosional surface in the notch position. The principal erosional surface under the main part of the bench is 6 m below the geomorphic expression, indicating an erosional surface on the Oats transect at 68 m ASL.

Exploration drilling by Cable Sands near Jamieson Transect 25 km to the west, (Heptinstall 2003) indicates

Table 1. Bench widths, slopes and elevations of the Yelverton Bench on selected transects from east to west, showing Whicher Toe-line elevations for reference. See Figure 6 for locations.

Transect	Yelverton Bench: Bench width (m)	Yelverton Bench: Seaward slope (°)	Yelverton Bench: Elevation	Whicher Toe-line elevation (m ASL)
Gwynudup	390	0.99	83	41.2
Capel River N	940	0.70	80.1	41.5
Capel River S	1260	0.13	83.3	39.1
Cloverdale	1360	0.23	90	39.6
Tutunup	1540	0.53	77.4	42
Oats Road	1560	0.10	74	42
Abba E	1490	0.07	76	42.8
Abba W	1320	0.07	79.2	39
Vasse Hwy	1020	0.69	82	40.9
Sues Road	790	1.10	79.5	40
Chapman Hill	1140	0.46	72.8	39
Jamison Road	1450	0.28	64.3	42
Boalia Road	1240	0.25	66.5	42
Jindong	3610	0.34	75	42.4
Carbunup	4510	0.20	80.2	41.4
Yelverton	2720	0.10	75.6	39.8
Yallingup	1420	0.10	75.6	38.7

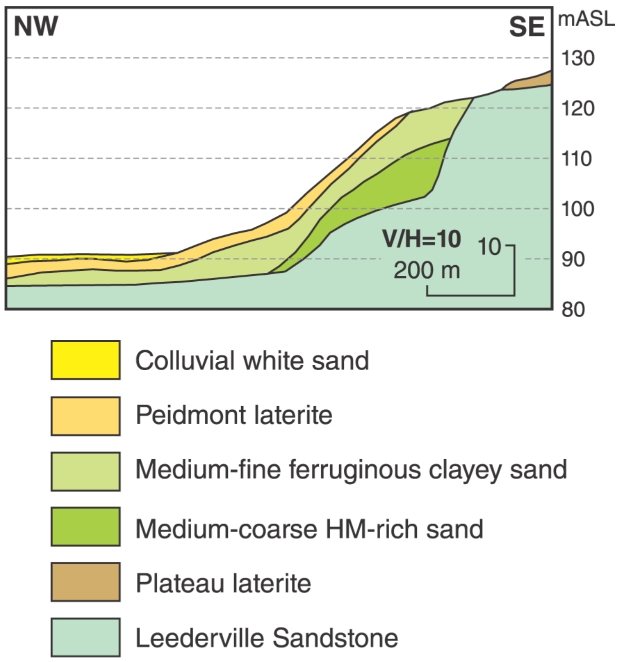


Figure 7. Geological cross-section of the Yelverton Bench based on Cable Sands drilling data in Heptinstall (2003); centre of section is at 115.5443°E, 33.7215°S and its location is shown on Figure 5.

only 4–6 m of residual sand on the bench and an erosion surface at 70 m ASL. Near the Metricup Transect, 18 km farther west, exploration drilling by Iluka, (Johnston 2004b) indicates 3 m of sediment overlies the Leederville Formation erosion surface at 72 m ASL. Thus, the apparent westward fall of the Yelverton Bench is due to the removal of sediment from the erosional bench rather than tectonic tilting.

PIEDMONT LATERITE

Piedmont laterite is younger than the plateau laterite and forms a thin apron of duricrust on and below the Yelverton Bench. It does not physically join with the plateau laterite higher up the scarp. Except where eroded it extends continuously to the base of the Whicher Scarp, where it characteristically exhibits convex morphological profiles (Fig. 8a).

The duricrust is platy, 1–2 m thick on the slopes, thickening to 2–3 m at the base of the Whicher Scarp. It is heterogeneous and contains 0.5 – 5 cm angular fragments of reddish-brown hematite-cemented sandstone, and composite clasts with thin goethite cutans, together with small pellets of detrital maghemite (Fig. 8b). The matrix is goethite-cemented quartz grit showing varying degrees of angularity. It is devoid of concentric pisolites and the clay (gibbsite) matrix characteristic of the plateau laterite. Patches of matrix form potholes in irregular surfaces on fragmental duricrust. The duricrust is underlain by a mottled zone 2–3 m of loose nodular gravels in clay matrix, (Fig. 8c), indicating mostly in situ development. These gravels have been scraped extensively along the lower scarp for use as road base and land fill.

The piedmont laterite is intact in the eastern tracts of the Whicher Scarp, between Preston River and Vasse Highway, where Wilde & Walker (1982) and Belford (1987) mapped it as lower-level laterite. In these eastern tracts it abuts and overlaps the plateau laterite where it traverses down paleovalley slopes. Mapping in the present study shows kilometre-scale re-entrants of piedmont laterite into the valleys of the two older rivers (viz. the Preston and Capel rivers). In a cutting of the Capel–Donnybrook Road (115.6601°E, 33.6266°S),

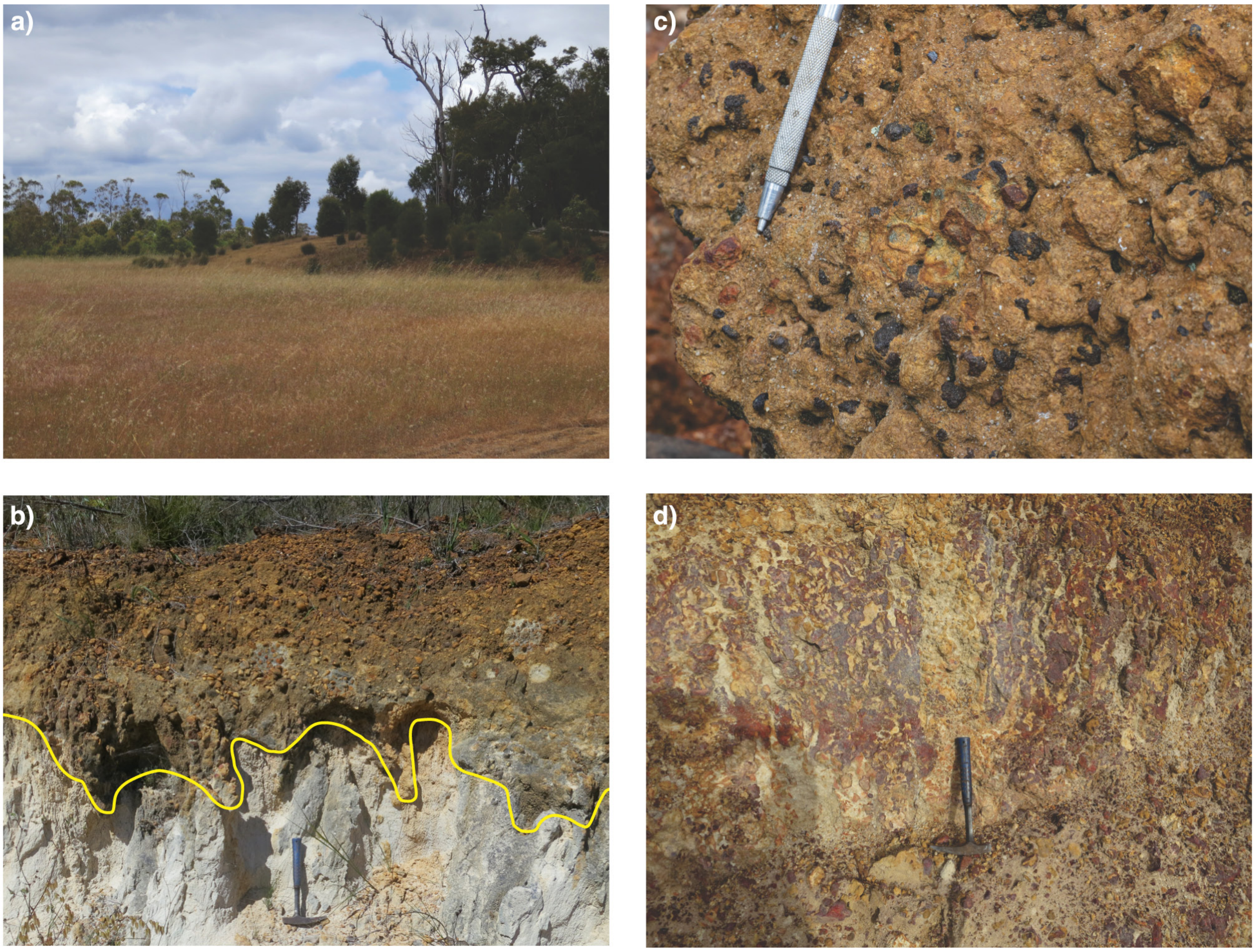


Figure 8. Piedmont laterite: **a)** convex apron of duricrust of piedmont laterite descending under alluvial fan at base of Whicher Scarp, southern end of Jamison Road (115.2929°E, 33.7889°S); **b)** piedmont laterite unconformably overlying Leederville Formation, Capel–Donnybrook Road cutting (115.6601°E, 33.6266°S); **c)** piedmont laterite showing angular clasts of ferruginized sandstone, maghemite pellets and quartz-limonite matrix. Palmer Road (115.5085°E, 33.7256°S); and **d)** mottled zone below duricrust indicating insitu development of piedmont laterite, Leeuwin Civil quarry, Price Road (115.2318°E, 33.7969°S).

2 km into the Capel River valley, the laterite is crudely bedded with internal potholes and neptunian dykes. It unconformably overlies the Leederville Formation (Fig. 8d) and at this lower level is interpreted as lateritized talus.

Westward around the arc of the Whicher Scarp, the piedmont laterite becomes increasingly dissected and is expressed as a line of isolated aprons of duricrust shelving down to the base of the scarp. These remnants are surrounded by sand shed from the underlying Leederville Formation and the exhumed clastic wedge of the Yelverton Bench. In these western tracts the piedmont laterite is always separated from the plateau laterite by exposed Leederville Formation.

Whicher Toe-line

Baxter (1977) initially used 'Yoganup Shore Line' for the conspicuous geomorphic feature at the toe of the Whicher Scarp, a term well embedded in subsequent geological literature. The precise position or elevation of this ancestral shoreline is uncertain. Moreover, not all of the superimposed stacked sedimentary successions on this line can be attributed to the Yoganup Formation. To avoid confusion the term Whicher Toe-line is applied to just the geomorphic feature.

The Whicher Toe-line forms a 100 km arc extending from Boyanup (Fig. 2) to Dunsborough. It has been intensely investigated because of associated rich ilmenite sands, of which the Yoganup deposit is the archetype. Baxter (1977) noted a clay unit, buried laterite and superimposed alluvial fans overlying the shore-facies sands. Such alluvial fans are evident on DSM images along the entire Whicher Toe-line (Figs 2 and 5). Elevations of the Whicher Toe-line derived from the 17 transects averages 40.7 m ASL with a standard deviation of only 1.4 m. There is no regional variation in elevation over the entire arc, demonstrating no tilting since its formation. This is at variance with Cope (1975) who suggested northward tilting based on his placing the shoreline at 47 m ASL at Yoganup and 37 m ASL at Dardanup.

Ambergate Plain

The term Ambergate Plain is introduced for the coastal plain between the Whicher Toe-Line at 41 m ASL and an erosional scarp at its seaward edge at 19 m ASL (Fig. 5). This flat featureless plain extends through the Busselton rural localities of Ruabon, Yalyalup, Ambergate (after which it is named) and Yoongarillup. It is 10 km across with a gentle seaward slope of 0.06°, is covered by a veneer of loose sand and, except for some low sand hills northeast of Capel, is largely devoid of recognisable dunes. This sand layer has been ascribed to the Bassendean Dunes (McArthur & Bettenay 1960) and the Bassendean Sand (Playford & Low 1972, Bufurale *et al.* 2019). Despite its seemingly featureless aspect, Ambergate Plain had a complex evolution.

Alluvial fans on the Whicher Toe-Line are up to 8 m thick and extend onto the Ambergate Plain for up to 4 km (Fig. 5). They are not lateritized. Smaller fans relate to the young watercourses that arise within the scarp. Larger fans relate to outflows of the Capel, Ludlow, Abba and Sabina rivers, and have distal fronts terminated by a subtle feature at 34 m ASL that forms a median trace on the Ambergate Plain (Fig. 5). This 34 m ASL feature swings in a broad arc to the Ludlow area to meet the seaward edge of the Ambergate Plain (Fig. 5). It may reflect an underlying paleo-embayment caused by a buried paleo-headland of Bunbury Basalt. An equally subtle embayment, etched into the seaward edge of the Ambergate Plain, occurs in the tract between Ludlow and Vasse rivers (Fig. 5. This area is characterised by swamps and a 'pock-marked' pattern on the DSM at an elevation 1.5 – 2.5 m lower than the plain. This etch-like feature unearthed the underlying Capel ilmenite-rich strands thereby facilitating the discovery and initial development of eolian heavy-mineral sands on the Ambergate Plain.

The Ambergate Plain equates to parts of the Pinjarra Plain (McArthur & Bettenay 1960). However, that geomorphic term, if applied to the Busselton area, would cover several diverse erosional and depositional features, and therefore is not used here. Internal features discussed below show the Ambergate Plain is a terrestrially re-sedimented marine planation surface.

YOGANUP FORMATION

The term 'Yoganup Formation' (Playford *et al.* 1976) was originally applied to the variably lateritized, mixed association of sand, conglomerate and clay along the 'Yoganup shoreline' at the base of the Whicher Scarp. This usage inappropriately groups the talus phase of the piedmont laterite, the 'Yoganup strands', lateritized clays and the overlying alluvial fans. Current industry practice is to use 'Yoganup Formation' for the beach-facies sand that extends continuously in the subsurface across the full width of the Ambergate Plain, rather than just under the Whicher Toe-Line. The Ambergate Plain has been probed by thousands of drillholes for mineral-sand mining. Full interrogation of these massive datasets is beyond the scope of this study; however, selective cross sections are presented to illustrate the subsurface strata.

Below the landward edge of the Ambergate Plain (i.e. under the Whicher Toe-Line), the eroded top of the Leederville Formation progressively steps down through a series of buried paleo-seacliffs and benches to reach a base level at 22 m ASL (Fig. 9a). These features are recognised in drill sections at Tutunup mine (Dixon 2008) and Yoganup Extended (Johnston 2004a). From this landward location, the unconformity between the underlying Leederville Formation and the overlying Yoganup Formation gently shelves through a series of small steps, to reach 11 m ASL at the seaward edge of the Ambergate Plain near Ruabon and Capel South mines (Dixon & Johnson 2007, Dixon 2008).

A series of stacked, partially overlapping seaward-dipping beach-facies strands, many with ilmenite enrichments, extend well beyond the Whicher Toe-Line, under the Ambergate Plain. For example, the Cloverdale Strand (Dixon & Johnston 2007) occurs 4 km seaward from the Whicher Toe-Line (Fig. 9b) whereas the Ruabon (Capel) Strands occur 9 km seaward of the Whicher Toe-Line (Fig. 9c).

The Yoganup Formation is correlated with the Ascot Formation near Perth (Baxter & Hamilton 1981), which

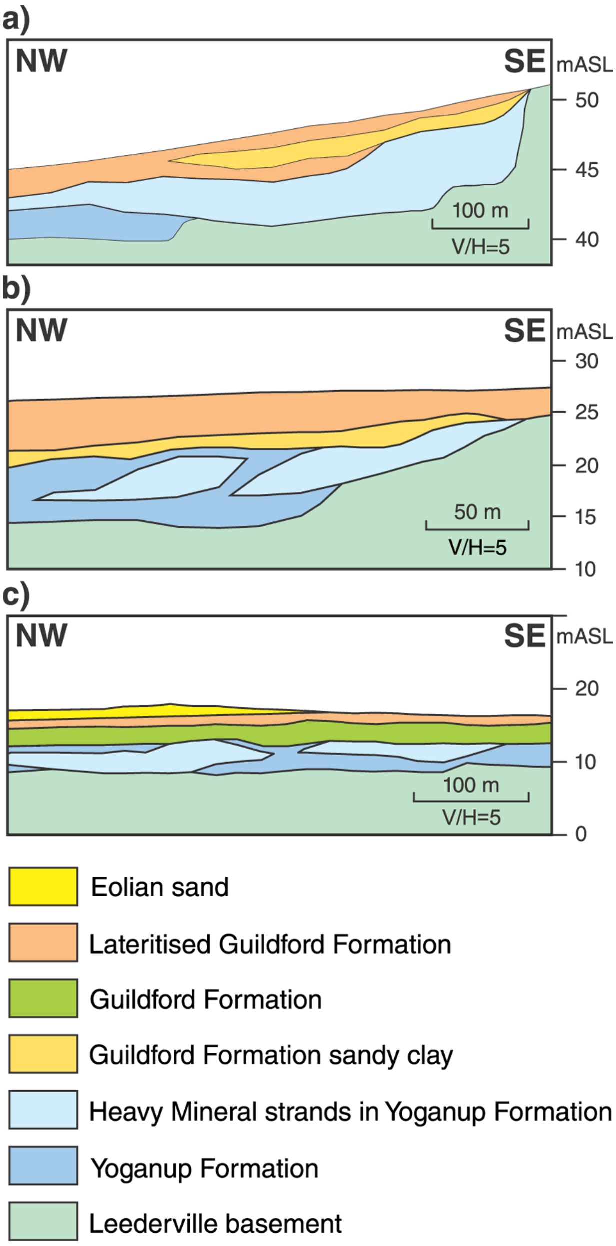


Figure 9. Geological cross sections of strands of the Yoganup Formation beneath Ambergate Plain from mineral exploration drilling: **a)** Yoganup deposit, eastern margin of Ambergate Plain (Dixon 2008); and **b)** Cloverdale deposit, central Ambergate Plain, (Dixon & Johnston 2007); and **c)** Ruabon (South Capel) deposit, western margin of Ambergate Plain (Dixon & Johnston 2007); locations shown on Figure 5.

contains diagnostic mollusc and bivalve fossils indicating late Pliocene age (Kendrick 1981, Kendrick *et al*. 1991). The Yoganup Formation is generally devoid of fossils. However, a sandy shell bed was encountered in an Iluka drill hole at 115.6001°E, 33.5264°S, 4.5 km northeast of Capel town at a depth of 16–19 m below the Ambergate Plain, equating to 3–6 m ASL (Johnston 2005). George Kendrick (in Appendix 2 of the Iluka report by Johnston (2005) confirmed correlation with Ascot Beds and the late Pliocene age.

Floaters of fossiliferous limestone have been reported on the Ambergate Plain at a locality 11 km southwest of Busselton (115.2698°E, 33.7321°S), at 28 m ASL—this locality was examined by Edgell (1967), reported by Lowry (1965) and discussed in Playford *et al*. (1976). The material was re-examined by Kendrick *et al*. (1991) who considered it middle–late Pleistocene rather than Pliocene, which is consistent with the interpretations in this paper. Field examination of this locality indicates the limestone floaters lie within surficial quartz sand and are probably introduced 'Tamala-type' limestone. This locality can no longer be used to claim that lateritisation continued through the Pleistocene.

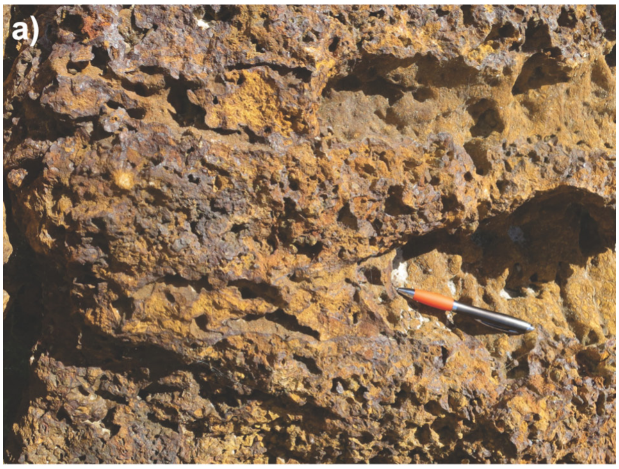
GUILDFORD FORMATION

Below the Ambergate Plain the Guildford Formation forms a continuous unit up to 12 m thick of estuarine and alluvial sandy clay, which always overlies the Yoganup Formation. The Guildford Formation extends 250 km to the north along the plains adjacent to the Darling Scarp and marks the terrestrial advance of sediment across this plain during a marine regression. The age of the formation is not well constrained (Playford *et al.* 1976), and the name is commonly applied to any clay of Pleistocene and Holocene age. Gozzard (2007) considers the term should be restricted to strata directly below paleochannel sediments of the ancestral Swan River. This is consistent with the present sedimentological model for the Ambergate Plain and points to a late Pliocene to early Pleistocene age (~2.6 Ma).

The Guildford Formation is extensively lateritized, with exposures typically found in excavations and streambeds, a situation which has led some commentators to use 'valley ferricrete'. However, mineral-sand drilling indicates the lateritized clays extend continuously beneath surficial sands of the Ambergate Plain. When exposed it is seen to be crudely stratified goethite-cemented gritty sand and limonitic ironstone with a platy biscuit-like texture (Figs 10a, b). It is typically vermiform with dense ironstone linings of tubes and voids, which may be after tree rootlets. Pisolites and nodules are absent. It is distinct from the older forms of laterite and represents a period of lateritization that post-dates the cutting of the marine erosional surface at the base of the Yoganup and Guildford formations, and pre-dates the development of alluvial fans on the Ambergate Plain.

Cemetery Scarp

The 'Cemetery Scarp is introduced here for the geomorphic feature that forms the seaward edge of the Ambergate Plain and marks its separation from the lower coastal plains closer to the present coast. It is an erosional scarp cut into the Ambergate Plain. It is well expressed by the incline on the Vasse Highway at the Busselton Cemetery (115.3858°E, 33.6825°S—otherwise known as Four-Mile Hill. Here the Ambergate Plain drops sharply from 22 m ASL to 11 m ASL. Elsewhere the scarp is subject to varying degrees of erosional degradation, but it can be mapped on the DSM from Capel to Dunsborough as an arc mimicking the shape of other ancestral shorelines. There is no measurable regional variation in its level.



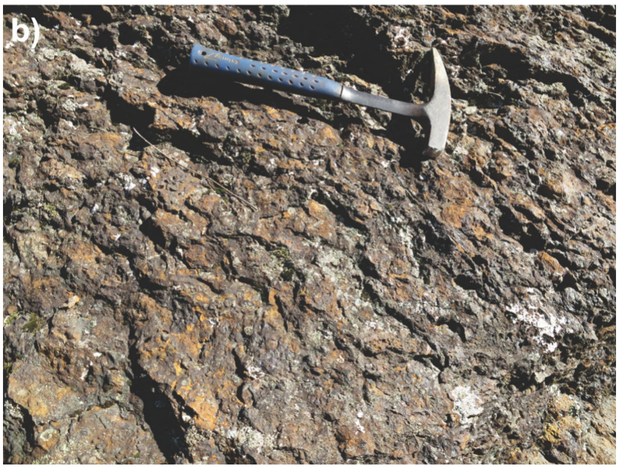


Figure 10. Lateritized clay of the Guildford Formation: **a)** crudely stratified quartz-rich gritty laterite developed on sandy clay, Willmott Farm (115.3802°E, 33.6990°S); and **b)** claystone showing disrupted platy fabric, Coolilup Road crossing of Ludlow River (115.5236°E, 33.6061°S).

The scarp is draped by yellow-brown windblown sand, such that the underlying strata are not exposed. However, 'Yoganup-type' strands and lateritized clays akin to those of the Guildford Formation are present in exploration drill holes under much of the Ambergate Plain adjacent to the Cemetery Scarp (Hill 2014; Carruthers 1998a). In the far western tracts Lowry (1965) recognised it as a sandy rise which he called the Carbunup Dunes. Here the scarp is degraded to the extent that the Yoganup and Guildford formations have been removed and only 3–4 m of eolian sand directly overlies Leederville Formation (Stewart 2007).

The Cemetery Scarp marks the seaward limit of the Yoganup and Guildford formations, and the beginning of marine carbonate deposition. It also coincides with the last lateritic duricrusts. The postulations of late Pleistocene and Recent laterite by Lowry (1965), leading to the often-repeated statement that laterite is forming today (Johnstone *et al*. 1973, Playford *et al*. 1976), cannot be substantiated in the study area. Geological observations indicate lateritization was episodic with principal events in the Eocene, Miocene and Pliocene.

Ludlow Plain

The Ludlow Plain extends around the full arc of Geographe Bay between the Ambergate Plain and the Busselton Wetland Plain. It is 3–4 km wide, with an altitude of ~11 m ASL at the base of the Cemetery Scarp, and ~8 m ASL at its seaward edge, where it shelves perceptibly into the Busselton Wetlands Plain (Fig. 5). In undisturbed areas it is covered with a mixture of eolian quartz and calcareous sand 2–3 m thick, through which limestone caprock protrudes. The map of Belford (1987) depicted this feature as a thin strip of Tamala Limestone.

Exploration drilling indicates the Ludlow Plain is underlain by 5–6 m of 'Tamala-type' limestone across its full width (Carruthers 1998b). Heavy-mineral concentrations occur in the surficial eolian sands above the limestone such as at the old Ludlow mine pits (Harewood 2001) where the buried top of the limestone at 2 m ASL is an irregular karstic surface with low pinnacles and hardcap formed by paleo-subaerial weathering. Exploration drilling in the Tuart Forest along the line of the degraded Cemetery Scarp indicates a wedge of poorly sorted sand, grit and gravel (McGoldrick 1990) which probably represents the paleo-shoreline against which the limestone sheet was deposited.

The limestone is mostly underlain by Leederville Formation sandstone, but in places multi-coloured (red, purple, green, black) sandy clay with patches of ferruginous 'coffee rock' are noted in drill holes. Passmore (1962) ascribes this latter material to the glauconitic Osborne Formation above the Leederville Formation. Hirschberg (1989) records glauconite below limestone in water bore BN4 drilled through the Ludlow Plain in the Tuart Forest, which supports this correlation. A cored geotechnical hole drilled by WML Consulting Engineers (Gorczynska 2020) through the limestone at the pedestrian bridge (115.3281°E, 33.5146°S) as part of the Vasse Diversion Drain upgrade, gave incomplete recovery through a calcarenite with shell fragments throughout and coral rubble in the lowermost 20 cm. At 1 m below sea level this hole passed into Leederville Formation with thin coaly intercalations.

SIGNIFICANCE OF 'TAMALA-TYPE' LIMESTONE

Traditionally, the thick calcareous eolianite deposits, together with the thinner marine and estuarine shelly beds, which extend for over 700 km along the west coast of Western Australia, are grouped into the Tamala Limestone (Playford *et al*. 1976). Recent research discussed below on the morphology, stratigraphy and age of this unit has shown that it is a composite entity with separate episodes of carbonate production, deposition and re-working, that can be related to glacial–interglacial cycles and associated sea level changes through the late Pleistocene. For this paper it is convenient to use 'Tamal-type", as it does not imply lithostratigraphic correlation.

In the Perth–Rottnest area an extensive eolianite ridge close to the present coast has yielded optically stimulated luminescence (OSL) ages from 120–103 ka (with appropriate uncertainty errors), indicating various sub-stages in Marine Isotope Stage (MIS) 5 (Brooke *et al*. 2014). Geological features indicate sea level at 2 m ASL. They also record eolian ridges well inland from the coastal ridge with OSL ages of 415 ka (MIS 11) and

310 ka (MIS 9). Farther north on the mid-west coast, including the Pinnacles Desert, Lipar & Webb (2014) and Lipar *et al*. (2017) identify five morphostratigraphic 'members' of the Tamala Limestone, each consisting of a cycle of eolian calcarenite and calcrete microbiolite with a karstic paleosol. Dating of the paleosol by OSL and U/Th methods shows a progressive seaward younging of the eolianite members which can be related to the major interglacial highstands of MIS 13 (landward) through MIS 11, 9, 7 and late 5 (seaward). Still farther north at Cape Cuvier a cluster of ~125 ka ages indicative of MIS 5e are recorded from corals in eolianite and related strand deposits near the coast at ~3.5 m ASL (Hearty *et al*. 2007, Stirling *et al*. 1995). The regional chronologic framework for much of the Tamala Limestone along the west coast facilitates correlation of limestone members from their morphostratigraphy. Central to this is the recurrence of the MIS 5e member along the present coast only a few metres above present sea level.

In contrast to the extended west coast, there is no build-up of the signature eolian facies of the Tamala Limestone around Geographe Bay. Eolian dunes on the rocky coast of the Leeuwin Ridge reappear on the plains north of Capel River. It is likely the Leeuwin Ridge protected the hinterland from strong onshore winds that built these facies. In its place is a 6 m-thick shelly limestone that accumulated on a shallow sub-tidal marine terrace, and which underlies the Ludlow and Busselton Plains.

Bunting (2014) describes a shelly conglomeratic limestone below eolian facies limestone at Shelley Beach 12 km east of Dunsborough (115.0298°E, 33.5379°S) a few metres above sea level. This is probably a talus deposit peripheral to the shelly limestone on the Ludlow Plain. McCulloch and Mortimer (2008) dated corals in a similar limestone at 2.5 m ASL on the ocean-side of the Leeuwin Ridge at 128–125 Ka. This age is the last interglacial equating to MIS 5e. It is likely that the shelly facies of the Tamala Limestone around Geographe Bay is of this age.

On the tectonically stable southern coasts of Australia the highstand of the last inter-glacial at 125 ka was 2–4 m ASL (Lewis *et al*. 2012, Murray-Wallace *et al.* 2016) and preceded the staged fall into the last glacial maximum, believed to be 23–17 ka in Australia. At this time sea level was about 130 m below its present level, exposing an extensive wind plain to the west. Thus, the shelly facies limestone under Ludlow Plain was sub-aerially exposed for over 100 000 years, during which time the hard cap and karstic surface formed.

Busselton Wetland Plain

This feature is expressed by silt-covered marshy flats that contain estuarine and lagoonal tracts of the Busselton, Broadwater and Wonnerup wetlands. It forms the lowermost coastal plain, extending laterally from Ludlow Plain at 4 m ASL to the modern coastal dunes at 1 m ASL. Low ridges of poorly sorted, medium-grained, quartz–carbonate sand occur on the seaward margin of the Ludlow Plain in the Tuart Forest. These are evident as gentle undulations on Layman Road at 115.4300°E, 33.6304°S, and mark the Holocene interglacial highstand.

The Busselton Wetlands Plain is underlain primarily by multi-coloured green–purple–reddish sandy clays of likely Osborne Formation, as well as underlying Leederville Formation. However, there are some tracts of shelly facies 'Tamala-type' limestone, similar to that under the Ludlow Plain, as indicated in water bores around Busselton (Passmore 1962; Wharton 1982; Hirschberg 1989) and in the partially excavated canals at Port Geographe. The limestone is 6–7 m thick with a recrystallized hardcap at 0 m ASL.

Geotechnical drilling and penetrometer probing associated with the Port Geographe development suggests the limestone forms ribbons or bars, rather than a continuous sheet as under the Ludlow Plain. This may indicate either multiple bars of buried limestone, or eroded remnants of a larger single sheet.

Quindalup Dunes

The present coast is characterised by the Quindalup Dunes (McArthur & Bettenay 1960; Semeniuk *et al*. 1989). This back-beach system consists of twin ridges, the anatomy of which has been studied by Hamilton & Collins (1997). The landward ridge is the higher of the two at up to 18 m ASL and encroaches onto the sandy muds of the Busselton Wetlands Plain. It is composed of quartz-calcarenite sand with landward dipping eolian fore-sets. Radiocarbon dates indicate the landward (older) dune commenced building at 6850±130 years before present (y BP) and continued till at least 5650±90 y BP. The seaward (younger) dune extends up to 10 m ASL and developed on an organic layer of seagrass peat giving carbon ages of 3770±60 y BP. It is likely that the older dune ridge was a barrier system with marine lagoons on the landward side, which were the precursors of the current wetlands.

DISCUSSION

Sea Levels

Because of the paucity of datable material, assigning ages to the erosional surfaces that underpin the landscape features is best done by relating them to global sea-level curves. The germinal Exxon curve (Haq *et al*. 1987) denotes a Late Cretaceous erosion surface 220 m ASL, descending to a Paleocene–Eocene surface at 110 m. These levels accord with the erosional plateau of the adjacent Yilgarn Craton and the Blackwood Plateau respectively. Modern curves (Miller *et al.* 2020) denote the Eocene Climatic Optimum as a global ice-free period with its true sea level 90 m ASL.

The Whicher Scarp formed by marine erosion and removal offshore of a large volume of sediment during an extended period when sea level fell slowly falling by some 115 m. If the Whicher and Gingin scarps are related, the volume of sediment removed between these two features during the Eocene to Miocene was at least 1000 km^3. The sea-level curve of Miller *et al*. (2020) depicts a progressive fall through the Oligocene–Miocene transition to ephemeral non-global ice caps, an interval of some 40 million years.

The age of the Yelverton Bench remains uncertain and correlation with sea-level curves is equivocal. The bench could represent either a stillstand during the progressive fall in sea level through the Oligocene and Miocene, or an oscillatory rise related to the Middle Miocene Climatic Optimum of Miller *et al.* (2020).

The Whicher Toe-line at 41 m ASL marks the sharp boundary between the Whicher Scarp and the marine-cut coastal pediments. In this respect it is analogous to the Roe Plain at 19–31 m ASL on the south coast of Western Australia. Rovere *et al*. (2014) relate this feature to the Mid Pliocene warm period of 3.3 – 2.9 Ma. At that time the stillstand was 30 m ASL, which is close to the observed erosional surface under the Whicher Toe-line.

The Mid Pliocene warm period preceded the global cooling trend that descended into the cyclic bi-polar Pleistocene ice ages and the commensurate oscillatory falls in sea level. These trends are now well documented by global $\delta^{18}O$ data (Lisiecki & Raymo 2005; Spratt & Lisiecki 2016). It is here proposed the erosional surface below the Ambergate Plain, which steps down from 29 m to 8 m ASL, relates to the early Pleistocene stage of this trend.

The Cemetery Scarp marks the seaward limits of Yoganup and Guildford formations, and the cessation of lateritic regimes. It also coincides with the onset of widespread carbonate production on marine terraces, a phenomenon tentatively attributed to the commencement of the warm Leeuwin Current (Collins *et al.* 1991).

The Ludlow Plain is substantially built from shallow-marine shelly limestone, provisionally assigned to the last interglacial MIS 5e (~125 ka). The limestone accumulated on a pre-cut erosional surface 3–5 m ASL, cut into sandstone of the Leederville Formation and abutting the Cemetery Scarp. It is unlikely that the sedimentary processes that deposited the limestone were responsible for the cutting of the scarp, inferring that the scarp is older than MIS 5.

If the Ludlow Plain limestone is MIS 5 in age, the morphological expressions and sedimentary products of previous interglacials (MIS 7, 9, 11 and 13) are to be expected, but are not obviously evident. The warmest and most long-lived interglacial of the ~100 ka cyclic phase of global Pleistocene glaciations is MIS 11 (~400 ka), which induced highstands of up to 13 m ASL for a period of some 30 000 years (Dutton *et al*. 2015). As such, it is possible that the Cemetery Scarp formed at this time, as may the shelly unit within the Ambergate Plain in the Elgin area just northeast of Capel, but the latter requires further investigation. Alternatively, the 'Tamala-type' limestone under the Ludlow Plain may represent a condensed sequence of several interglacial stages. The author is unaware of any continuous core through the limestone with complete recovery to test this possibility.

The highstand of the last inter-glacial at 125 ka was 6–9 m ASL (Dutton *et al*. 2015) and preceded the staged fall into the last glacial maximum. In Australia this maximum is believed to be 20 000 to 17 000 y BP (Barrows *et al*. 2002) when the sea level fell to about 130 m below its present level (Miller *et al.* 2020) exposing an extensive wind plain to the west. Thus, the shelly facies limestone was sub-aerially exposed for over 100 000 years, during which time the hard cap and pinnacles would have formed.

The sea level curve for the last 10 000 years of Twiggs & Collins (2010) is the key to interpreting near-shore processes in Geographe Bay. From this curve it is inferred that the post-glacial marine transgression passed the current position of the coast at 7500 y BP to reach a highstand of 2–3 m ASL at 7000 y BP. A mini scarp with low sand ridges near Wonnerup House marks this highstand. Subsequently the sea level slowly receded to its present position. This last recession exposed the Busselton Wetlands Plain, upon which coastal barrier dunes developed, creating wetlands and river diversions.

River Evolution

River activity has played a significant, but secondary role to sea-level changes, in shaping the scarps and plains. The Preston and Capel rivers, which form the larger drainages of the area, have catchments on the adjacent Yilgarn Craton, and cut substantial valleys through the Whicher Scarp. They dissect the old lateritized surface of the Blackwood and Darling Plateaus and have remnants of plateau laterite that descend partially down the valley spurs, indicating initial valley development commences during the Eocene about 40 million years ago. Rivers experienced slow prolonged rejuvenation by sea-level fall, leading to deep incision into sandstone of the Leederville Formation during the major erosional event that formed the Whicher Scarp. The re-entrant of the Yelverton Bench into the Capel River valley indicates it was already a substantial gorge by the mid-Miocene (around 15 Ma). These rivers also have re-entrants of piedmont laterite into their range-front valleys at the Whicher Toe-line. The rejuvenation process that formed the Capel River therefore probably lasted more than 30 million years.

In contrast, the smaller rivers (viz. the Ludlow, Abba, Sabina, Vasse, Carbunup and Buayanup) drain only the Whicher Scarp, and probably were initiated during the Pliocene (around 3 Ma) when sea-level retreat became more rapid and the coastal plains developed over a much shorter period. After disgorging from their range-front valleys, all rivers build alluvial fans at the Whicher Toe-line and incise the coastal plains as they flow down the gentle topographic gradient. Depth of incision is up to 11 m in the upper tracts of the Ambergate Plain and 7 m at its western edge. Submarine paleo-valleys evident on bathymetric light-detection-and-ranging (LIDAR) images align with some of the present rivers, indicating they were extant during the Pleistocene glacial maxima when sea levels were markedly lower than at present and the shore extended some 80 km to the west.

RIVER DIVERSION ON THE WETLAND PLAIN

In the present interglacial, all rivers were subject to obstruction and diversion by the build-up of the post-glacial Quindalup dune barrier. The Vasse River at the present site of Busselton City deflects orthogonally onto the east-draining estuary. LIDAR bathymetry indicates it previously continued across the wind plain during the glacial maximum. The barrier at Busselton appeared soon after 7500 y BP, when the coast assumed its present position and coastal dunes started to build. All vestiges of the ancestral outlet of the Vasse River at Busselton have disappeared but is projected to have been directly west of the Busselton Jetty.

After gathering flows from the Abba and Sabina rivers, the re-directed Vasse River takes a major bend toward the present coast at Wonnerup and then turns again eastward to its present outlet (Fig. 11). The Capel River joined the Vasse at this S-bend prior to its engineering

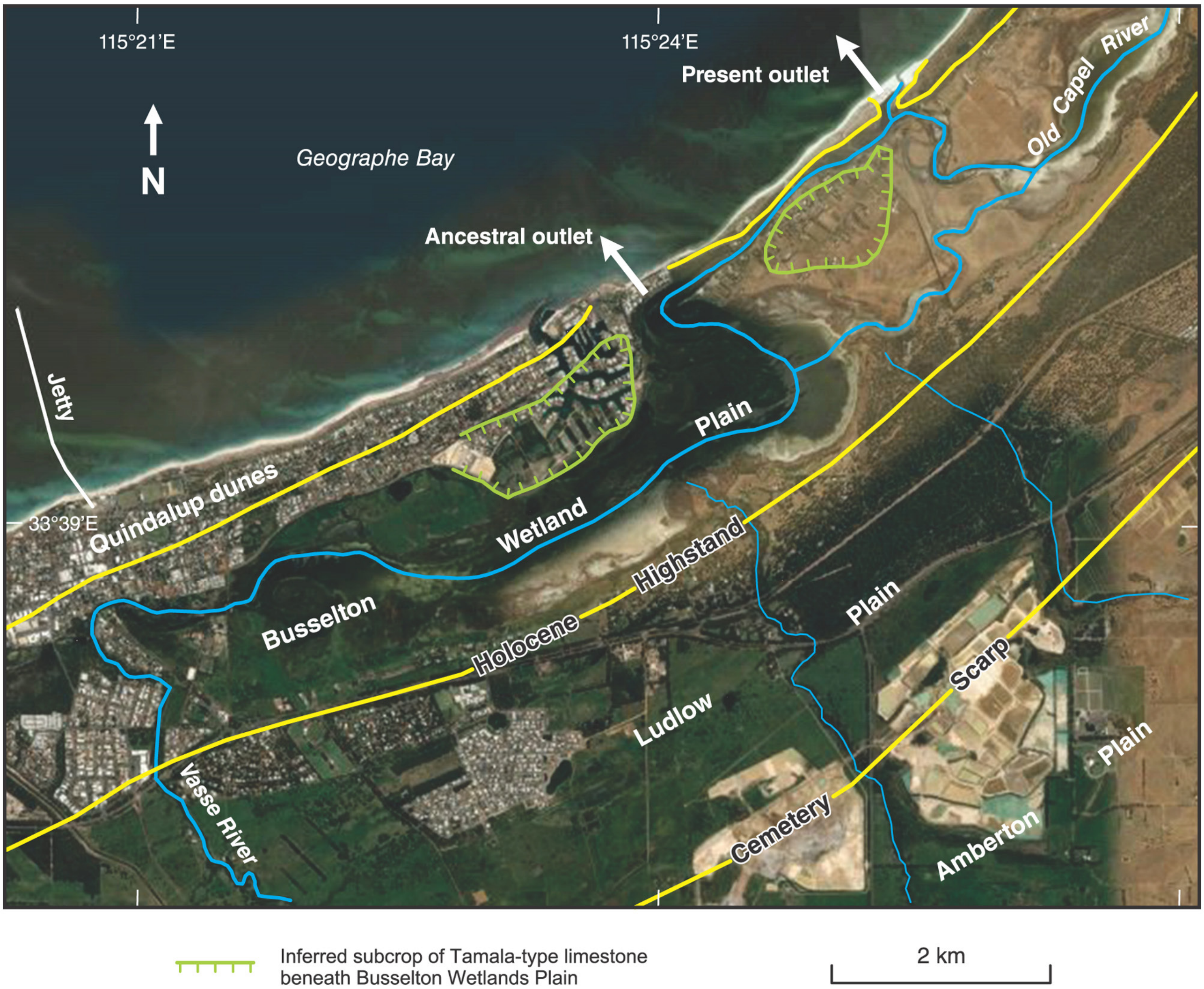


Figure 11. River systems and geomorphic elements of Busselton – Port Geographe area showing distribution of 'Tamala-type' limestone (green barbed line) and position of ancestral Vasse–Capel outlet at Wonnerup.

diversion directly to the coast in the late 1880s. The two rivers discharged into the sea at the Wonnerup townsite. This explains the relatively low profile of the present-day barrier dunes at this point. Drillholes and geotechnical penetrometer probes put down during the Port Geographe development (Cocks 1990, 1995, 2000, 2005) show the position of the ancestral Wonnerup outlet. A sand-filled channel at least 18 m deep cuts through a bar of 'Tamala-type' limestone at the position of the eastern revetment of the Port Geographe development (Fig. 11). The present-day Vasse River outlet is 2 km east of the now-sealed Wonnerup outlet. Altogether, the Vasse River has deflected 7 km since the early outlet at Busselton Jetty was sealed some 7000 years ago. This amounts to a 1 km per millennium migration. On this metric, the ancestral Wonnerup outlet was operating 2000 years ago.

CONCLUSIONS

All principal geomorphic elements, and their elevations (Fig. 2, Table 2) can be interpreted in terms of marine erosion of the underlying Leederville Formation during progressively falling sea levels through the Cenozoic, rather than through tectonic uplift. The last possible uplift is recorded by the low northerly dip of internal stratigraphic markers within the Leederville Formation. Lateritization was episodic throughout the Cenozoic, principally in the Eocene, Miocene and Pliocene, but not thereafter.

The oldest landform is the top of the Whicher Range which is a remnant of the Blackwood Plateau. This pre-Eocene marine erosional surface lies at 166–112 m ASL and has been subjected to deep chemical weathering and plateau lateritization prior to dissection by rivers. The Whicher Scarp formed by coastal marine erosion during a progressive fall in sea level of 115 m over a period about 40 Ma between the Eocene and the Pliocene. A Miocene stillstand during the otherwise progressive development of the Whicher Scarp, formed the Yelverton Bench, with an erosional surface at 72 m ASL. An apparent westerly fall in elevation is attributed to loss of stranded sediment from the bench.

The Whicher Toe-line at the base of the Whicher Scarp

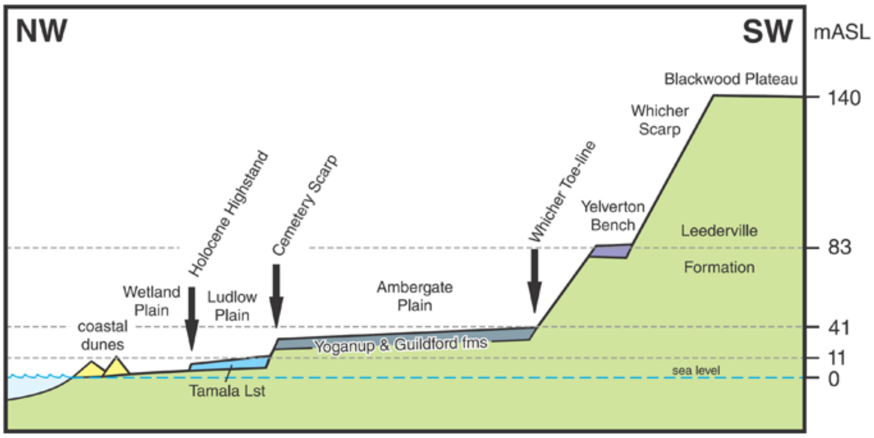


Figure 12. Schematic profile of geomorphic elements, showing key elevations (not to scale).

Table 2. Attributes of the key geomorphic elements in chronological order

Feature	Genesis	Altitude (m ASL) Geomorphic	Altitude (m ASL) Erosional	Age	Climatic Event
Blackwood Plateau	Marine erosion	166–112	166–112	Eocene (42–39	Eocene Climatic Optimum, subsequent progressive sea-level regression
Yelverton Bench	Marine erosion	83	72	Miocene (~15	Miocene Climatic Optimum high stand, subsequent progressive sea-level regression
Whicher Toe-line	Toe of scarp	41	n/a	Pliocene (3.3 – 2.9	Pliocene Climatic Optimum still stand
Ambergate Plain	Terrestrial re-sedimented marine erosion surface	41–21	29–8	Late Pliocene – early Pleistocene	Onset of oscillatory ice ages
Cemetery Scarp	Marine erosion	21	n/a	400 000 y BP (MIS 11)	MIS 11 stillstand
Ludlow Plain	Terrestrial & marine sedimented marine erosion surface	11–8	5–3	125 000 y BP (MIS 5E)	Onset cyclic Pleistocene ice ages. Beginning of carbonate production on marine terraces
Layman Ridges	Mini scarp	4	n/a	7000 y BP	Holocene highstand
Busselton Wetlands	Marine & terrestrial erosion	4–1	0 to -6	7000 y BP to present	Regression in current interglacial

marks the beginning of rapid post-Pliocene cyclic marine erosion that shaped the bounding surfaces of younger deposits across the coastal plains. The geomorphic level of the Whicher Toe-line is regionally consistent at 41 m ASL, whereas the marine erosional surface, which more precisely records the sea level, is at 29 m ASL.

The coastal plains of the Geographe Bay hinterland consist of three different coastal plains, (Ambergate, Ludlow and Busselton Wetlands) each with distinct geology, geomorphology, genesis and age pointing to a complex history for the commonly applied term 'Swan Coastal Plain'. The Ambergate Plain is a terrestrially re-sedimented, marine-cut surface upon which the Yoganup Formation strands were deposited during a late Pliocene marine regression. The erosion surface cut into the Leederville Formation shelves gently seaward from 22 m ASL through a series of erosional steps to 11 m ASL. The 'Yoganup strands' were subsequently covered by paralic lagoonal and fluvial mud and sand attributed to the Guildford Formation.

The distinctive Cemetery Scarp, which cuts the Ambergate Plain, marks the seaward extent of paralic sedimentation, the limit of lateritized terrains and the beginning of carbonate shelf sedimentation in the region. A thin layer of 'Tamala-type' limestone, of likely MIS 5e age (~124 ka) underlies the Ludlow Plain and was probably deposited against the pre-cut Cemetery Scarp that may be as old as MIS 11 (~400 ka).

The Busselton Wetlands Plain formed after sea level receded from the Holocene highstand at 2–3 m ASL in the current interglacial, after the last glacial maximum. It has been the site of significant river diversions caused by the build-up of the present coastal dunes.

With tectonic stability, and the absence of masking dune systems, this area offers a key reference for Cenozoic global sea levels; this will require further precise dating and the construction of a form surface of the erosion surface of the Leederville Formation from the voluminous open-file mineral exploration drilling. In extrapolating the sea-level indicators outside the Geographe Bay hinterland, it is essential that sub-surface data, particularly from mineral exploration, be taken into account. Meaningful correlation cannot be done on geomorphic levels alone.

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