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An Archive of Environmental and Global Sea-Level Changes

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Cover illustration: View looking south-east from Cape Dombey, Robe, southern South Australia, towards the actively eroding cliffs of Robe Range, an aeolianite coastal barrier complex of Late Pleistocene to Holocene age. The original dune crest of the Late Pleistocene landform is highlighted by the strongly indurated calcrete profile (light coloured band), which is overlain by vegetated Holocene dunes. The cliff is 20 m high. In the horizon, near-shore islands of Robe Range illustrate the active erosion of this coastal barrier. Similar erosional residuals occur up to 1.5 km offshore and illustrate the high rates of erosion along this coastline since the attainment of the Holocene sea-level highstand 7000 years ago. The Late Pleistocene components of Robe Range were deposited during Marine Isotope Substage 5c (105 ka; Robe III) and MIS 5a (82 ka; Robe II); only Robe III is visible in the photograph. The overlying Holocene dunes (Robe I) were deposited since the culmination of post-Last Glacial Maximum sea-level rise (Photograph: Murray-Wallace, 2017).

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For my darling daughter Deirdre

Preface

Besides being a region of fragile and subtle beauty, attracting the interests of artists, poets, novelists, naturalists (Theile and McKelvey 1972; Harris 1996; Paton 2010) and those with an interest in the aesthetics of landscapes and their preservation (Heyligers 1981), the Coorong Coastal Plain in Southern Australia is internationally significant for its long record of Quaternary sea-level changes and coastal landscape development. In particular, the region preserves a long record of temperate sedimentary carbonate deposition and evidence for sea-level highstands spanning at least the past 1 million years. The coastal plain is situated within the modern world's largest temperate carbonate realm (James and Bone 2011). An older succession of coastal barriers extends several hundred kilometres farther inland and awaits further developments in geochronological methods before their numeric ages can be satisfactorily resolved.

In a global context, the Coorong Coastal Plain and the more landward portion of the Murray Basin are unique for their preservation of coastal barrier shoreline successions in a terrestrial realm extending back in time some 7 million years. The coastal barrier landforms chronicle the latter stages of shallow marine-coastal deposition within the Murray Basin of Southern Australia. The coastal plain has attracted international interest from people with diverse research interests such as Quaternary geochronology, palaeopedology, palaeomagnetism, palaeontology in its various forms including megafaunal extinctions, volcanology, Quaternary sea-level changes, karst geomorphology, cool-water temperate carbonate deposition, as well as sedimentary facies models for hydrocarbon exploration.

This book provides an overview of the Quaternary geological and geomorphological evolution of the region and its significance in a global context, particularly in quantifying Pleistocene sea-level highstands. In its scope and coverage, the work seeks to complement the magisterial volume by Noel P. James and Yvonne Bone, *Neritic Carbonate Sediments in a Temperate Realm*, also published by Springer.

The rationale for writing this book is the firm conviction that the region examined needs even greater recognition on the international stage in terms of its long Quaternary record of relative sea-level changes and coastal landscape evolution, making it an important global reference site in investigations of interglacial sea-level highstand events.

There are several distinctive geomorphological attributes of the coastal plain that particularly leave an impression in the minds of international visitors to the region. First, the spatial scale of the landforms is striking, such as the uninterrupted coastal barrier dune complex of Younghusband Peninsula, which extends for 194 km and represents the longest beach in Australia. Similarly, the Coorong Lagoon, landward of Younghusband Peninsula extends over 150 km and was even larger in the mid-Holocene. In a similar manner, many of the relict coastal barrier landforms of the coastal plain can be traced along their strike length for up to 300 km, such as the last interglacial barrier Woakwine Range (Marine Isotope Substage 5e; 125 ka). Many visitors to the region have also been struck by the prolific bio-productivity of sedimentary carbonates and the seemingly ubiquitous development of calcretes (relict calcareous soil profiles), which blanket the landscape and effectively armour the ancient barrier dunes, thereby preserving much of their original morphology. Another remarkable attribute of the region is that it is situated within one of the modern world's highest wave energy settings of the Southern Ocean with a high capacity for coastal erosion, yet a remarkably long record of coastal barrier deposition is preserved.

My earliest introduction to the Coorong area was on a family holiday, camping at Policeman's Point. A few years later, the significance of the geomorphology of the Coorong Coastal Plain was clearly articulated in a first-year geography lecture given by Dr. Nick Harvey at the University of Adelaide. I was so impressed by the remarkable geomorphological character of the region that I scurried off to the South Australian Department of Mines and Energy to buy what turned out to be one of the few remaining copies of Bulletin No. 29 by Reg Sprigg on the *Geology of the South-East Province* which was published in 1952.

This book builds upon my collaborative research with several colleagues since 1989 on the long-term evolution of the coastal plain—Antonio Belperio, Amy Blakemore, Debebrata Banerjee, Alan Brenchley, Robert Bourman, Brendan Brooke, John Cann, Patrick De Deckker, Nick Harvey, Dave Huntley, Terry Lachlan, Jon Olley, the late John Prescott, David Price, Deirdre Ryan and Frances Williams. The book also builds upon many research field trips to the coastal plain as well as three previously 'road-tested' field guides (Belperio and Cann 1990; Belperio et al. 1996; Murray-Wallace and Cann 2007) produced under the auspices of the Geological Society of Australia (South Australia Division), the International Geological Correlation Program, IGCP Project 367 (*Late Quaternary Coastal Records of Rapid Change: Applications to Present and Future Conditions*) funded by the International Union of Geological Sciences and UNESCO, and a field trip associated with the XVII INQUA Congress (2007—the International Union for Quaternary Research). Two recently produced small format field guides will also assist visitors to the area (Cann 2013, 2014).

Other researchers who have influenced my thoughts about the geology and geomorphology of the region include Yvonne Bone, Jim Bowler, Steve Eggins, Victor Gostin, Rainer Grün, the late John Hutton, Noel James, Brian

Jones, Bernie Joyce, Fred Leaney; the late Orson van der Plassche, Jim Rose and Colin Woodroffe.

During the production of this book, numerous people have provided help and encouragement. I particularly thank Petra van Steenbergen, Executive Editor in Earth Sciences, Geography and Environment at Springer International in commissioning this project, and Ram Prasad Chandrasekar and Mohammed Ali with technical production of the book. I also thank Dr. Thomas Oliver for assistance with the manipulation of SRTM images, Peter Johnson, Cartographer *par excellence*, in preparing the line drawings, Sandra De La Fosse of Big Vision and Print for assistance in map reproduction, and Peter Waring of the Resources and Energy Division, Department of Premier and Cabinet (DPC), South Australia, for assistance in obtaining references that would have otherwise been more difficult to acquire. I also thank people for their assistance in granting permission to reproduce maps and photographs still covered by copyright including, Dr. Craig Williams, Editor of the Royal Society of South Australia, for permission to reproduce maps and figures published in the Transactions of the Society; Peta Abbot and Peter Waring, Resources Information, Resources and Energy Group, Department of the Premier and Cabinet, South Australia; CSIRO Land and Water Business Unit; Debbie Barrett, Elsevier Science, and Natasha Mangeruca, Mapland, Department of Environment, Water and Natural Resources. I thank Bob Bourman for reading a draft of the entire manuscript of this book.

I gratefully acknowledge research funding support from the Australian Research Council over many years, as well as the *GeoQuEST Research Centre* in the University of Wollongong.

Given the dynamic nature of many of the coastal environments examined in this book, the years that many of the photographs were taken are indicated, as this will serve to be of historical interest in subsequent investigations of the coastal landscapes. Since first visiting some field sites close to 30 years ago, with the passage of time they have become almost completely overgrown by *Acacia* (coastal wattle) such as a large borrow pit in Holocene coquina near Lake St Clair (see Fig. 3.13; field site SE#44 of Cann et al. 1999). Some of the exposed coastal localities such as portions of Robe Range have been eroded during this period, also highlighting the pace of coastal landscape change.

Wollongong, Australia — Colin V. Murray-Wallace

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Contents

Abbreviations

AAR	Amino acid racemization
AHD	Australian Height Datum
APSL	Above present sea level
b2k	Before 2000 AD
BP	Before present (a radiocarbon term referring to years before 1950 AD)
BPSL	Below present sea level
cal BP	Calibrated years before present (sidereal years)
CMAT	Current Mean Annual Temperature
D/L	Ratio of D- to L-amino acids
De	Equivalent dose
DSDP	Deep Sea Drilling Project
EPICA	European Project for Ice Coring Antarctica
ESR	Electron spin resonance
FAA	Free amino acids
GRIP	Greenland Ice Core Project
GSSP	Global Stratotype Section and Point
Gy/ka	Gray/thousands of years (radiation dose)
h	Hour(s)
ha	Hectare(s)
IODP	International Ocean Discovery Program
IR-OSL	Infrared-optically stimulated luminescence dating
ka	Kilo-anna (thousands of years)
km	Kilometre(s)
m	Metre(s)
Ma	Mega-anna (millions of years)
MIS	Marine isotope stage
mm	Millimetre(s)
mol/L	Moles per litre
NGRIP	North Greenland Ice Core Project
$^{18}O/^{16}O$	Ratio of stable oxygen isotopes
ODP	Ocean Drilling Program
OSL	Optically stimulated luminescence
SRTM	Shuttle Radar Topography Mission
THAA	Total hydrolysable amino acids
TL	Thermoluminescence dating

About the Author

Colin V. Murray-Wallace is a Quaternary geologist and currently a Professor in the School of Earth and Environmental Sciences in the University of Wollongong, Australia. He completed his Ph.D. and D.Sc. degrees in Geology at the University of Adelaide. His long-standing research interests include investigations of Quaternary sea-level changes, coastal evolution, neotectonics, carbonate sedimentary environments and amino acid racemization dating. Professor Murray-Wallace was project leader of the International Geological Correlation Program Project 437 (1999–2003) 'Coastal environmental change during sea-level highstands', and leader of the INQUA (International Union for Quaternary Research) Coastal and Marine Commission (2004–2007). He served as Editor-in-Chief of the journal *Quaternary Science Reviews* from 2008 to 2016. His previous jointly written books include *Quaternary Sea-Level Changes: A global perspective* (Cambridge, 2014) and *Coastal Landscapes of South Australia* (Adelaide, 2016). He received the A. H. Voisey Medal from the Geological Society of Australia and the Mawson Medal from the Australian Academy of Science.

1 The Coorong Coastal Plain, Southern Australia—An Introduction

Abstract

The Coorong Coastal Plain is a distinct morphotectonic province in southern Australia covering an area of approximately 34,600 km^2. The coastal plain preserves a long Quaternary record of temperate carbonate sedimentation in the form of high wave energy barrier shoreline successions and associated back-barrier facies formed in low energy, estuarine-lagoon environments. The barriers occur sub-parallel to the modern coastline and to each other due to ongoing epeirogenic uplift. The coastal barriers (locally termed Dune Ranges), the principal focus of this book, formed during successive sea level highstands over the past 1 Ma and generally increase in age landwards. Some barriers, however, are composite structures having formed in more than one interglacial or interstadial. An older succession of Pliocene to possibly Early Pleistocene coastal barriers occur farther inland as part of the later stage progradational sequence of the Murray Basin and have been mapped as Loxton-Parilla Sands. The preservation of successive Quaternary shoreline features has resulted from slow epeirogenic uplift, calcareous cementation of dune limestone (aeolianite), and regional calcrete development. Across the coastal plain from Robe to Naracoorte, the mean uplift rate is approximately 70 mm/ka. In the region surrounding the Holocene and Pleistocene volcanic centres in the southern-most portion of the coastal plain, a higher rate of uplift of 130 mm/ka has been determined.

Keywords

Coorong Coastal Plain · Coastal barriers
Bridgewater formation · Pleistocene interglacials

1.1 Introduction

The Coorong Coastal Plain in southern Australia is a natural laboratory for examining the response of coastal barrier landscapes and depositional systems to relative sea-level changes (Fig. 1.1). The region is also internationally significant for quantifying long records of ice-equivalent, glacio-eustatic sea-level changes during the Quaternary Period. The region provides direct evidence of coastal barrier sedimentation during successive interglacials and numerous interstadials over the past 1 million years, as well as geologically recent volcanism. The volcanic episodes are associated with widespread volcanism in

Photos by the author, if not indicated differently in the figure/photo legend.

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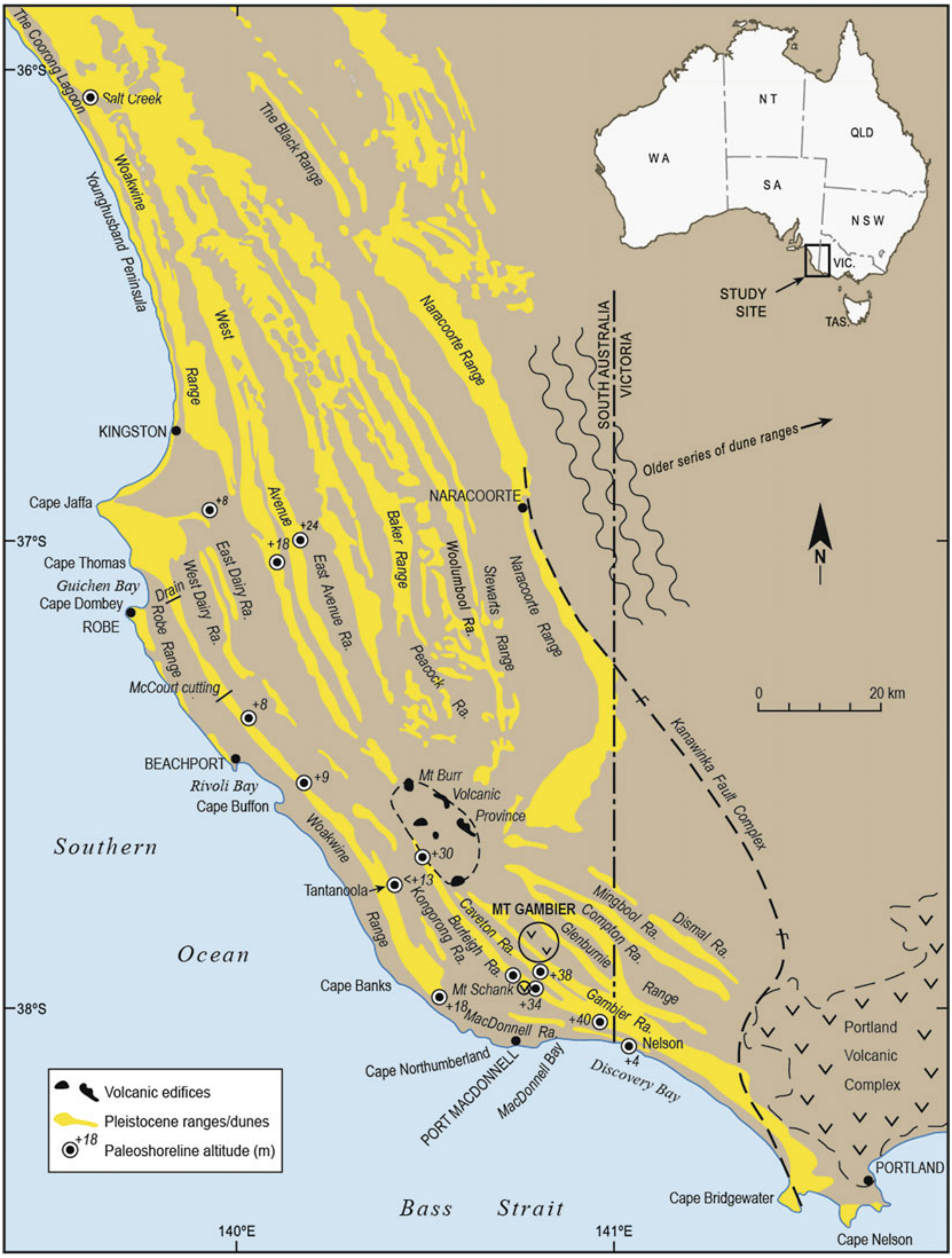

Fig. 1.1 Map of the Coorong Coastal Plain, southern Australia based on research by Hossfeld (1950), Sprigg (1952) and Murray-Wallace et al. (1996)

western Victoria, and the Pleistocene volcanic groups have directly influenced long-term coastal sedimentation.

One of the major challenges in understanding the longer record of Pleistocene global sea-level changes is the paucity of direct evidence from well-preserved shoreline successions to infer former sea levels. In a global context, the Quaternary stratigraphical record is highly fragmentary, particularly in marginal marine environments and few coastal regions around the world provide landform and stratigraphical evidence for Pleistocene sea levels before the Antepenultimate Interglacial (Marine Isotope Stage—MIS 9; c. 322 ka) leaving a gap of approximately 2.3 Ma or 89% of Quaternary time in which the record of palaeosea-level has not been directly defined from relict shoreline successions. This is due to the generally low preservation potential of relict shoreline deposits and coastal landforms resulting from erosion by terrestrial and marine processes. Although indirect inferences for palaeosea-level may be derived from oxygen isotope records of global ice volume change from deep sea and ice cores (Rohling et al. 2008; Masson-Delmotte et al. 2010), such records are enhanced by calibration, based on the dating and surveying of palaeosea-level indicators (i.e. direct measures of palaeosea-level). This is particularly important in view of local variations in ocean temperatures and salinity which may introduce variability in stable isotope records and increase the uncertainty in the magnitude of inferred former ice volumes and palaeosea-levels (Bradley 2015).

Oxygen isotope records from marine and ice cores reveal long records of climate changes of global significance. The time-series isotopic records reflect ice-volume changes associated with the waxing and waning of the continental ice sheets and valley glaciers, and as a corollary provide indirect insights into the nature of glacio-eustatic (ice-equivalent) sea-level changes during the Quaternary, in terms of their relative magnitude and timing (Murray-Wallace and Woodroffe 2014). The longest records span up to 800 ka for ice cores such as the European Project for Ice Coring (EPICA) Core from Dome C, Antarctica (Masson-Delmotte et al. 2010; Schilt et al. 2010) and longer time-series oxygen isotope records have been derived from deep sea sediments such as the LR04 compilation of 57 records that span the past 5.3 Ma (Lisiecki and Raymo 2005).

While the relative intensities of successive interglacials may be inferred from oxygen isotope records (Masson-Delmotte et al. 2010), how these data are expressed in a more quantitative manner for the magnitude of glacio-eustatic sea levels for different interglacial highstands and from different geographical realms, remains a challenging task. It is in this sense, that direct records of relative sea-level changes for long Quaternary timescales from terrestrial environments are so important despite their paucity.

The Coorong Coastal Plain in southern Australia is uniquely placed to address these issues. Situated within an intra-plate, tectonic setting and in the far-field of Pleistocene ice sheets and therefore characterised by a relative sea-level record dominated by glacio-eustatic change, and within a region not directly glaciated in the Quaternary, the coastal plain provides important stratigraphical and geomorphological evidence for glacio-eustatic sea-level changes, and in particular, interglacial and interstadial hightsands over the past 1 Ma. The relative sea-level record of the region is dominated by glacio-eustasy with a minor but quantifiable, locally-based hydro-isostatic contribution and an even smaller contribution from glacio-isostatic adjustments within near-field settings (Conrad 2013).

Given the low gradient of the coastal plain and in global terms, the slow rates of epeirogenic uplift (e.g. 70 mm/ka in the transect from Robe to Naracoorte; Fig. 1.1), modest differences in the height of sea level during successive highstands dramatically affected the geographical location of the barrier shorelines. The region can thus be described as having experienced a 'Goldilocks tectonic regime' during Quaternary time, as the rate of epeirogenic uplift is not too fast to cause erosion of the emergent shoreline complexes through substantial changes in base level, and just sufficient for many of the successive interglacial highstand events to be represented in the geological record. In addition, the absence of large river systems across the coastal plain has significantly curtailed rates of denudation and enhanced the preservation of the stratigraphical record.

The coastal plain is located within the modern world's largest temperate carbonate factory, a region characterised by very high calcium carbonate bio-productivity on the adjacent continental shelves of the southern and Western Australian margins (James and Bone 2011). The level of carbonate bio-productivity is also attested by the spatial scale of the coastal landforms. Individual coastal barriers, termed 'Dune Ranges' such as the last interglacial (MIS 5e; 125 ka) Woakwine Range can be traced along their strike lengths for over 300 km in largely uninterrupted form as low relief landforms, '… across the otherwise flat, featureless country' (Mawson and Dallwitz 1944, p. 192). Commonly the barriers are 1–3 km wide in cross-section and attain maximum heights of up to 40 m above the general surface of the coastal plain. The coastal barriers conform to the classical definition of these landforms, in being laterally-persistent sand accumulations formed by wave and wind action and backed on their landward side by an estuarine-lagoon system at the time of their formation (Otvos 2012).

The Coorong Coastal Plain is also globally significant in representing one of the few coastal barrier landscapes in which empirical evidence for the Early-Middle Pleistocene Transition is preserved. This is manifested by the onset of prolific sedimentary carbonate production during the sea level highstands following the end of Early Pleistocene time. The sediment of the Middle Pleistocene West Naracoorte Range for example, comprises up to 90% calcium carbonate (bioclastic, skeletal carbonate sand) in contrast to the older East Naracoorte Range (>781 ka) which comprises only 21% sedimentary carbonate (Murray-Wallace et al. 2001). From about 940 ka ago corresponding to MIS 22 (Head and Gibbard 2005), to the Last Glacial Maximum, substantially larger ice volumes are evident during glacial maxima in oxygen isotope records (Lisiecki and Raymo 2005). By implication, geographically more extensive subaerial exposure of the continental shelves and the landward entrainment of larger volumes of bioclastic sand is likely to have occurred at times of de-glacial sea-level rise to produce volumetrically larger coastal barrier landforms.

1.2 The Coorong Coastal Plain as a Morphotectonic Province

From the River Murray Mouth and its terminal lakes, Lakes Alexandrina and Albert, the Coorong Coastal Plain extends for some 300 km south-east along the modern coastline to the east of Mount Gambier and into western Victoria (Fig. 1.1). The coastal plain is a distinctive morphotectonic domain in southern Australia, and for the purposes of this book, is defined as extending from the modern coastline, landward to the Marmon Jabuk, Coonalpyn, Hynam and East Naracoorte Ranges covering an area of approximately 34,600 km^2 (Fig. 1.2).

Morphotectonic regions are characterised by distinctive landform assemblages that define a particular area, and which differ from adjacent regions. Tectonic processes commonly create a level of landscape uniformity within a morphotectonic region irrespective of whether a region is tectonically highly active or highly stable. Accordingly, morphotectonic regions show some uniformity in the scale and types of landforms present that confer an internal coherence to the regional landscape (Fenner 1930; Jennings and Mabbutt 1986). The presence of different morphotectonic regions at a continental-scale is a direct expression of contrasting modes of tectonic behaviour. In southern Australia, the Yilgarn Craton (Western Australia) and Gawler Craton (Eyre and Yorke Peninsulas, South Australia) are examples of morphotectonic regions of high tectonic stability. In contrast, the Mount Lofty Ranges (part of the Adelaide Foldbelt; also termed Adelaide Geosyncline) is a region that is more seismically active and shows evidence of neotectonic activity in the later Quaternary,

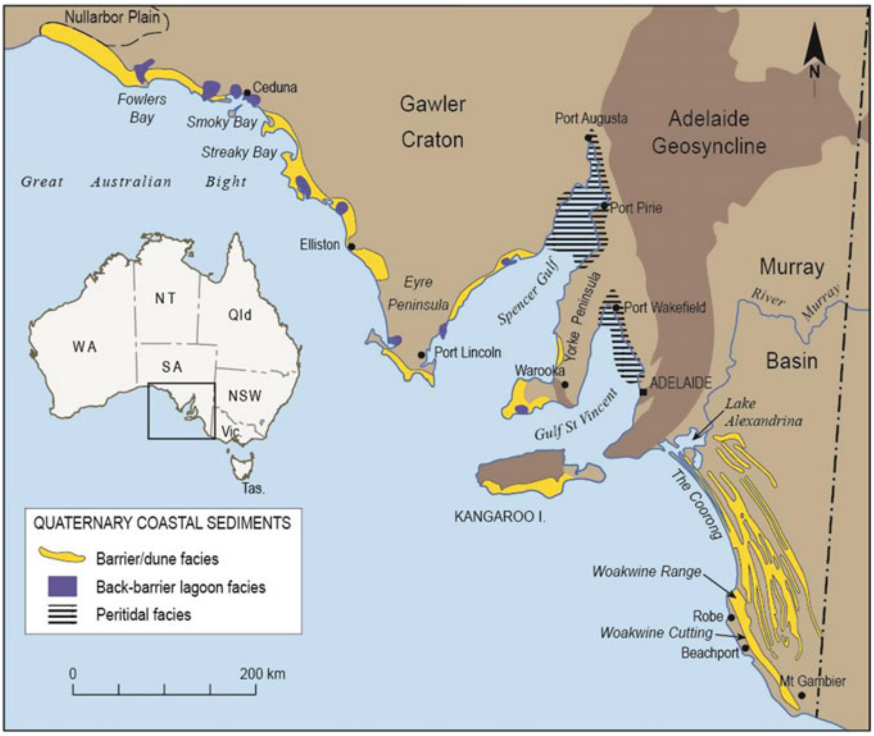

Fig. 1.2 Map of principal morphotectonic provinces of southern Australia illustrating the location of the Coorong Coastal Plain in southern South Australia

manifested by uplift of well-defined horst blocks along range-bounding faults (Bourman et al. 1999; Jayawardena 2013).

The Coorong Coastal Plain is a distinctive morphotectonic province distinguished by a sequence of coastal barriers that extend along the entire length of the coastal plain. The barrier landforms have been uplifted during the Quaternary by epeirogenic processes. The magnitude of uplift, although small in global terms (10s metres over 100s ka), is evident in transects landward across the coastal plain from the modern coastline, and along the shore parallel length of the coastal plain for individual barriers.

The coastal plain is a low relief seaward sloping landscape of 0.5° punctuated by a series of coastal barrier landforms in a transect between the towns of Naracoorte and Robe (Fig. 1.1). The coastal plain is bounded by Proterozoic and Cambrian strata of the Mount Lofty Ranges to the north-west, by an older succession of Pliocene to Early Pleistocene barriers (Loxton-Parilla Sands) of the Murray Basin to the north-east, and by the Pleistocene volcanic plains (Newer Volcanics) of western Victoria. The coastal plain represents the latest stage of progradational development of the Murray Basin following a major phase of deeper water marine inundation after the final separation of Australia and Antarctica some 43 Ma ago (Brown and Stephenson 1991). The earlier phase of deposition within the Murray Basin was characterised by deeper water marine limestones (Brown and Stephenson 1991; Lukasik and James 2006).

During the Quaternary the coastal plain has evolved progressively from the interplay of repetitive sea-level transgressions and regressions associated with a succession of Pleistocene interglacials and interstadials. The geomorphological evolution of the region has also been profoundly influenced by the prolific bio-productivity of sedimentary carbonates on the inner continental shelf (Lacepede and Bonney Shelves), high wave and wind energy to form substantial coastal barrier dune systems, and slow epeirogenic uplift associated with plate tectonic ridge push and localised volcanism and crustal doming of the Paleogene/Neogene bedrock.

The shoreline successions, representing the depositional product of successive sea level highstands, have been preserved by ongoing uplift to remove the relict coastal landforms from erosion by younger sea level highstands. Extensive subaerial calcrete development, an expression of regional aridity, has effectively blanketed the regional barrier beach landform complexes aiding the preservation of their original morphostratigraphic form. The Coorong Coastal Plain to the north and the Mount Gambier Coastal Plain (Gambier Sunklands of Sprigg 1952) to the south are separated by a region of localised upwarp termed the Mount Burr Peninsula (Sprigg 1952; Blakemore et al. 2015). This book adopts the term Coorong Coastal Plain for the entire region acknowledging the importance of the modern landscapes as an analogue for the Pleistocene coastal landscapes.

Modern and Holocene coastal sediments and sedimentary environments that have developed during the past 7000 years since the attainment of the Holocene highstand are of particular significance for interpreting the preserved sediment facies and for making inferences about palaeosea-levels from the Pleistocene successions. In south-eastern Australia, present sea level was attained by 7000 years ago, representing the cessation of sea-level rise following the post-Last Glacial Maximum transgression (Lewis et al. 2013). The coastal sedimentary successions and landforms that developed during this period provide a more recent analogue of the Pleistocene barrier shoreline successions.

1.3 Historical Background

Numerous studies have examined aspects of the Quaternary environmental history and record of past sea levels of the Coorong Coastal Plain. Some of the more significant earlier studies that have led to a more detailed understanding of the geological history of the region, particularly in terms of relative sea-level change as currently understood, include those of Hossfeld (1950), Sprigg (1952), Firman (1973), Cook et al. (1977), Schwebel (1978, 1983, 1984) and Huntley et al. (1993a, b, 1994).

Early impressions of the coastal landscapes of the region were documented by Nicolas Baudin and Matthew Flinders during their respective voyages in 1802 charting the coastline of Australia. The two met on Friday 9th April, 1802 at what Flinders would later term Encounter Bay, approximately 11 km SSE of the mouth of the River Murray (S 35° 44′; E 139° 28′), although they were too far offshore to identify this feature. Baudin in *Le Géographe* had sailed north along the coast from Lacepede Bay, while Flinders in HMS *Investigator* had sailed from Gulf St Vincent, through Backstairs Passage between Fleurieu Peninsula and Kangaroo Island, arriving at Encounter Bay. Baudin noted that;

> The entire stretch of coast that we have examined since yesterday consists solely of sand-hills and inspires nothing but gloom and disappointment. Quite apart from the unpleasant view that it offers, the sea breaks with extraordinary force all along the shore, and two or three swells preceding the breakers indicate that there is a bar there which must reach at least half a mile out to sea. (Baudin 2004, p. 379).

After their encounter exchanging information about the respective coastlines they had both charted, Flinders sailed south-east along the Lacepede Bay coastline (Younghusband Peninsula) noting that;

> From Encounter Bay to this slight projection [Cape Bernouilli of the French Navigators; south-west of Cape Jaffa], the coast is little else than a bank of sand with a few hummocks on the top, partially covered with small vegetation; nor could any thing (sic) in the interior country be distinguished above the bank. (Flinders 1814, p. 197).

The first detailed geological observations made in this region were reported by Reverend Julian Edmund Woods in 1862, resulting from his missionary travels from Penola to Naracoorte, Bordertown, Robe and Mount Gambier (note that he subsequently published under the name Tenison-Woods; Fig. 1.3). Woods made many astute observations about the nature of the regional geology and landscapes of the Coorong Coastal Plain, as well as more extensive regions of southern Australia. He noted the pronounced lateral extent of the coastal barriers over distances of tens of kilometres, locally termed 'dune ranges', that ongoing 'upheaval' of the coastal plain explained the origin of the raised beaches, that each range corresponded with a former coastline and that the flats on the landward side of each barrier represent former estuaries. The findings of Woods (1862) were published when little was known about the nature and complexity of Quaternary sea-level changes. Accordingly, glacio-eustatic sea-level changes were not distinguished from uplift of the coastal plain. He assumed that the succession of coastal barrier landforms resulted from periodic phases of quiescence in uplift rather than a series of eustatic-changes. Woods (1862) also described the marine fossils from the Paleogene—Neogene limestones representing the local basement to the Quaternary sedimentary successions as well as the volcanic landforms and cave and karst features of the region, providing detailed engravings made from photographs. This new-found appreciation of the physical landscape of the coastal plain was independently supplemented by the highly accurate renderings of the accomplished artist and landscape painter Eugene von Guérard (1811–1901) in his series of paintings of the Newer Volcanics (Pullin 2016).

Woods subsequently published a more detailed map of the coastal plain outlining the positions of eleven of the coastal barriers from Salt Creek to the Glenelg River area to the east of Mount Gambier and across to Naracoorte in the north (Woods 1866; Fig. 1.4). His map is significant in several respects particularly given that his observations were made on horse-back before an age of remote sensing technology. Woods completed much of his survey work with a compass on horseback before the residents of his home base in the Penola District donated funds to buy him a buggy (Press 1994). The broad shape of many of the ranges in plan-view is relatively accurately rendered in his map of 1866; Fig. 1.4). Woods correctly deduced the lateral continuity of what is now termed the Last Interglacial (125 ka) Woakwine Range along the entire length of the coastal plain. He also astutely depicted the curvature of some of the ranges in relation to the Mount Burr Volcanic Province and in broad view, correctly determined the relative spacing of many of the barriers across substantial parts of the coastal plain. Accounts of the early life of Tenison Woods are given by Press (1994) and Hamilton-Smith (2006).

Based on a short visit to the area of Robe and Guichen Bay, the Chief Justice of South Australia (1861–1876) Sir Richard Davies Hanson, set out to describe the landforms of the region (Hanson 1867) and to clarify some interpretations made by Tenison Woods in his book *Geological Observations in South Australia* (Woods 1862). Hanson described the sand hills of the region and mistakenly identified middens within pedogenically modified dune sands as natural shell accumulations, and invoked changes in elevation of the land to account for their preservation, as well as for other geological features. Hanson also made numerous other factually incorrect interpretations based on his field observations. Tenison Woods (1867) prepared a carefully crafted response outlining the short comings of many of Hanson's field observations and interpretations. Given the status of Hanson in Adelaide society, the exchange must have caused embarrassment in the early history of the Adelaide Philosophical Society (later to become the Royal Society of South Australia in 1880).

Crocker and Cotton (1946) described several raised beaches and associated fossil marine mollusc assemblages in the southern portion of the coastal plain, particularly in the Mount Gambier region of South Australia. They introduced the terms Burleigh and Caveton Ranges, correlatives of the Reedy Creek and West Avenue Ranges respectively, which occur within the region between Robe and Naracoorte some 120 km to the north-west. Another notable aspect of their paper is a time-slice map

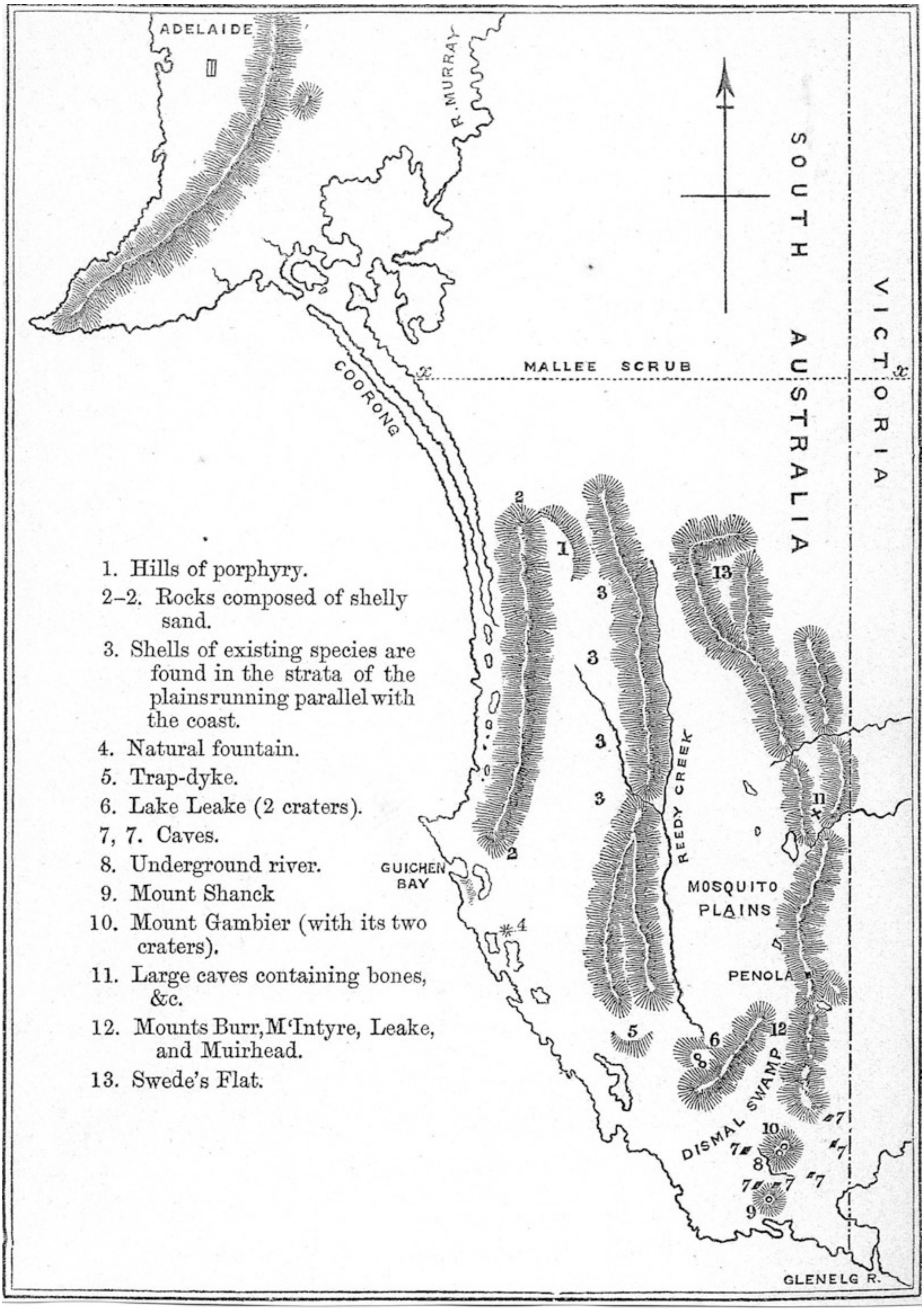

Fig. 1.3 Regional map of the Coorong Coastal Plain, southern Australia, compiled by Reverend Julian Edmund Tenison Woods, as published in 1862 in his book *Geological Observations in South Australia* (*Source* Woods 1862)

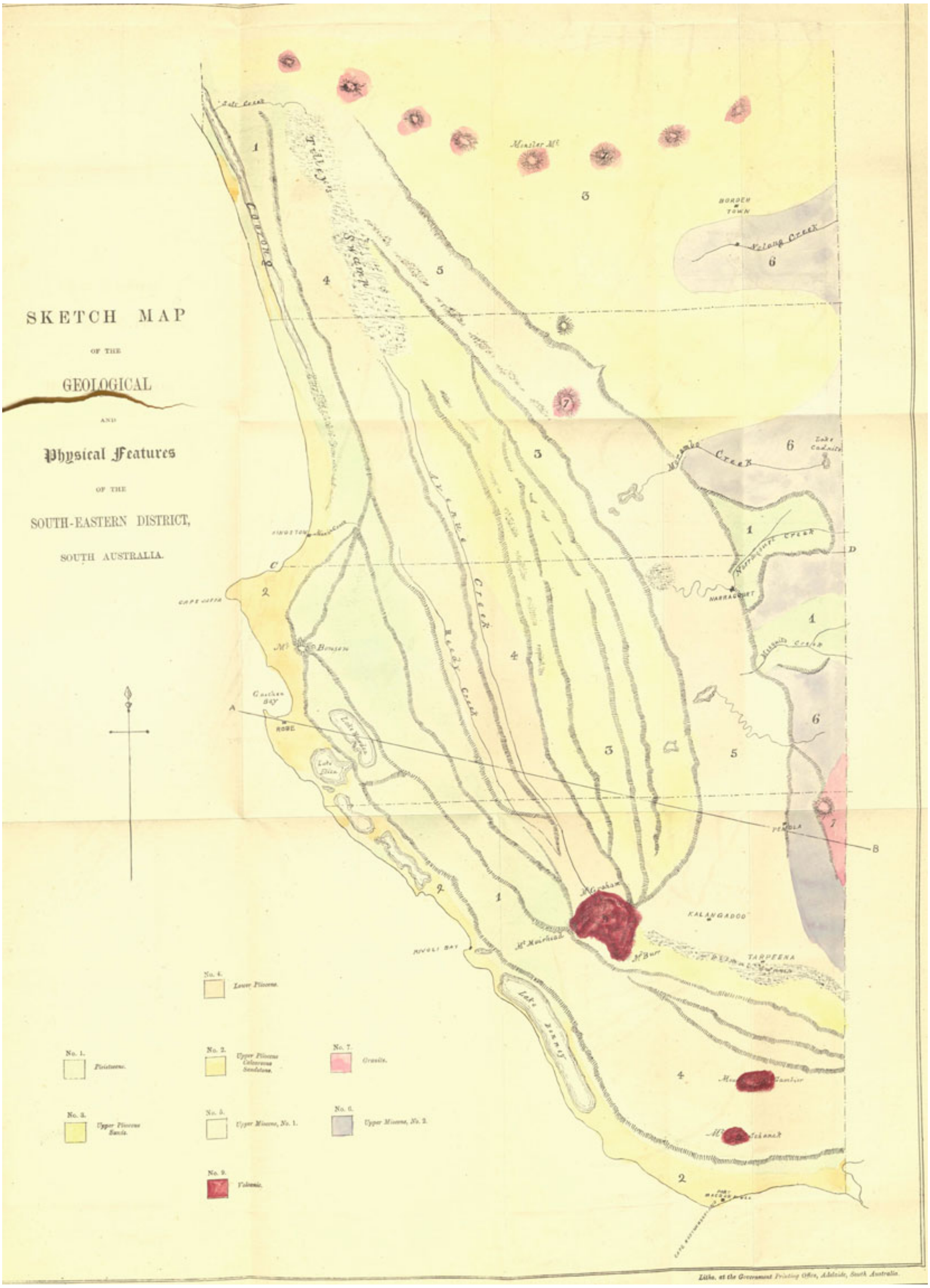

Fig. 1.4 Regional map of the Coorong Coastal Plain, southern Australia, compiled by Reverend Julian Edmund Tenison Woods in 1866. The map presents considerably greater detail on the spatial distribution of the relict coastal barrier landforms than his map published in *Geological Observations in South Australia* which was published four years earlier (cf. Fig. 1.3; *Source* Woods 1866)

illustrating four sequential stages in the evolutionary development of the coastal plain.

Hossfeld (1950) presented an overview of the late Cenozoic history of the coastal plain based on his field investigations undertaken between 1931 and 1949. The availability of thousands of topographical elevation measurements by the South-Eastern Drainage Board and aerial photographs enabled a more detailed evaluation of the spatial configuration of the coastal barrier landforms in the regional landscape. Hossfeld identified 18 coastal barriers across the coastal plain and noted that due to local geological factors, not all 18 barriers occur within a single line of section across the plain (Fig. 1.5). He noted that by tracing some of the dune ranges along their strike that some gradually disappear or terminate abruptly or coalesce with other ranges. Subtle variations in the original topography of the coastal plain and differential rates of uplift are likely to contribute to these irregularities in the spatial distribution of the dune ranges. In addition, Hossfeld referred to two ranges that had been eroded, which relate to earlier phases of deposition of the Woakwine Range concluding that in total, 20 dune ranges had formed across the coastal plain. He also acknowledged that additional ranges may have been completely destroyed by erosion. This conclusion was based on the composite structure of dune ranges such as the Woakwine Range which was found to comprise four distinct components separated by major erosional truncations defined by shelly detritus and pebbles, an observation subsequently affirmed by Sprigg (1952).

Hossfeld presented a detailed map of the coastal plain illustrating the spatial distribution of the dune ranges (Fig. 1.5). It has been suggested that Hossfeld's work was overshadowed by the research outcomes reported by Reg Sprigg in a Bulletin of the Geological Survey of South Australia in 1952 (Twidale 2012). This is also seen in terms of stratigraphical priority as the West Woakwine and Canunda Ranges of Hossfeld (1950) were subsequently termed Woakwine and Robe Range by Sprigg (1952) and have since become entrenched in the literature as noted by Carter (1985).

Sprigg (1951) was highly critical of Hossfeld's paper citing problems in map interpretation, as well as observations related to evidence for faulting and other stratigraphical interpretations. Sprigg (1952) subsequently published his benchmark geological bulletin on the geology of the coastal plain ("South-East Province") and presented one of the most detailed maps hitherto published of the dune ranges (Fig. 1.6). The work was based on fieldwork undertaken between 1947 and 1949. Sprigg (1952) assigned ages to each of the dune ranges within a framework of the Croll-Milankovitch Hypothesis of global climate and sea-level fluctuations that were influenced by the changing configuration of the Earth's orbital movement around the Sun. This represented a significant and perhaps courageous achievement, as at the time of publication, the Croll-Milankovitch Hypothesis had fallen into disfavour and was not to regain broad acceptance until significant developments in oxygen isotope stratigraphy and geochronology (Shackleton and Opdyke 1973; Hays et al. 1976). More detailed discussions of the wider research accomplishments of Reg Sprigg are given elsewhere (Weidenbach 2008; McGowran 2013).

Sprigg (1979) reappraised the Quaternary stratigraphy of the Coorong Coastal Plain, concluding that two associations of dune ranges occur across the coastal plain (the *Wimmera* and *Bridgewater Catenas*). He suggested that the *Bridgewater Catena*, located between the present coastline and extending up to 100 km inland to the Hynam Range and at a lower elevation, comprised dune limestones (calcarenites), representing beaches of glacial age (Lowstand sedimentary successions), while the *Wimmera Catena*, situated landward of the Bridgewater Catena and at about 100 m above the level of the Bridgewater Catena, represented an interglacial dune range complex of predominantly siliciclastic sediments (Highstand sedimentary successions). Sprigg (1979) stated that these ideas were originally formulated in 1966 but were not published until 1979. Although the change in his reasoning about the genetic association of the Bridgewater Formation (Catena) with glacial age lowstands, rather than interglacial highstands is

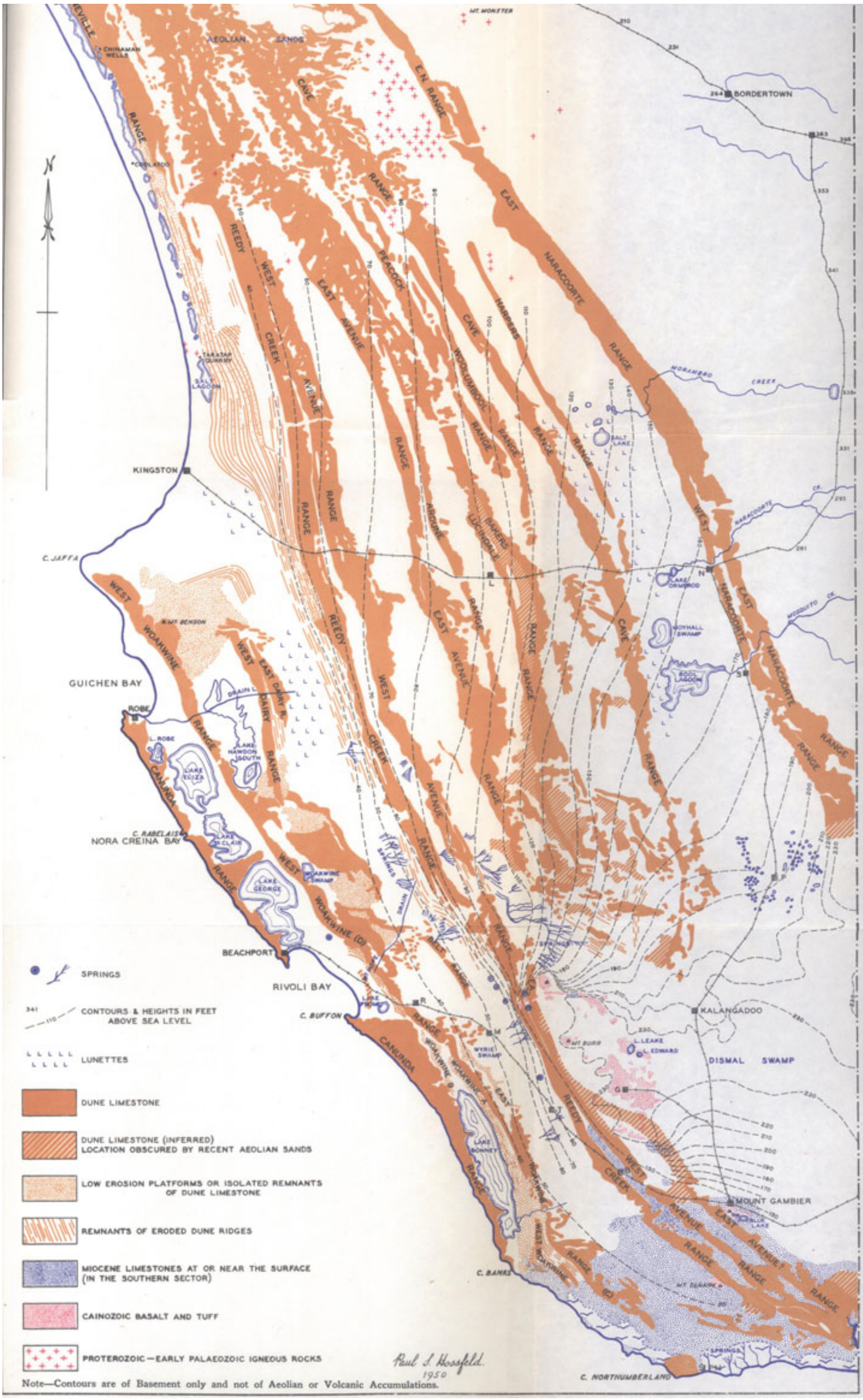

Fig. 1.5 A portion of Paul Hossfeld's map of the Coorong Coastal Plain, southern Australia, based on fieldwork undertaken between 1931 and 1949. (*Source* Hossfeld 1950; reproduced with permission of the Royal Society of South Australia)

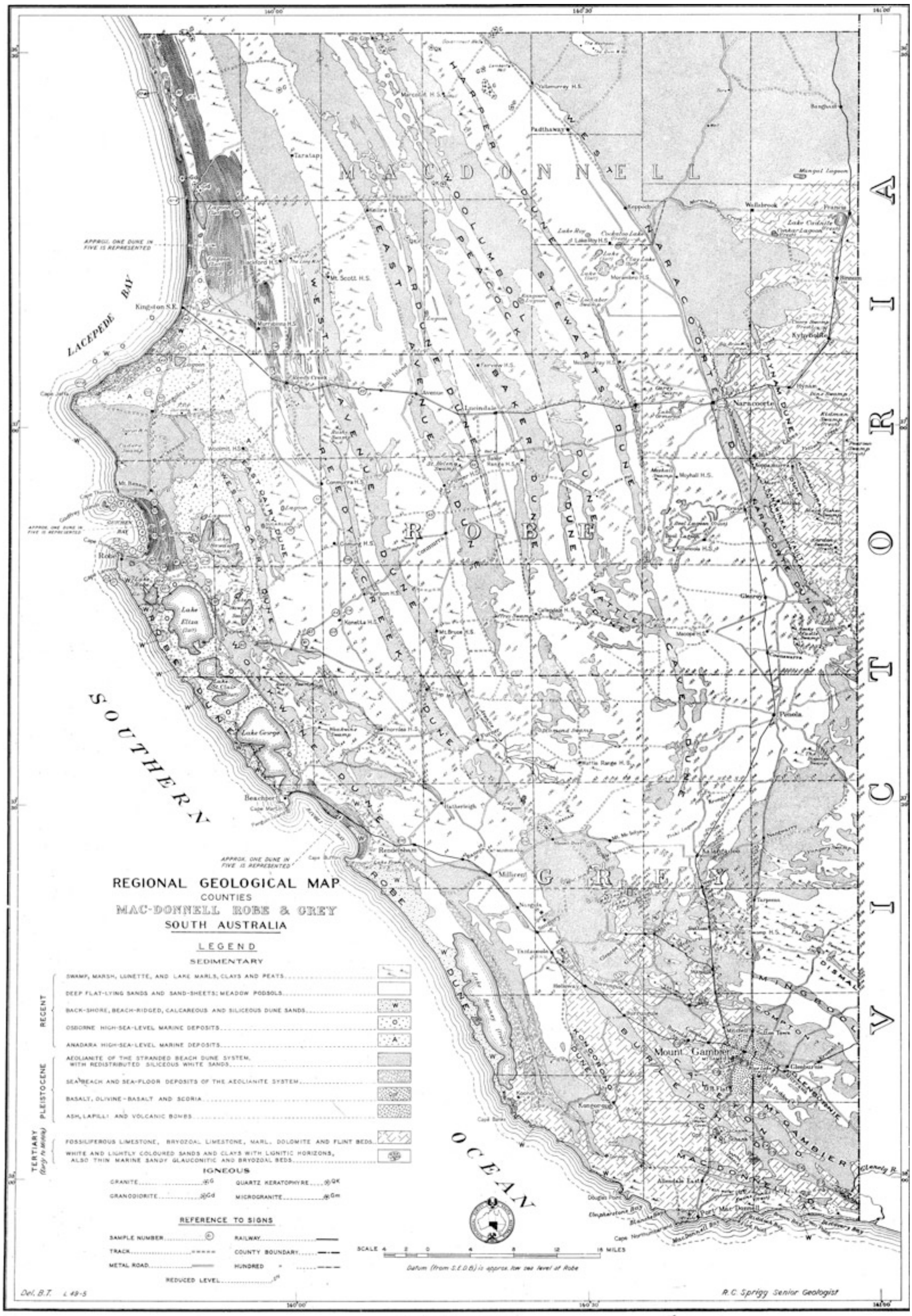

Fig. 1.6 Reg Sprigg's 1952 map of the Coorong Coastal Plain, southern Australia, illustrating the spatial distribution of the coastal barriers (dune ranges), volcanic landforms and principal areas of outcropping Oligo-Miocene Gambier Limestone (map reproduced with permission of the Resources and Energy Group, Department of the Premier and Cabinet (DPC), South Australia)

not explicitly discussed in his 1979 paper in the journal *Sedimentary Geology*, it would appear that several factors influenced his thoughts. The azimuths of some of the cross-bedded aeolianite beach sand drift successions capping the Bridgewater Catena were not in accord with modern wind patterns and appeared to correspond with glacial age dune directions in parts of central Australia. The sand drifts, however, post-date deposition of the Bridgewater Formation as revealed by subsequent geochronological investigations (Fitzsimmons and Barrows 2012). The contrasting elevations of the two successions also favoured in Sprigg's reasoning, the notion of a glacial age lowstand and interglacial age highstand dichotomy. Sprigg also invoked a Croll-Milankovitch Winter Insolation model for the assignment of numeric ages to the barriers of the Bridgewater Catena, and the position of the Brunhes–Matuyama geomagnetic polarity reversal, then dated at 690 ka, further influenced his thoughts about the ages of the barrier successions younger than the East Naracoorte Range. Sprigg (1979) did not consider the preservation potential of the dune ranges closest to the sea (Bridgewater Catena) which would have been submerged during successive transgressions and potentially subjected to extensive marine erosion were his hypothesis correct.

In the first volume of his autobiographical account of his research accomplishments, Sprigg (1989) reveals that following his 1979 publication in *Sedimentary Geology*, that he became even more convinced about the dichotomy of a lowstand calcarenite Bridgewater Catena and a highstand siliciclastic Wimmera Catena. In his memoirs he refers to the presence of 'ancient consolidated beach rock (aeolianite)' (Sprigg 1989, p. 260) on the shelf up to 100 km from Cape Jaffa implying a sea level fall of at least 70 m to subaerially form these deposits; hence his subsequent reasoning that the Bridgewater Catena formed at times of glacial low sea level.

Blackburn et al. (1965) reported the results of an extensive field investigation examining the regional soil groups of south-eastern South Australia. They produced a map of the 'stranded beach ridges' (relict coastal barriers) based on their own field observations during several soil surveys and noted that their interpretation of the overall spatial arrangement of the relict coastal landforms was in substantial agreement with the mapping of Hossfeld (1950) and Sprigg (1952) (Fig. 1.7). The map is notable in that it illustrates the connection of the barrier systems in the southern portion of the coastal plain with those farther north in the River Murray Mouth and terminal lakes area as mapped by de Mooy (1959a, b). Blackburn et al. (1965) noted the presence of 29 ridges across the coastal plain and remarked on the role of outcropping bedrock in influencing coastal configuration in different areas of the coastal plain. Their interest in the coastal barrier sequence related to comparing the relative ages of the landforms with the degree of soil development upon them. Blackburn et al. (1965) disagreed with Hossfeld (1950) that the barrier sequence did not represent an orderly sequence with time. They reasoned that it was unlikely for a younger barrier landform to develop in the protected lee side of an older barrier, and that apart from the Woakwine Range, there was no empirical evidence for multiple components to the barriers landward between the Woakwine and West Avenue Ranges.

Cook et al. (1977) described the sedimentary successions of the Coorong Coastal Plain based on a drilling transect from Robe to Naracoorte. The work was based on 36 continuously cored drill holes undertaken by the Bureau of Mineral Resources (now Geoscience Australia) during 1974–1975. They were the first to report the reversely magnetized sediments of the East Naracoorte Range and to show that the Pleistocene successions from the West Naracoorte Range to the modern coastline are all of Normal polarity. Based on a study of 29 calcarenite samples (nine from the East Naracoorte Range), Idnurm and Cook (1980) reported more detailed palaeomagneitc results from a transect between Robe and Naracoorte and concluded that the Brunhes–Matuyama magnetic reversal, then regarded as at 690 ka (now dated at 781 ka and coinciding with MIS 19), is situated between the East and West Naracoorte Ranges. Their work

Fig. 1.7 Map of the 'stranded beach ridges' (coastal barriers) of the Coorong Coastal Plain, southern Australia. The Early Pleistocene Marmon Jabuk Range defining the northern limit of the coastal plain is clearly highlighted (*Source* Blackburn et al. 1965; map reproduced with the permission of the CSIRO)

reaffirmed that all of the dune ranges seaward of the East Naracoorte Range revealed Normal magnetic polarity. The position of the Brunhes–Matuyama reversal between the East and West Naracoorte Ranges provided a critical tie point to evaluate the ages of the younger barrier complexes. Based on the magnetostratigraphical evidence, Idnurm and Cook (1980) concluded that there was a direct correlation between the barriers and the insolation maxima relating to interglacial events which occurred with a frequency of 100 ka. They also suggested that the subsidiary ridge spacings within the multi-component barrier systems agreed with time intervals between insolation maxima such that narrowly spaced barriers (c. 3 km apart) corresponded with 20 ka intervals and wide (7 km apart) spacings with 40 ka intervals and therefore reaffirming Sprigg (1952) that the landforms could be explained in terms of the Croll-Milankovitch Hypothesis.

Cook et al. (1977) noted three topographically-defined groups of coastal barriers in their transect from Robe to Naracoorte. The most seaward and topographically lowest group included the Robe, Woakwine, and Dairy Ranges. An intermediate group included the Reedy Creek, West Avenue, East Avenue and Ardune Ranges, and the topographically highest ranges included Baker, Woolumbool, Stewarts, Harper and West Naracoorte Ranges. The East Naracoorte Range and Hynam–Koppamurra Dune may define an additional group but their higher elevation is more likely to be associated with their position on the up-thrown block of the Kanawinka Fault for which there is 40 m of displacement at Naracoorte (Cook et al. 1977).

Von der Borch et al. (1980) reported the first application of amino acid racemization to the dating of fossil molluscs from the Late Quaternary successions of the Bridgewater Formation and associated back-barrier estuarine-lagoon facies near Robe. Based on the extent of racemization of three amino acids (alanine, glutamic acid and leucine) and isoleucine epimerization, they derived ages of 92 and 120 ka for specimens of the cockle *Katelysia scalarina* from the back-barrier lagoon facies of the prominent coastal barrier, Woakwine Range and concluded that this dune range formed during the Last Interglacial Maximum (MIS 5e) 125 ka ago.

Schwebel (1983, 1984) presented a summary of aspects of his doctoral research (Schwebel 1978) on the Quaternary stratigraphy of the coastal plain near Robe. He identified several sedimentary facies genetically-related to the emergent barrier shorelines and reported results of uranium-series disequilibrium dating, also supporting a last interglacial age for the Woakwine Range. In addition he derived a relative sea-level curve for the past 400 ka concluding that apart from the Last Interglacial Maximum (MIS 5e), the interglacial highstands during this period were not higher than present sea level.

Brown and Stephenson (1991) presented a detailed and comprehensive report of the geological history of the Murray Basin. Their work is significant in reappraising and clarifying confusing terminological aspects of the regional stratigraphical frameworks of the Cenozoic strata of the basin as mapped by three Australian State Geological Surveys (e.g. the confusing stratigraphical terminology of the Loxton-Parilla Sands).

Huntley et al. (1993a, b, 1994) and Huntley and Prescott (2001) provided a comprehensive overview of their thermoluminescence dating results from the aeolian dune facies of many of the coastal barriers across the coastal plain from the modern coastline to the East Naracoorte Range. Their papers represented the culmination of many years of fieldwork and detailed and meticulous laboratory investigations particularly in refining the methodological aspects of luminescence dating. As luminescence methods define the timing of sedimentation based on the last exposure of sedimentary particles (quartz and feldspars) to sunlight, the method represented a revolutionary development in dating the coastal barrier successions. This was particularly the case as many of the requirements for applying geochronological methods to date the coastal landforms were not upheld in their field setting (e.g. absence of corals for uranium-series dating). Their geochronological results quantified and largely corroborated previous inferences about the ages of many of the dune ranges. The ability to date the Pleistocene successions as old as approximately 800 ka by thermoluminescence is due to the low and remarkably consistent radiation dose rate of 0.5 Gray/ka across the entire coastal plain (Huntley et al. 1993a, b, 1994; Murray-Wallace et al. 2002). The significance of these studies is examined in greater detail later in this book (see Chaps. 6 and 7).

1.4 Geological and Geomorphological Setting of the Coorong Coastal Plain

Several distinctive regional geological attributes distinguish Australia from other continents and help to contextualise the basis for the regional landscapes of the Coorong Coastal Plain. The Australian continent is remote from plate boundaries. Geographically extensive cratonic regions confer a high level of tectonic stability and explain the basis for the antiquity of many Australian landscapes and their low topographical relief (Twidale 2007; Heimsath et al. 2010). Australia is the flattest of continents with the lowest relief at a continental scale. Australia generally experiences only minor seismic activity and throughout the Quaternary, volcanism was geographically restricted to the eastern portion of the continent with the most recent volcanic episodes of mid-Holocene age (Mount Gambier and Mount Schank) in the southern-most portion of the Coorong Coastal Plain (Sheard 1995) and in northern Queensland (Cohen et al. 2017).

Few coastal areas in Australia are characterised by significant neotectonic uplift particularly as commonly experienced at plate boundaries. In places, however, evidence for neotectonic activity can be confidently distinguished from smaller scale glacio-hydro-isostatic adjustment processes (Murray-Wallace and Belperio 1991; Murray-Wallace 2002; Bourman et al. 2016). Australia also experienced limited ice cover during Quaternary glaciations being largely confined to the Snowy Mountains and the highlands in central Tasmania (Colhoun et al. 2010). The general absence of significant glacial activity manifested by ice sheet development since Permian time, explains the widespread occurrence of deep weathering profiles over wide areas of the continent. Since the separation of Australia from Antarctica in the late stages of fragmentation of the Gondwanan landmass, Australia has been characterised by particularly slow rates of continental-scale denudation (Heimsath et al. 2010). The general absence of ice cover during Quaternary glaciations also means that glacio-isostatic processes have not figured directly in the evolution of the continent's coastline.

The present geographic location of Australia and the northward movement of the Indo-Australian Plate (c. 60–70 mm/year) is the product of passive rifting and separation from Antarctica during the final phase of Gondwanan fragmentation. On the southern margin initial rifting commenced approximately 160 Ma ago and changed to a 'drifting' phase approximately 43 Ma ago (Veevers 2000). The separation of Australia from Antarctica enhanced the influence of ocean currents about its coastal margins (e.g. Leeuwin Current in western and southern Australia), which in turn enhanced carbonate bio-productivity in southern Australia (James and Bone 2011; Murray-Wallace 2014).

Several Precambrian cratons (typically >1100 Ma) occur over large areas of western and southern Australia (Pilbara, Yilgarn and Gawler Cratons) and significantly influence the tectonic quiescence of coastlines developed on these features. The widespread occurrence of cratons has led to the erroneous conclusion that Australia is an ideal setting to quantify recent sea-level change from tide-gauge records. Subtle isostatic and neotectonic effects influence all coastlines, and at sites remote from stable cratons, greater variation is evident in both last interglacial and early Holocene palaeosea-level records (Belperio 1995, Belperio et al. 2002).

Australia is the flattest continent with an average land surface altitude of 330 m (Jennings and Mabbutt 1986). Mount Kosciusko, the highest mountain, extends up to 2228 m above present sea level (APSL). In an east-west cross-section, the Great Dividing Range (Eastern Highlands) and the Darling Range in Western Australia define two areas of significantly higher relief on the margins of the continent. Between these highlands, a substantial portion of the central continent is represented by low lands accounting for the extensive network of inland drainage to Lake Eyre, the lowest point on the continent (15 m below present sea level; BPSL). Half the drainage of Australia flows inland. The extensive inland drainage network and generally low topographical relief at a continental scale, combined with extensive aridity, ensures that few perennial streams debouch to the open ocean. This has also enhanced temperate carbonate sedimentation in southern Australia, to the extent that carbonate bio-productivity in this region during the Quaternary has far exceeded that of the better known Great Barrier Reef (Gostin et al. 1988; James and Bone 2011).

The width and depth of the continental shelf varies significantly around Australia, and these differences influence sediment availability for coastal evolution as well as the spatially variable magnitude of hydro-isostatic behaviour. Southern and north-western Australia have wide continental shelves that extend for distances up to 300 km from the modern coastline and terminate at the shelf break at approximately 130–110 m BPSL. In contrast, the continental shelf of south-eastern Australia is only up to 70 km wide with the shelf break at approximately 160–150 m BPSL (Murray-Wallace 2014).

Covering an area of 30,000 km^2, the Lacepede Shelf (Fig. 1.1) is a large arcuate-shaped embayment that adjoins the Coorong Coastal Plain and Murray Basin. From the mouth of the River Murray, the shelf is up to 180 km across to the 100 m isobath. The Lacepede Shelf edge is a regular feature bounded to the south and south-east of Kangaroo Island by a series of submarine canyons, some of which are related to the former courses of the River Murray at times of glacial low sea level and represent some of the world's largest submarine canyons (Sprigg 1947; Hill et al. 2009). The palaeochannels of the River Murray are 10–20 m deep and 450–1000 m wide (Hill et al. 2009). Their sediment infill records differential inputs of fluvially-derived clays from the Murray-Darling drainage basin (Gingele et al. 2004; Schmidt et al. 2010). The Lacepede Shelf sediments include terrigenous-clastic sediment on the inner shelf derived from the River Murray (James and Bone 2011). Other facies associations on the Lacepede Shelf include calcareous quartz sand, quartzose-bryozoan/bivalve sand, bryozoan mud, bivalve-coral gravel and pelagic mud (Foram-nanno ooze) (James et al. 1992). Farther to the south-east the Lacepede Shelf merges with the narrower Bonney Shelf.

From Cape Jaffa to Port MacDonnell (Fig. 1.1) the Bonney Shelf is a narrow feature some 20–40 km across to the 100 m isobath, covered by recent skeletal carbonate sands including a significant component of reworked carbonate grains from the erosion of the Robe Range barrier during the Holocene. At a regional scale, shelf mega-facies include encrusted rocky substrates on the inner shelf, relict-rich skeletal sand and gravel on the inner- to middle-shelf, bryozoan sand and gravel on the middle-shelf and fine skeletal sand and delicate branching, bryozoan muddy sand on the outer shelf (James and Bone 2011).

1.5 Pre-Quaternary Geology—An Antecedent Framework for Quaternary Coastal Landscape Evolution

The Quaternary sedimentary successions of the Coorong Coastal Plain overlie sediments of the Cretaceous Gambier Embayment of the Otway Basin, the Paleogene-Neogene Murray Basin and deformed Proterozoic to Cambrian basement rocks of the Adelaide Foldbelt and Kanmantoo Trough (Fig. 1.8). Cambrian meta-sediments (Kanmantoo Group) are exposed in the eastern Mount Lofty Ranges from Mount Barker to Murray Bridge with equivalent strata underlying much of the coastal plain at depth. These older rock units and structures have influenced coastal sedimentation at the macro-scale and have provided an antecedent framework to understand the geometry in plan-view of some of the barriers across the coastal plain over distances of tens to

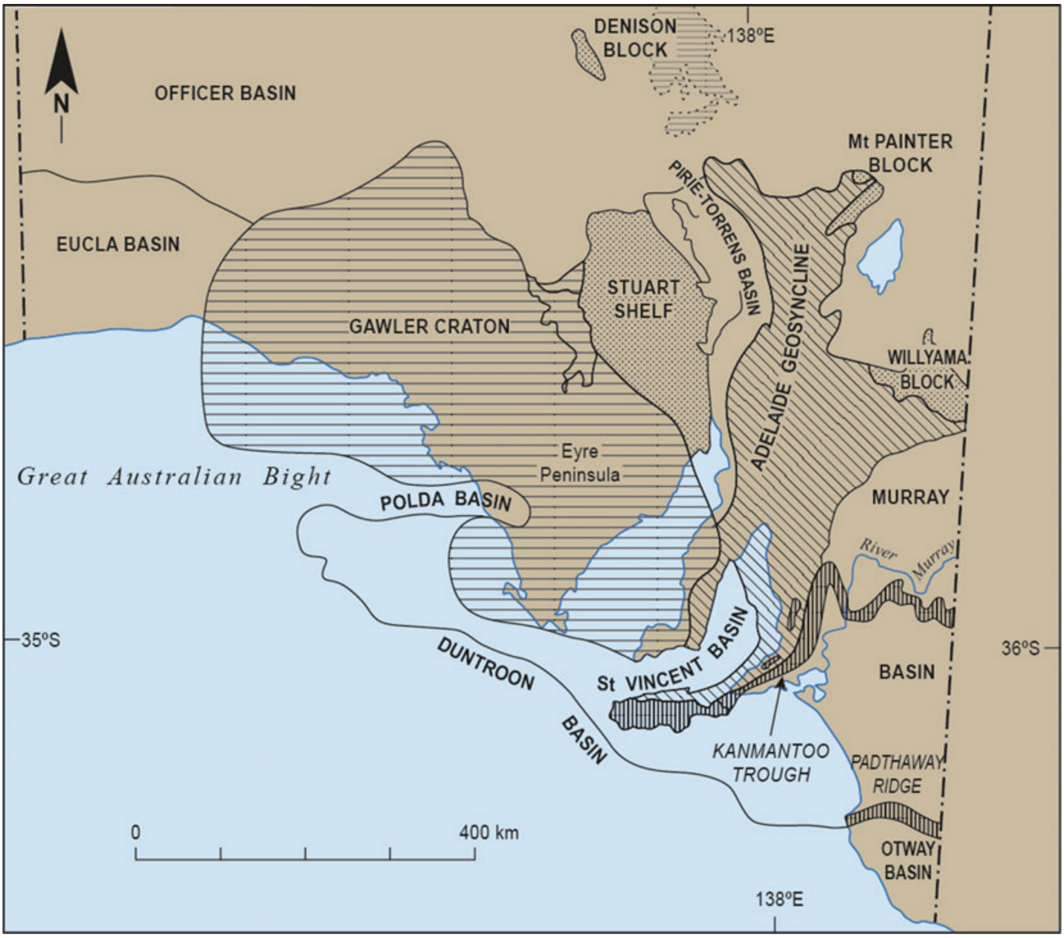

Fig. 1.8 Regional map of structural geological provinces illustrating the location of the Adelaide Foldbelt, Kanmantoo Trough, Murray Basin and Otway Basin

hundreds of kilometres. In addition to the afore-mentioned features, Permian glacigene sediments have been identified at depth within an over-steepened bedrock trough trending NW-SE beneath the Coorong Lagoon (O'Driscoll 1960). In one bore near Salt Creek, glacigene sediments were encountered at a depth of between 168 and 308 m below the modern land surface (Hossfeld 1950).

Cambro-Ordovician volcanics and intrusive granitoids associated with the Delamerian Orogeny (c. 510–490 Ma; Foden et al. 2006) that regionally deformed and metamorphosed the rocks that now constitute the Mount Lofty Ranges, crop out sporadically as domes, inselbergs and whalebacks (Twidale et al. 1983; Fig. 1.9) across the coastal plain along a basement-high structure termed the Padthaway Ridge (Rochow 1971). The Padthaway Ridge refers to a basement high separating the Gambier Embayment of the Otway Basin from the Murray Basin. The structure rises steeply from the south. At the land surface the ridge is demarcated by numerous residual domes of acid igneous rocks comprising adamellite, microgranites, granites, quartz keratophyres and quartz porphyrys (Mawson and Dallwitz 1944; Rochow 1971). The Padthaway Ridge is in part an exhumed Ordovician igneous complex with some granitoid rocks that post-date the Delamerian Orogeny (Farrand and Preiss

Fig. 1.9 Whalebacks at The Granites formed on the Cambro-Ordovician Taratap Granite north of Kingston SE, southern South Australia. (*Photograph* Murray-Wallace 2014)

1995). The exhumed intrusive features represented islands and archipelagos at various times during Quaternary sea level highstands. The granite residuals are typically between 3 and 10 m high and have adopted a variety of shapes reflecting prolonged subaerial weathering. High monolithic forms and pillars are common. Their northern faces have resistant case-hardened surfaces. The preferential weathering of feldspars on their south-facing sides has fostered cavernous weathering with the development of tafoni (Mawson and Segnit 1945; Twidale et al. 1983). In general terms, the Padthaway Ridge extends from Kingston SE at the present coastline, landwards to Padthaway (Fig. 1.10).

Since Late Cretaceous time, regional warping with more limited faulting has been responsible for the deformation of strata within the Gambier Embayment of the Otway Basin. The Kanawinka Fault (also termed Naracoorte Fault) is a laterally persistent structure that extends from the Mount Lofty Ranges and western Murray Basin, where it has also been termed the Marmon Jabuk Fault (Rogers 1980a, b), south-easterly into south-western Victoria. It represents one of the world's longest relict sea cliffs extending over 600 km (Kenley 1971; Bourman et al. 2016; Fig. 1.9). The fault in part defines the eastern limit of the Gambier Embayment of the Otway Basin and the Coorong Coastal Plain. The Kanawinka Fault escarpment ranges between 17 and 100 m in height. In places, gentle back-tilting and minor folding on the up-thrown block is evident in the Gambier Limestone attesting to the presence of the fault (Kenley 1971). The escarpment has been responsible for structural control of the coastline during earliest Middle Pleistocene time with the formation of the West Naracoorte Range coastal barrier. Two other prominent faults within the region that have surface expression are the north-west trending Tartwaup and Nelson Faults, characterised by zones of dolomite within

Fig. 1.10 Map of the regional structural framework of the southern portion of the Coorong Coastal Plain illustrating the location of significant subsurface features that have influenced regional landscape development (after Sprigg 1952 and other sources)

the Gambier Limestone. The presence of the Tartwaup Fault was questioned by Waterhouse (1973) who concluded that the feature could be explained by the presence of a buried erosion surface. An open-style anticlinal fold in the Gambier Limestone and older Paleogene successions has been associated with the Tartwaup Fault (Smith et al. 1995).

The Gambier Basin (also termed Gambier Embayment of the Otway Basin) developed as a result of Mesozoic rifting and the early phase of separation of Australia and Antarctica. The basin contains thick accumulations of alluvial, deltaic, lacustrine and marine sediments south of the latitude of Robe (Drexel and Preiss 1995; Holdgate and Gallagher 2003). The more widespread Paleogene-Neogene sediments of the Murray Basin reach a maximum thickness of approximately 1000 m near Port MacDonnell. They include characteristic cool-water bryozoan limestone (Gambier Limestone of Oligo-Miocene age) exposed at Mount Gambier, crinoidal, echinoidal and bryozoal Mannum Limestone exposed along the River Murray cliffs, and regressive coastal and fluviatile Pliocene sands (Loxton-Parilla Sands) marking the demise of the epicratonic Murray Basin. Karst development is another feature of the Paleogene-Neogene limestones, which is well-developed in the Mount Gambier area (Marker 1976; Twidale et al. 1983; Belperio 1995; see Chap. 5).

1.6 Early Notions of Aeolianite Formation and Pleistocene Sea Levels—the Relevance of the Coorong Coastal Plain

Armed with the knowledge that during Glacial Maxima sea level was at least 250 ft. (83 m) below present (Daly 1934) and that many of the aeolianite successions of southern Australia extend below present sea level, several earlier writers concluded that the successions formed at times of significantly lower sea level during glacials, rather than accompanying high sea levels during interglacials or warm-interstadials (Coulson 1940; Johns 1959, 1961; Twidale 1973; Hills 1975). The geographically extensive accumulations of aeolianite reaching thicknesses of over 200 m and extending inland for distances of up to 25 km, that characterise the tectonically highly stable, open ocean coastlines of south-western Eyre Peninsula and southern Yorke Peninsula were interpreted as of glacial age. It was inferred that the continental shelves needed to be largely subaerially exposed so that skeletal carbonate sediment could be entrained landwards by onshore winds to explain the spatial scale and volume of the aeolianite successions. These views were bolstered by the observations of Sayles (1931) in Bermuda, where the carbonate dunes were considered to have formed at times of glacial low sea level and the superposed *terra rossa* soils to have formed during warmer conditions in interglacials. An interesting discussion concerning the hermeneutical basis for Sayles' reasoning is provided by Vacher and Rowe (1997) who show the influence of earlier workers such as Agassiz (1895) and Verril (1907) in setting the constraints in the geological reasoning for inferring the relative ages of the aeolianite and interstratified palaeosol successions.

The stratigraphical architecture of the emergent coastal barriers of the Bridgewater Formation of the Coorong Coastal Plain, however, provides compelling evidence that these aeolianite successions have formed predominantly during times of interglacial and interstadial high sea levels (see Chap. 2). The critical lines of evidence for this relate to the inter-fingering relationship of the back-barrier estuarine-lagoon facies with the landward advancing lee-side dunes of the barriers. The back-barrier facies are characterised by poorly-sorted shelly, mud-rich calcarenite with shallow subtidal to intertidal molluscan faunas deposited during sea level highstands as shown by geochronological evidence (Schwebel 1983, 1984; Murray-Wallace et al. 1999). In a similar manner, the aeolian dune facies of the barriers have been shown compellingly to be of interglacial or warm interstadial age based on thermoluminescence dating (Huntley et al. 1993a, b, 1994; Huntley and Prescott 2001), aminostratigraphy (Murray-Wallace et al. 2001), and electron spin resonance dating (Rittner 2013). Such a geohistorical scenario does not preclude localised reworking of some aeolianite successions independent of relative sea level history as indicated by some luminescence ages (Banerjee et al. 2003).

1.7 Arrangement of This Book

The principal objective of this book is to present an overview of the unique geological and geomorphological characteristics of the Coorong Coastal Plain of southern Australia. The book outlines the evolutionary history of the coastal plain, and its significance for understanding the global problem of quantifying sea levels during successive Pleistocene interglacials. A broad geological overview and a discussion of the current understanding of the geochronology, sea level history and neotectonic history of the coastal plain are presented. In addition, the soils, regional karst landscapes and the record of Quaternary volcanism are also discussed.

Chapter 2 examines the Pleistocene history of the coastal plain and highlights the remarkable record of coastal barrier sedimentation since latest Early Pleistocene time. The record is testimony to the prolific production of sedimentary carbonates on the adjacent continental shelves. The modern and Holocene sedimentary environments and depositional products are discussed in Chap. 3. The chapter reveals the importance of the Holocene successions in understanding the longer-term sedimentary history of the coastal plain. Chapter 4 examines the two distinctive phases volcanic activity which occurred in the southern portion of the coastal plain during earliest Middle Pleistocene time and in the middle Holocene. The interaction of volcanic processes with pervasive karst development in this region resulted in highly explosive volcanic episodes as attested by the spatial distribution of tephra. Aspects of the neotectonic history of the region are also discussed in Chap. 4. The regional soils, palaeosols, calcrete and karst landforms are briefly reviewed in Chap. 5. The geochronological frameworks for understanding the age of the coastal barrier landforms are discussed in Chap. 6 and illustrates the site specific challenges of using a variety of different methods to the specific field contexts within the region. Chapter 7 reviews the evidence for Quaternary sea-level changes within the region. The history of investigations is examined within the context of changing geohistorical paradigms of Quaternary sea-level changes. The current understanding about the nature of the sea level record is reviewed and the need for further research is highlighted. The evolutionary development of the coastal plain in response to Quaternary sea-level changes, neotectonism and other processes is also examined. Some final reflections on the Quaternary environmental history of the region is presented in the epilogue.

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The Pleistocene Barrier Sequence of the Coorong Coastal Plain, Southern Australia

2

Abstract

The succession of coastal barrier landforms of the Coorong Coastal Plain in southern Australia has been mapped as the Pleistocene Bridgewater Formation in reference to partially consolidated mixed quartz-skeletal carbonate sands (aeolianites). Up to 20 distinct barriers have been identified relating to interglacial or interstadial sea level highstands across the 90 km wide coastal plain, 17 of which are younger than the Brunhes-Matuyama geomagnetic polarity reversal at 781 ka. Not all the barrier landforms are identified in a single line of section across the coastal plain due to the combined influences of barrier deposition on a subtly irregular land surface, differential rates of neotectonic uplift along the shore-parallel length of the coastal plain, and more localised factors such as bedrock outcrops affecting the broad regional pattern of barrier sedimentation. Many of the barriers can be traced laterally along their strike lengths for distances of 10–100 s of kilometres, such as the last interglacial (MIS 5e) Woakwine Range which extends for 340 km along the entire length of the coastal plain. Some of the barriers are composite structures having formed in more than one interglacial, attesting to the similarity in the height of successive interglacial sea level highstands (±6 m) during the Middle to Late Pleistocene. Composite barriers are characterised by superposed, unconformity-bounded successions of aeolian dune facies (aeolianite) with thinly interbedded transgressive shelly gravels and palaeosols defining the surfaces of unconformity.

Keywords

Aeolianite · Coastal barriers · Bridgewater Formation · Pleistocene · Quaternary sea-level changes

2.1 Introduction

The subdivisions of Quaternary time used in this book and relevant to the timing of coastal barrier formation correspond with ages defined in the 2012 Geological Time Scale (Pillans and Gibbard 2012). The base of the Quaternary System/Period with an age of 2.59 Ma is defined by the Global Stratotype Section and Point (GSSP) for the Gelasian Stage at Monte San Nicola in Italy. The Brunhes–Matuyama geomagnetic polarity reversal (781 ka) corresponding with Marine Isotope

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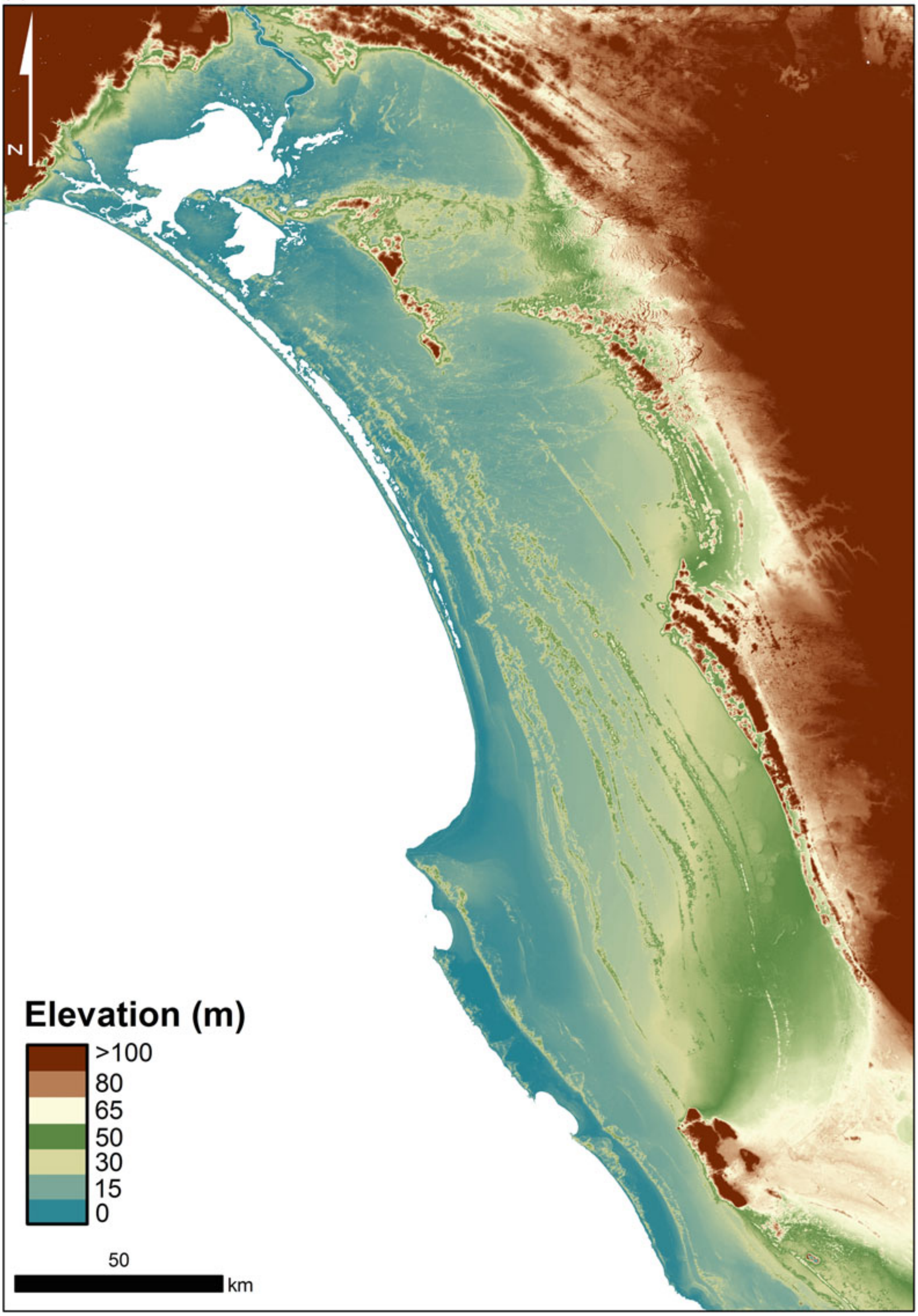
(a)



◀ **Fig. 2.1** **a** Shuttle Radar Topography Mission (SRTM) image of the Coorong Coastal Plain, southern Australia and **b** a map interpretation of the principal Pleistocene coastal barriers across the coastal plain. The relict coastal barrier landforms in the transect from Robe to Naracoorte include; 1. Robe Range; 2. Woakwine Range; 3. West Dairy Range; 4. East Dairy Range; 5. Reedy Creek Range; 6. West Avenue Range; 7. East Avenue Range; 8. Ardune Range; 9. Baker Range; 9a Lucindale Range; 10. Peacock Range; 11. Woolumbool Range; 12. Stewarts/Cave Range; 13. Harper Range; 14. West Naracoorte Range; 15. East Naracoorte Range; 16. Hynam Range; 17. The Black Range; 18. Mount Monster Range; 19. Coonalpyn Range; 20. Cannonball Hill Range; 21. Marmon Jabuk Range. In the Mount Gambier region, barriers featured in the image include; 22. MacDonnell Range; 23. Burleigh Range; 24. Caveton Range; and 25. Gambier Range. (*Source* SRTM image based on data available from the U.S. Geological Survey)

Stage (MIS) 19 for the end of Early Pleistocene epoch and beginning of the Middle Pleistocene is adopted in this work (although it is noted that some favour an age of 773 ka for the polarity reversal; Head and Gibbard 2015). The Middle Pleistocene concludes with the onset of the last interglaciation at approximately 132 ka (MIS 5e) which heralded the beginning of Late Pleistocene epoch (Shackleton et al. 2002) and ends at the termination of the Younger Dryas. This latter event represents the start of the current, Holocene interglacial (Gibbard 2003). The base of the Holocene Series/Epoch is defined in the North Greenland Ice Core Project (NGRIP) ice core with an age of 11,700 years b2k (before AD2000) (Rasmussen et al. 2014).

The Pleistocene in Australia is characterised by increasing aridity as the continent moved northward, punctuated by climatic oscillations and associated cyclic transgressions and regressions of the oceans. Emiliani (1955), Shackleton and Opdyke (1973) and countless subsequent workers have outlined the major characteristics of global glacial-interglacial fluctuations by measuring oxygen isotope ($^{18}O/^{16}O$) values in planktonic foraminifers extracted from deep ocean sediments and air bubbles trapped within ice cores (Jouzel et al. 2007; Masson-Delmotte et al. 2010). Collectively, these works established the quasi-periodic cycling of climate and sea-level change that is manifested on the Coorong Coastal Plain as a series of stranded, predominantly interglacial coastal barrier landforms (sea level highstand successions).

2.2 The Pleistocene Bridgewater Formation—A Record of Successive Coastal Barrier Formation

The sedimentary successions forming the sub-parallel shoreline barriers across the Coorong Coastal Plain have been mapped as Bridgewater Formation (Sprigg 1952; Sprigg and Boutakoff 1953; Boutakoff and Sprigg 1953; Boutakoff 1963; Rogers 1980a, b; Belperio 1995; Fig. 2.1a, b). The Bridgewater Formation was originally defined at Bridgewater Bay in western Victoria in reference to a thickly stacked succession of calcarenites (aeolianites) of presumed Early to Late Pleistocene age (Boutakoff 1963). The Bridgewater Formation extends continuously from Bridgewater Bay in a NNW direction across the entire coastal plain to the River Murray Mouth region adjacent the south-eastern Mount Lofty Ranges (Fig. 2.1a, b). On the Coorong Coastal Plain, the Bridgewater Formation comprises time-transgressive aeolianite barrier complexes associated with Quaternary interglacial and interstadial sea level highstands.

The sedimentary successions formerly mapped as Bridgewater Formation in Victoria have been ascribed Group status (Cupper et al. 2003), based on the presence of several lithostratigraphically distinct formations in the Warrnambool area as mapped by Gill (1967, 1988). This book retains the previously assigned lithostratigraphical designation of formation status for the Bridgewater

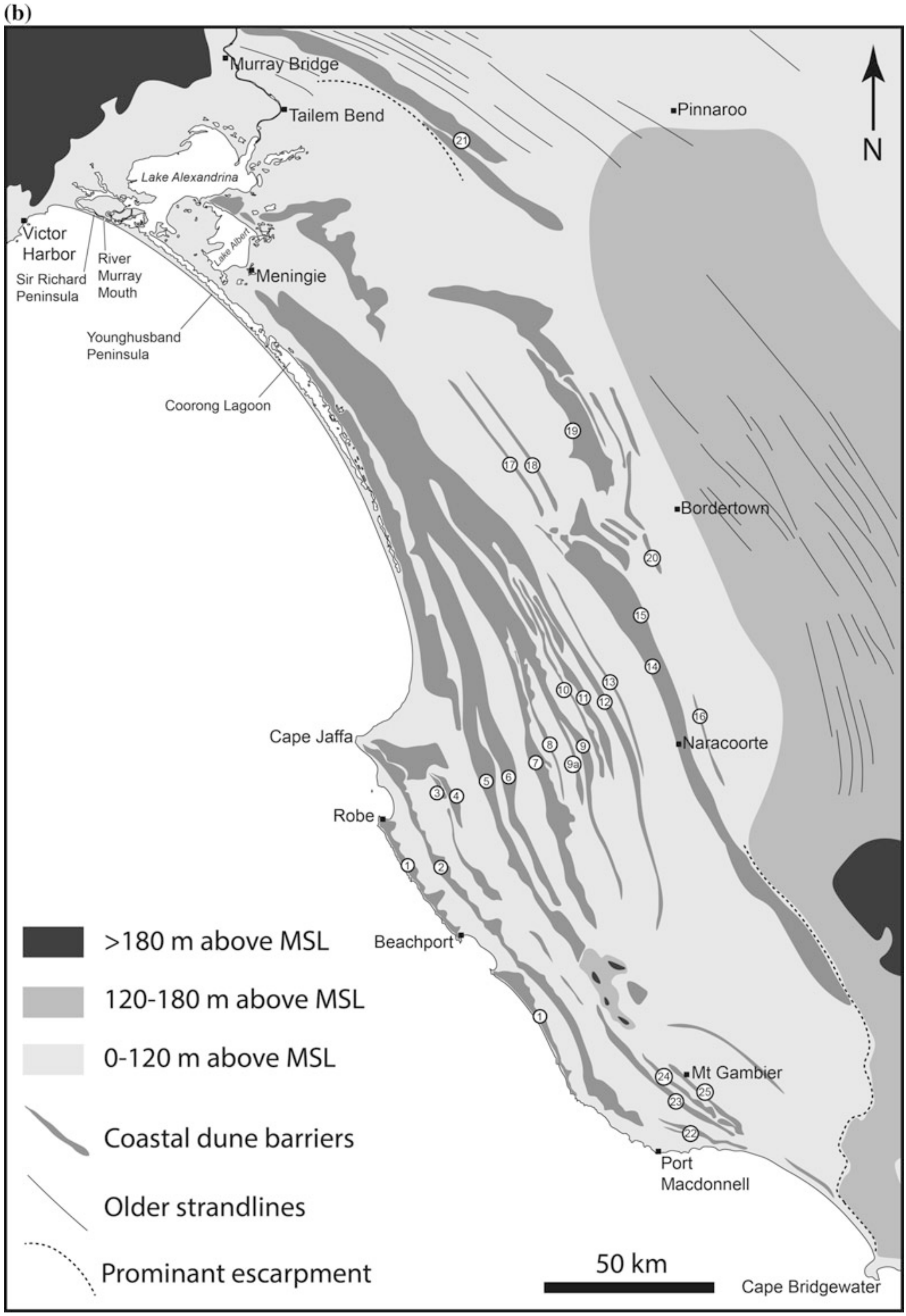


Fig. 2.1 (continued)

Formation given the uniformity of the sedimentary successions across the coastal plain and the recommended stratigraphical protocol in the 'Field geologist's guide to lithostratigraphic nomenclature in Australia' for the designations of Formations and Groups (Staines 1985).

The basal age of the Bridgewater Formation is not well-defined. At Warrnambool on the western Victorian coastline, correlative successions of the Bridgewater Formation overlie and occur beneath a basalt flow dated at 1.8 Ma (Orth 1988). Based on a study of the provenance of foraminifers from the Bridgewater Formation at numerous sites in southern South Australia, Milnes and Ludbrook (1986) suggested that deposition of the formation may have occurred at some time following the regression of the Middle Miocene seas. This was based on the presence of foraminifers of 'Miocene aspect' similar to those found within the Miocene Nullarbor Limestone such as *Pararotalia* sp. Although of low abundance, the reworked microfossils are commonly within older calcarenite clasts within calcretes, and in the more inland dune successions found within the cores of ooliths. Based on these observations, Milnes and Ludbrook (1986) inferred that the Miocene limestones must have represented a source for some of the oldest portion of the Bridgewater Formation, and accordingly raised the question of whether the basal part of the formation pre-dates the Early Pleistocene. On balance, the low numerical abundances of the older foraminifers argue against the Miocene limestones representing a significant source for the bioclastic sediment of the basal portion of the Bridgewater Formation. The fundamental point raised by Milnes and Ludbrook (1986) is worthy of consideration as the base of the formation may well be diachronous, especially given that the formation extends along some 1000 km of open ocean coastline of southern South Australia (including Eyre and Yorke Peninsulas) and into western Victoria.

The Late Miocene to earliest Pleistocene (?) Loxton-Parilla Sands (although predominantly of Pliocene age) occur landward of the Bridgewater Formation in South Australia as a well-defined strandplain (Brown and Stephenson 1991). Miranda et al. (2009) place the seaward limit of the Loxton-Parilla strandplain immediately in the lee of the Coonalpyn Range. The Loxton-Parilla Sands comprise bright yellow, reddish or cream coloured, glauconitic, micaceous silty and shelly sands deposited as coastal sand ridges (the more landward ridges evident in Fig. 2.1a, b). The upper portion of the succession comprises cross-bedded calcareous sands with shelly debris deposited as arcuate-shaped coastal barriers across the former Murravian Gulf (Sprigg 1952) as a regressive strandplain extending at least 355 km across the Murray Basin from the Bridgewater Formation (Miranda et al. 2009). Over 600 relict strandlines of the Loxton-Parilla Sands have been identified, covering an area of 135,000 km^2 (Kotsonis 1999; McLaren et al. 2011). The individual barrier ridges tend to be smaller than the younger Bridgewater Formation barriers and can be traced along their strike lengths for up to 100 km (Miranda et al. 2009). Average spacing between the coastal barrier ridges is approximately 1.6 km compared with a spacing of 5–10 km for the Bridgewater Formation barriers.

Although the Loxton-Parilla Sands in places contain the Early Pliocene (Kalimnan) foraminifer *Elphidium pseudonodosum*, it is likely that the most seaward portion of the succession is of Early Pleistocene age given the geographic proximity to the Early Pleistocene component of the Bridgewater Formation. In places the ridges and adjacent depressions are capped by calcretes. Equivalent features were first identified as relict coastal landforms in north-western Victoria by Blackburn (1962).

The Bridgewater Formation sediments comprise a mixture of low and high angle planar and trough cross-bedded, mixed quartz-skeletal carbonate sands of aeolian origin as seen in representative coastal cliff exposures at Cape Northumberland (Fig. 2.2). High angle cross-beds commonly at the angle of repose (c. 30–33°) represent the slip faces of formerly landward advancing coastal dunes. Inferred palaeocurrents reveal dune migration in response to a dominantly westerly to south-westerly wind regime. Within deep drainage cuttings constructed under the

Fig. 2.2 A representative section of the Pleistocene Bridgewater Formation as seen at Cape Northumberland, southern South Australia. In this example, a portion of the Late Pleistocene, warm interstadial (MIS 5c) Robe Range shows examples of high angle foreset beds of formerly landward advancing coastal parabolic dunes capped by topset beds and a laterally extensive calcrete at the top of the cliff. The cliff section is approximately 20 m high (*Photograph* Murray-Wallace 2012)

Anderson Scheme to drain the back-barrier flats for agricultural purposes, as well as in deeper quarries, the internal facies architecture of the aeolianite successions reveals the preservation of entire dune forms with top-set, fore-set and bottom-set beds. In their lee, the aeolian facies interfinger with back-barrier estuarine-lagoon facies that host molluscan faunas which assist palaeosea-level inferences (Murray-Wallace et al. 1999). A coquina unit dominated by the cockle *Katelysia* sp., for example occurs in the lee side of the last interglacial Woakwine Range at Lake Hawdon South, between Robe and Beachport (exposed in a road cutting on the Old Penola Road: S34° 15′ 44.4″; E139° 56′ 10.7″; Fig. 2.3 a, b).

Other facies present within the Bridgewater Formation include open ocean beach facies, back-barrier wash-over facies and thin transgressive lags associated with rising sea level during the early stages of interglacials or interstadials. The successions commonly include palaeosols and protosols that signify periods of prolonged and shorter-term landscape stability respectively, associated with the reduction of sediment supply and phases of vegetation colonization and soil development on the coastal dunes. The presence of rhizomorphs (plant root, stem and tree trunk replacement features resulting from the precipitation of calcium carbonate replacing the original organic material; Fig. 2.4) attest to periods of landscape stability. In a similar manner, the formation of calcrete units up to 2 m thick, mantle the individual barriers and have preserved the original morphology of the barrier landforms. The calcrete units have formed in association with prolonged periods of subaerial exposure and have involved multiple episodes of calcrete formation (Schwebel 1978) rather than a single event as suggested by Firman (1973).

Fig. 2.3 **a** Last interglacial Glanville Formation coquina, Lake Hawdon South, a back-barrier, estuarine-lagoon facies of the Woakwine Range. The shelly facies is capped by a laterally persistent calcrete; **b** a more detailed view of the shelly facies dominated by articulated cockles *Katelysia rhytiphora*, which frequents shallow subtidal to intertidal, low energy estuarine environments (*Photographs* Murray-Wallace 1998)

Fig. 2.4 Rhizomorphs (plant root replacement features) within former upper beach facies of the last interglacial Woakwine Range (Late Pleistocene Bridgewater Formation) exposed within the western side of McCourt Cutting near Beachport (*Photograph* Murray-Wallace 1998)

The regional land surface on which the barriers rest rises to 60 m above present sea level (APSL) at the Kanawinka Escarpment some 90 km inland from the present coastline and around the Mount Gambier—Mount Burr volcanic centres. In a transect from Robe to Naracoorte (Fig. 2.1), the coastal plain has an average gradient of 0.5°. The stranded coastal barriers average 15–20 m in height above the general level of the coastal plain, and their altitude and degree of separation from each other decreases to the north-northwest (NNW) towards the River Murray mouth region, and in the far south-east of the coastal plain extending into western Victoria. The coalescence of the barriers in these two regions relate to slower rates of uplift in these sectors of the coastal plain and subsidence in the extreme north-western portion of the coastal plain in the region of the River Murray Mouth (Fig. 2.1).

Twenty barriers (morphostratigraphically entire barrier forms and erosionally truncated barriers representing composite structures that formed in more than one sea level highstand event) have been identified across the coastal plain (Hossfeld 1950; Sprigg 1952; Alderman 1973). More commonly, however, about thirteen distinct and laterally traceable barrier landforms are evident in individual lines of section that extend some 90 km inland across the coastal plain from the modern coastline. The coastal barriers relate to specific Pleistocene sea-level highstands and thirteen are preserved between Robe and Naracoorte, but they converge and coalesce in a NNW direction into a composite aeolianite complex near Lake Alexandrina in the River Murray mouth region (Murray-Wallace et al. 2010; Ryan 2015; Bourman et al. 2016). Southwards, the older ridges lose their morphological expression due to karst weathering processes and only those seaward of the East Avenue Range (MIS 9c; 404 ± 23 ka; Huntley and Prescott 2001) can be traced clearly into western Victoria (Blakemore et al. 2015). The older, more landward coastal complexes to the north-east of Naracoorte Range are more siliceous than the younger more seaward successions and contain trace quantities of heavy minerals reworked from underlying Pliocene sands, reflecting less intense aridity and a greater dominance of siliciclastic sediments (Colwell 1979; Belperio and Bluck 1990).

The Bridgewater Formation also occurs extensively along the coastlines of Kangaroo Island, southern Yorke Peninsula and western Eyre Peninsula as stacked aeolianite successions, separated by calcrete and carbonate palaeosols and protosols (Belperio 1995; James and Bone 2015; Bourman et al. 2016). Along these coastlines the formation has a similar origin (barrier shoreline complexes), but includes far greater development of transgressive dune sands and aeolian sand bodies extending well inland (e.g. between 5 and 60 km inland from the modern coastline on western Eyre Peninsula defining the Chandada Plains). Without the subtle but consistent uplift experienced by the Coorong Coastal Plain, these coastal complexes lack the same degree of physical separation, and therefore resolution of successive sea-level highstands is more problematic (Lachlan 2011).

Uplift of the Coorong Coastal Plain has resulted in a clear physical and morphological separation of barrier shoreline successions that allow, as a first step, simple matching with the marine oxygen isotope record (see Chap. 7). The spacing between the individual shoreline complexes varies along the length of the coastal plain in response to differential uplift (Sprigg 1952).

2.3 Facies Associations Within the Coastal Barrier Complexes of the Bridgewater Formation

Each barrier shoreline succession, although representing a different time interval and varying degrees of preservation and exposure, displays a common suite of sedimentary facies having formed in comparable sedimentary environments and under similar climatic conditions (Fig. 2.5). These comprise bioclastic sands and muds deposited in shallow subtidal, littoral, dune, lagoon and ephemeral lacustrine environments associated with the former shorelines. The spatial relationship of the facies, as exposed in various drainage cuttings and quarry exposures, resembles that of the modern/Holocene Younghusband Peninsula—Coorong Lagoon system.

The principal sedimentary facies within the Bridgewater Formation include;

- *Shallow subtidal facies* that comprise seaward-dipping, coarse-grained skeletal carbonate sands with abundant broken shells of marine gastropods and bivalves together with foraminifers and coralline algae. This facies is seldom exposed in cuttings on the former seaward side of the main barrier structures

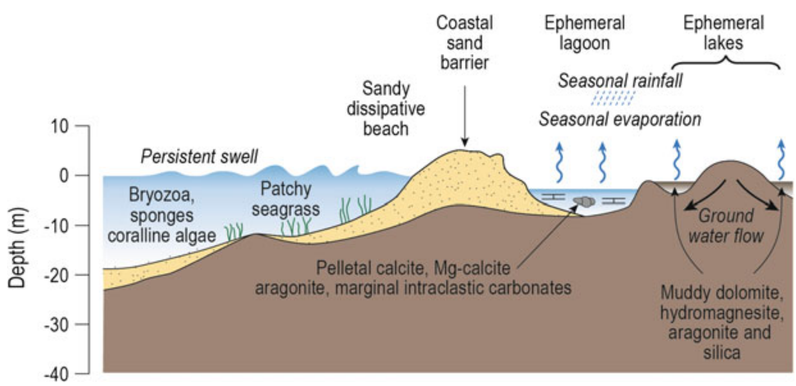


Fig. 2.5 Schematic representation of the coastal facies of the Coorong Coastal Plain, a cool water, temperate sedimentary carbonate, high wave energy, persistent swell environment (Modified after Belperio et al. 1996)

owing to the limited number of deep cuttings (Fig. 2.6a).

- *Sediments of the littoral zone*, consisting of well-sorted, medium to coarse-grained, mixed quartz-skeletal carbonate sand, occur as shoestring sand bodies sub-parallel to the present coast. The beach deposits, up to 3 m thick, extend into the core of the ranges as distinctive bidirectional trough cross-bedded strata. Based on the textural classification of limestone (Dunham 1962), Schwebel (1978, 1983, 1984) termed the sediments of this facies as skeletal grainstones.
- *Transgressive aeolian dune or aeolianite facies* form the bulk of the visible ranges (Fig. 2.6b). They comprise weakly cemented, fine to medium-grained mixed quartz-skeletal carbonate sand, composed of well-sorted and rounded molluscan, foraminiferal and algal grains. Reactivation surfaces, marked by weakly developed palaeosols or protosols and abundant rhizomorphs are common. These

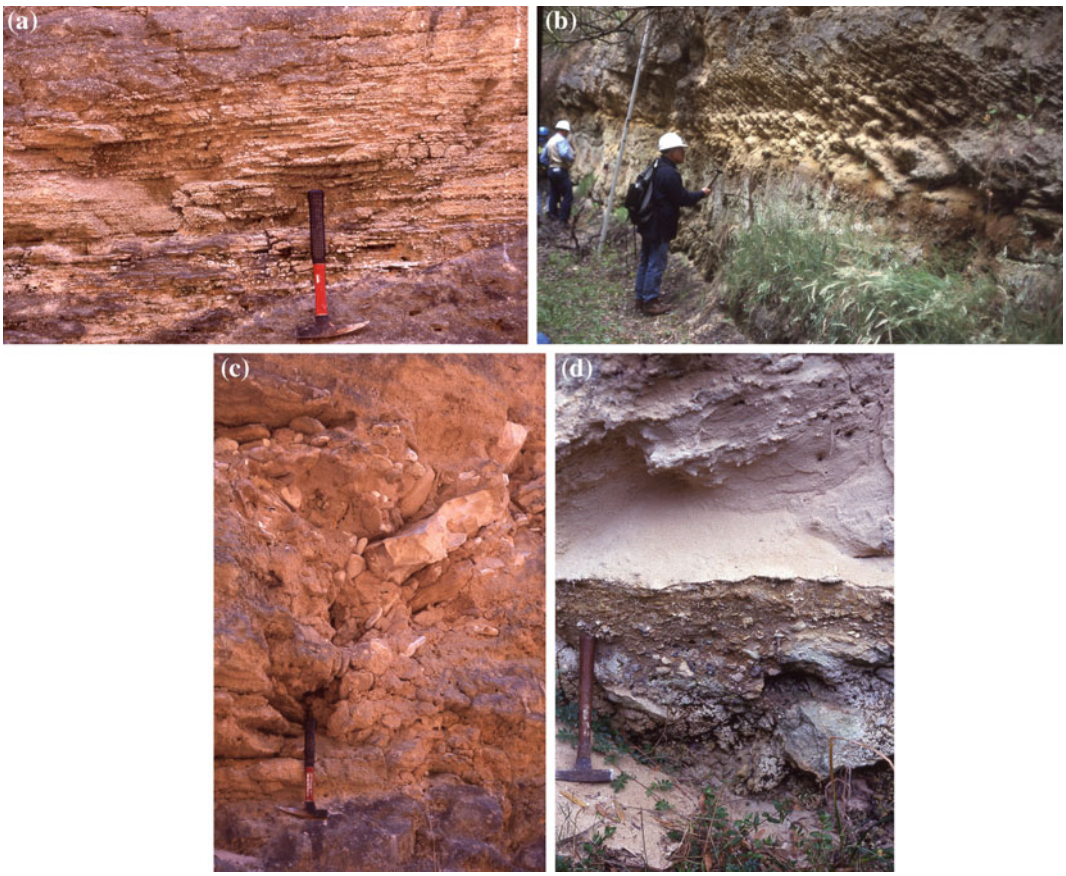


Fig. 2.6 Representative examples of sedimentary facies of the Bridgewater Formation as seen in the Woakwine Range exposed within the McCourt Cutting near Beachport; **a** Shallow subtidal facies comprising seaward dipping, planar cross-bedded, coarse grained skeletal carbonate sands on the western, seaward side of the barrier; **b** planar cross-bedded (foreset beds) of transgressive aeolian dune facies overriding back-barrier, estuarine-lagoon facies in the lee side of the Woakwine Range; **c** transgressive gravel-boulder lag deposit over-riding an older calcarenite core of Woakwine Range (Woakwine II) within the central portion of the dune range. The hammer head rests directly on the disconformity surface separating Woakwine I and II; **d** Poorly sorted, back-barrier estuarine-lagoon facies of Woakwine Range overlain by aeolian dune sediments (*Photographs* Murray-Wallace 1997)

separate the co-sets of very large-scale aeolian planar and trough cross-beds that dip consistently landward between 3 and 30°.

- *Transgressive lag deposits and boulder accumulations* occur as laterally persistent thin bands of shelly gravels with flint clasts derived from the Oligo-Miocene Gambier Limestone and large accumulations of cobble to boulder-sized clasts of calcarenite, the latter deposited adjacent relict sea cliffs formed in earlier phases of coastal barrier development (Fig. 2.6c).
- *Poorly sorted estuarine or lagoon facies* are preserved in back-barrier settings of the interdune corridors and were deposited in waters with marine salinities (Fig. 2.6d). These sediments are typically very shelly and muddy calcarenite with numerous gastropods and large articulated intertidal to shallow subtidal molluscs and texturally are termed Skeletal Grainstone, Packstone and Wackestone units (Schwebel 1978, 1983, 1984). The intertidal fauna provide a useful datum for determining shoreline elevation and reconstructing former sea levels.
- *Lacustrine sediments* that were deposited in the inter-barrier corridors. The successions commonly inter-finger with the aeolian dune facies of the Bridgewater Formation in the leeward side of the barriers attesting to their age equivalence. However, in some areas the back-barrier environments have also been re-flooded during a younger interglacial such as the high sea level of the last interglacial maximum (MIS 5e) flooding the back-barrier landscape of the East Dairy (MIS 9) and West Dairy (MIS 7a) Ranges (Fig. 2.1). The lacustrine sediments comprise dense, white calcitic and dolomitic mudstone (Schwebel 1978, 1983, 1984) with interbedded greenish clay and clayey quartz sand (a texturally inverted sediment resulting from wind-blown sand introduced to the low energy back-barrier environment). The calcilutite (calcareous mudrock) is amorphous to indistinctly bedded, commonly pelletal, and contains remains of a variety of fresh to brackish water molluscs, foraminifers, ostracods and charophytes. The lake deposits overlie lagoonal facies of the Bridgewater Formation which together comprise a characteristic upward-fining regressive sequence. Where thickly developed (up to 4 m), the lacustrine facies has been mapped separately and referred to as Padthaway Formation in the Early to Late Pleistocene successions (Brown and Stephenson 1991; Belperio 1995).

Preservation and exposure of the complete spectrum of these facies is greatest for the youngest ranges particularly for the Holocene (Younghusband Peninsula) and Late Pleistocene barriers (Robe Range and Woakwine Range), but elements of each have been recognised in most of the ranges across the 90 km wide coastal plain between Robe and Naracoorte where cuttings and excavations allow examination.

2.4 Sediment Properties of the Pleistocene Bridgewater Formation

The aeolian calcarenite sediments (aeolianites) of the Bridgewater Formation typically comprise medium to coarse grained, bioclastic skeletal carbonate sand with subordinate quartz. The sediments are characteristically a range of yellowish brown hues (yellowish brown 10YR 5/4 to very pale brown 10YR 8/3) (Murray-Wallace et al. 2001). The sediments are derived primarily from the shallow water inner continental shelf, indicated by the presence of fragments of molluscs, bryozoans and distinctive foraminifers such as *Discorbis dimidiatus*, *Elphidium crispum*, *E. macelliforme*, *Notorotalia clathrate*, *Ammonia beccarii* and *Cibicides* sp. Many of the foraminifers are infilled with cement. The sedimentary carbonate component comprises rounded and polished grains of comminuted molluscs (bivalves and gastropods), echinoids, bryozoans and foraminifers. The calcium carbonate content ranges from 21% for the East Naracoorte Range up to 90% for the West Naracoorte Range, with an average calcium carbonate content of 68 ± 19% for 12 of the other barriers across the coastal plain (Murray-Wallace et al. 2001). The quartz grain component includes vitreous lustre and 'milky' grain surfaces. The quartz grains are also commonly coated with authigenic carbonate.

Thin section analyses of the 63–500 µm sediment particle fraction reveals that the sediments dominantly consist of red algal, molluscan and bryozoan fragments and foraminifers (Murray-Wallace et al. 2001). Most grains are well-preserved but numerous grains are at least partially micritized and pores in foraminiferal and bryozoan grains have infilled with micrite and microsparite. Reworked grains from older barrier successions are a common component of the sediments.

Sediments of the Bridgewater Formation contain very low concentrations of terrestrially-derived heavy minerals (typically between 0.1 and 0.5% by total sediment mass; Colwell 1979). Heavy minerals include magnetite and ilmenite (25–40%), leucoxene (5–20%), zircon (5–25%), tourmaline (5–30%) and amphibole (0–10%). Other accessory minerals include epidote, rutile, garnet, anadulsite, kyanite, sillimanite and staurolite, topaz, zoisite, apatite, monazite, pyroxene, sphene, olivine and fluorite. Framboidal pyrite occurs within the back-barrier estuarine-lacustrine facies that interfinger with the Bridgewater Formation (Colwell 1979). Source areas for the heavy mineral assemblages of the Bridgewater Formation include igneous rocks of the Padthaway Ridge, metamorphic rocks of the Mount Lofty Ranges and Fleurieu Peninsula, Kangaroo Island, Paleogene-Neogene marine limestones, fluvio-lacustrine sediments and beach-dune quartz sands of the Murray Basin and local volcanic rocks of the Mount Burr region (Colwell 1979).

2.5 Other Quaternary Stratigraphical Units Relevant to the Evolution of the Coastal Plain

2.5.1 Coomandook Formation

Fossiliferous Early Pleistocene marine sediments mapped as Coomandook Formation underlie much of the Coorong Coastal Plain and equate with the most inland dune barrier complexes (East Naracoorte, Coonalpyn and Hynam–Koppamurra Dune Ranges; Fig. 2.1a, b). The Coomandook Formation extends across the coastal plain to the scarp foot of the Kanawinka Fault and in places overlies the Late Miocene to earliest Pleistocene (?) Loxton-Parilla Sands, and the Oligo-Miocene Gambier Limestone (Firman 1973). The formation attains a maximum thickness of 75 m near Mount Gambier (Belperio 1995), and has been identified as more thickly developed within former landscape depressions within the Tintinara area (Clark 1896). Dating and correlation of the Coomandook Formation is based on fossils of the pelagic marine gastropod *Hartungia* (*dennanti*) *chavani*, a biostratigraphically important mollusc in view of its geographically widespread distribution in the Early Pleistocene successions of southern Australia (Ludbrook 1978, 1984). During the transgression leading to the deposition of the Coomandook Formation, granite hills of the Padthaway Ridge formed a series of islands and shoals that influenced coastal sedimentation and palaeogeography (Fig. 2.1a, b). During this period, coastal barriers developed as major sand bodies attached to the promontories.

Correlative sedimentary successions that support an Early Pleistocene age for the Coomandook Formation and associated barriers include the Nelson Bay Formation and Werrikoo Limestone of western Victoria (Boutakoff 1963; Lawrence et al. 1976; Singleton et al. 1976; MacFadden et al. 1987). At Portland, the shallow marine Nelson Bay Formation and overlying Bridgewater Formation aeolianite are of reversed magnetic polarity. The Nelson Bay Formation is important for its wealth of vertebrate and invertebrate fauna and its flora. It also contains the planktonic foraminifer *Globorotalia truncatulinoides* which first appeared in the southern hemisphere at c. 1.9 Ma (Haq et al. 1977; Berggren et al. 1980; Mallett 1982). The Portland sequence is therefore constrained within the reversed magnetic chron of 1.66–0.78 Ma. A similar framework has been established for the sequence in the Glenelg River valley, where subaerial basalts, yielding K–Ar ages of 2.5–2.2 Ma are overlain by marine sand and littoral calcarenite of the Werrikoo Limestone (Holdgate and Gallagher 2003). *G. truncatulinoides* appears some distance above the base, indicating that this unit spans the Pliocene-Pleistocene boundary.

2.5.2 Padthaway Formation

The Padthaway Formation is stratigraphically a composite lithological unit of Early to Late Pleistocene age, comprising estuarine lagoonal and lacustrine facies that have formed in back-barrier environments across the entire coastal plain from the lee of the Woakwine Range to the lee of the Coonalpyn Range (Brown and Stephenson 1991). In this sense, the formation has developed in the landscape depressions between the higher relief of the coastal barriers mapped as Bridgewater Formation. The Padthaway Formation is typically 5–20 m thick across the entire coastal plain but a maximum thickness of 50 m has been recorded in the Naracoorte region (Brown and Stephenson 1991). In many respects, the modern Coorong Lagoon and its associated fresh water and saline lakes represent analogous depositional environments to those in which the Padthaway Formation was deposited.

The Padthaway Formation is not necessarily coeval with the formation of each coastal barrier (aeolian facies) as the back-barrier environments undergo a sequence of changes in their evolutionary development (Belperio 1995). In many instances the estuarine-lagoonal facies with fossil molluscs such as the cockle *Katelysia* sp., can be seen in deep drainage-cuttings to interfinger with their coeval, landward migrating dune facies such as within the Woakwine Range (Schwebel 1978; Murray-Wallace et al. 1999). However, this situation is rendered more complex by the re-flooding of some back-barrier environments by younger sea level highstands such as the last interglacial (MIS 5e) highstand flooding the landward side of the penultimate interglacial (MIS 7a) West Dairy Range and Antepenultimate interglacial (MIS 9) East Dairy Range. The Padthaway Formation also chronicles a change from estuarine lagoonal facies with an open marine salinity to a progressively more restricted brackish to freshwater environment as the back-barrier environment is isolated from the sea. This heralds the deposition of freshwater marls (moderately consolidated, white calcitic and dolomitic mudstone) which cap the estuarine successions. The freshwater marls contain fossil molluscs, foraminifers, ostracods and charophytes.

2.5.3 Glanville Formation

Shallow marine and coastal sediments deposited during the last interglacial maximum sea-level highstand (128–118 ka; MIS 5e) as well as erosional landforms attributed to this event, are common around much of the world's coastline (Murray-Wallace and Woodroffe 2014). Globally, some of the most intensively studied sites are from emergent coral reef settings affected by high rates of tectonic uplift such as the Huon Peninsula, Papua New Guinea (Chappell 1974; Chappell et al. 1996; Bloom et al. 1974), Timor and Atauro islands (Chappell and Veeh 1978), and Barbados (Schellmann and Radtke 2004a, b). In these settings uranium-series dating has been confidently applied to fossil corals and reliable inferences about paleaosea-level may also be derived from the reef successions. However, there are some limitations such as determining the rate of tectonic uplift of shoreline complexes, which also includes an uncertainty in the inferred elevation of the sea level of the last interglacial maximum. However, these uncertainties represent a minor contribution in the overall estimated rate of tectonic uplift and inferred palaeosea levels for older or younger successions than the last interglacial maximum (MIS 5e).

Fossiliferous peritidal sediments of last interglacial age (MIS 5e) occur extensively along the coastline of southern Australia and are referred to as Glanville Formation in geological survey reports in the State of South Australia (Firman 1966; Ludbrook 1976, 1984; Cann 1978; Belperio et al. 1995; Murray-Wallace et al. 2016; Pan et al. 2018). The coastal strata represent one of the world's most laterally-persistent successions of last interglacial age and can be traced laterally, although not continuously in outcrop, for over 2000 km along the coastline of the State of South Australia. Time-equivalent sandy coastal aeolian barrier facies are referred to as the Upper Member of the Bridgewater Formation (Belperio 1995). Schwebel (1983, 1984) reported uranium-series ages of 125 ± 20 ka and 100 ± 30 ka for molluscs and aragonite mud respectively from Glanville Formation lagoonal facies associated with the Woakwine Range near Robe. Belperio et al. (1984) reported an age of c. 110 ka from amino acid racemization measurements on fossil specimens of the arcoid bivalve *Anadara trapezia* in correlated sediments of northern Spencer Gulf, southern Australia. Subsequently, more detailed aminostratigraphic studies between different coastal deposits across much of southern Australia has confirmed the widespread occurrence of last interglacial successions (Murray-Wallace 1995, 2000; Murray-Wallace et al. 2010, 2016). Uranium-series ages of 127.3 ± 2.1 to 115 ± 5.4 ka have been reported on specimens of the solitary coral *Plesiastrea versipora* from shallow subtidal facies of the Glanville Formation at Hardwicke Bay, on southern Yorke Peninsula in southern Australia (Pan et al. 2018). Thermoluminescence (TL) dating has further confirmed the global MIS 5e correlation of the Glanville Formation with ages of 132 ± 9 ka and 118 ± 4 ka for aeolian dune facies of the Woakwine Range (Huntley et al. 1994) and 117 ± 8 ka on back-barrier washover facies of the Woakwine Range in the McCourt drainage cutting near Robe (Murray-Wallace et al. 1999).

The Glanville Formation is characterised by some elements of a warmer water fauna that no longer live in a substantial portion of southern Australia, spanning from the western Great Australian Bight to western Victoria. These include the Sydney blood cockle *Anadara trapezia*, the Shark Bay pearl oyster *Pinctada carchariarum*, the conical-fusiform gastropod *Euplica bidentata*, and the megascopic benthic foraminifer *Marginopora vertebralis* (Howchin 1888, 1909, 1924, 1935; Ludbrook 1976; Cann and Clarke 1993; Murray-Wallace et al. 2000). The flat calcreted surface to this key intertidal facies preserved in extensive palaeo-lagoons and sheltered embayments on Eyre Peninsula, consistently indicates a last interglacial sea level of between 2 and 4 m APSL (Murray-Wallace and Belperio 1991; Murray-Wallace et al. 2016). This is an important datum for coastal neotectonic studies in southern Australia in view of the long-term tectonic stability of Eyre Peninsula and the Gawler Craton (Belperio et al. 1995).

2.5.4 St. Kilda Formation

As redefined by Cann and Gostin (1985) the St Kilda Formation refers to all coastal, estuarine and continental shelf facies of Holocene age. The base of the St Kilda Formation is diachronous and relates to post-glacial sea-level rise which culminated at 7000 years ago in southern Australia (Lewis et al. 2013). The upper surface of the formation may be represented by active sedimentation. In terms of the Coorong Coastal Plain, the modern/Holocene barriers Younghusband and Sir Richard Peninsula and their associated back-barrier estuarine-lagoonal environments would be mapped as St Kilda Formation. This revised definition of the St Kilda Formation also includes the extensive beach ridge plains near Kingston SE, Guichen Bay and Rivoli Bay (Thom et al. 1981; Murray-Wallace et al. 2002) and the Holocene coquina successions in the former seaway between the Robe and Woakwine Ranges (Cann et al. 1999).

2.6 Early Pleistocene Coastal Sedimentation—Robe to Naracoorte Line of Section

In the following sections the barriers are described from oldest (more landward) to youngest (more seaward). In addition to the dune ranges in the line of section between the towns of Robe and Naracoorte (Fig. 2.1a, b), five dune ranges to the north of this line of section are also described.

The ranges to the north of this line of section include from oldest to youngest, the Marmon Jabuk, Cannonball Hill Range, Coonalpyn, Mount Monster and Black Ranges. All are of latest Early Pleistocene age.

The East Naracoorte Range is the youngest barrier of Early Pleistocene age on the coastal plain. Farther north, the Mount Monster and the Black Ranges are physically distinct ranges that superficially may represent equivalents of the East and West Naracoorte Ranges respectively (Fig. 2.1a, b). This is based on the observation that the Mount Monster and Black Ranges appear to follow the NNE-SSW regional trend of the Naracoorte Ranges. However, it is more likely that the Coonalpyn Range is a correlative of the East and West Naracoorte Ranges. The Coonalpyn Range has a significantly larger sediment volume and is a more complex dune range with multiple components. Its arcuate form in plan-view was influenced by local outcrops of crystalline basement rocks, located at the junction with the Naracoorte Ranges. The large volume of sediment available to generate the Naracoorte Ranges may therefore favour its correlation with the similarly large-scale Coonalpyn Range. The Naracoorte and Coonalpyn Ranges converge as a cuspate structure in an area of outcropping granitic basement rocks (Fig. 2.1a, b). According to this scenario, the Mount Monster and Black Ranges formed as separate entities in the progressive change in coastal configuration. The essentially linear form of these barriers reflects a more even depositional surface for barrier formation.

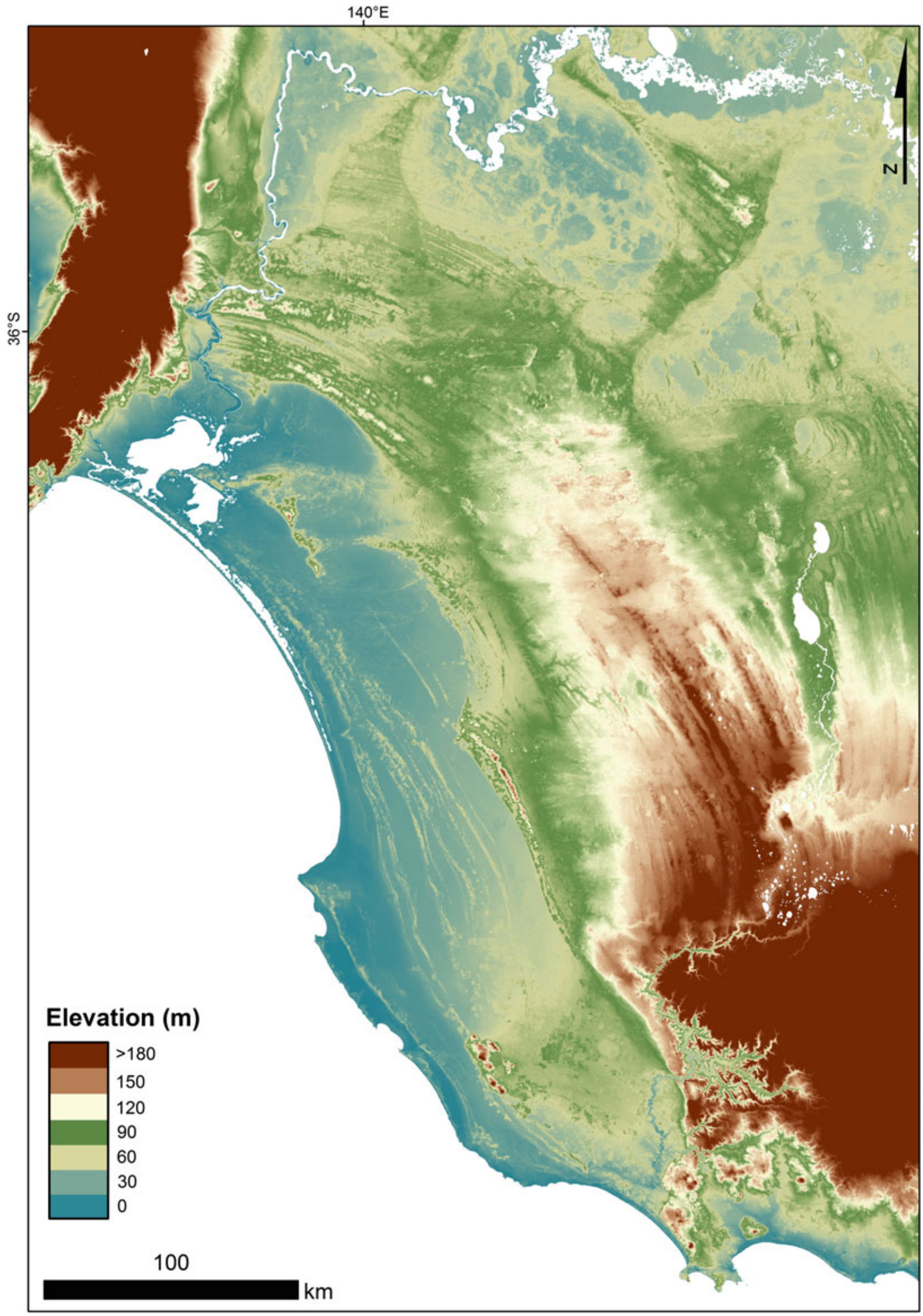
Based on its more landward position, the Marmon Jabuk Range is most likely a significantly older feature. Collectively the Marmon Jabuk, Cannonball Hill, and Coonalpyn Ranges are likely to have formed in the latest Marine Isotope Stages of the Early Pleistocene during the Early–Middle Pleistocene Transition, an interval that heralded the end of the 41 ka-dominated orbital insolation cycles and preceded the onset of the 100 ka-dominated cycles of Middle and Late Pleistocene time (Head and Gibbard 2015).

The Early–Middle Pleistocene Transition on the Coorong Coastal Plain is manifested by a change from siliciclastic-dominated coastal barrier sedimentation of the Loxton-Parilla Sands to an increase in sedimentary carbonate production on the adjacent Lacepede and Bonney Shelves heralding the development of the Pleistocene Bridgewater Formation. Higher calcium carbonate bio-productivity is evidenced from the latest Early Pleistocene through to the present day. The afore mentioned barriers most likely represent the earliest phase of the 100 ka-dominated orbital insolation cycles, as the East Naracoorte Range is of reversed magnetic polarity and therefore at least 781 ka. In terms of their spatial distribution, the Naracoorte, Coonalpyn, and Marmon Jabuk Ranges while being broadly arcuate-shaped in plan-view are offset in a northerly direction in an *en echelon* pattern (Figs. 2.7 and 2.8).

The pronounced shift from siliciclastic to carbonate-dominated sedimentation also coincides with an intensification of aridity (Bowler et al. 2006). This has most notably been documented from alluvial fan successions flanking the Mount Lofty Ranges and Kangaroo Island in southern Australia (Bourman and Pillans 1997; Pillans and Bourman 1996, 2001). Within these successions, there is a consistent depositional signature of an upward transition from ferruginous sediments signifying moister conditions to a progressive drying of the continent manifested by pedogenic carbonate.

2.6.1 Marmon Jabuk Range

Based on its geographic position relative to the other dune ranges, the Marmon Jabuk Range is the oldest and most landward of the Pleistocene dune barriers considered in this book. Older barrier shoreline successions extending up to 400 km inland from the present coastline are associated with the Late Miocene to earliest Pleistocene (?) Loxton-Parilla Sands (Brown and Stephenson 1991; Kotsonis 1999). The Marmon Jabuk Range extends along its strike for approximately 60 km with its northern limit


140°E
36°S
N
Elevation (m)
>180
150
120
90
60
30
0
100
km

◀ **Fig. 2.7** Map of the coastal barriers of the Coorong Coastal Plain and Murray Basin, illustrating the geographical location of the Marmon Jabuk Range, Coonalpyn Range, Murray Lakes Range, Mount Monster Range and Black Range and the northern-most part of the Naracoorte Range. The older barriers of the Murray Basin (Pliocene Loxton-Parilla Sands) are situated on the higher relief to the NE of the Naracoorte, Coonalpyn and Marmon Jabuk Ranges. The River Murray, and terminal lakes, Lakes Alexandrina, Albert and Coorong Lagoon are also evident. See Figs. 2.1b and 2.8 for names of specific dune ranges (*Source* SRTM image based on data available from the U.S. Geological Survey)

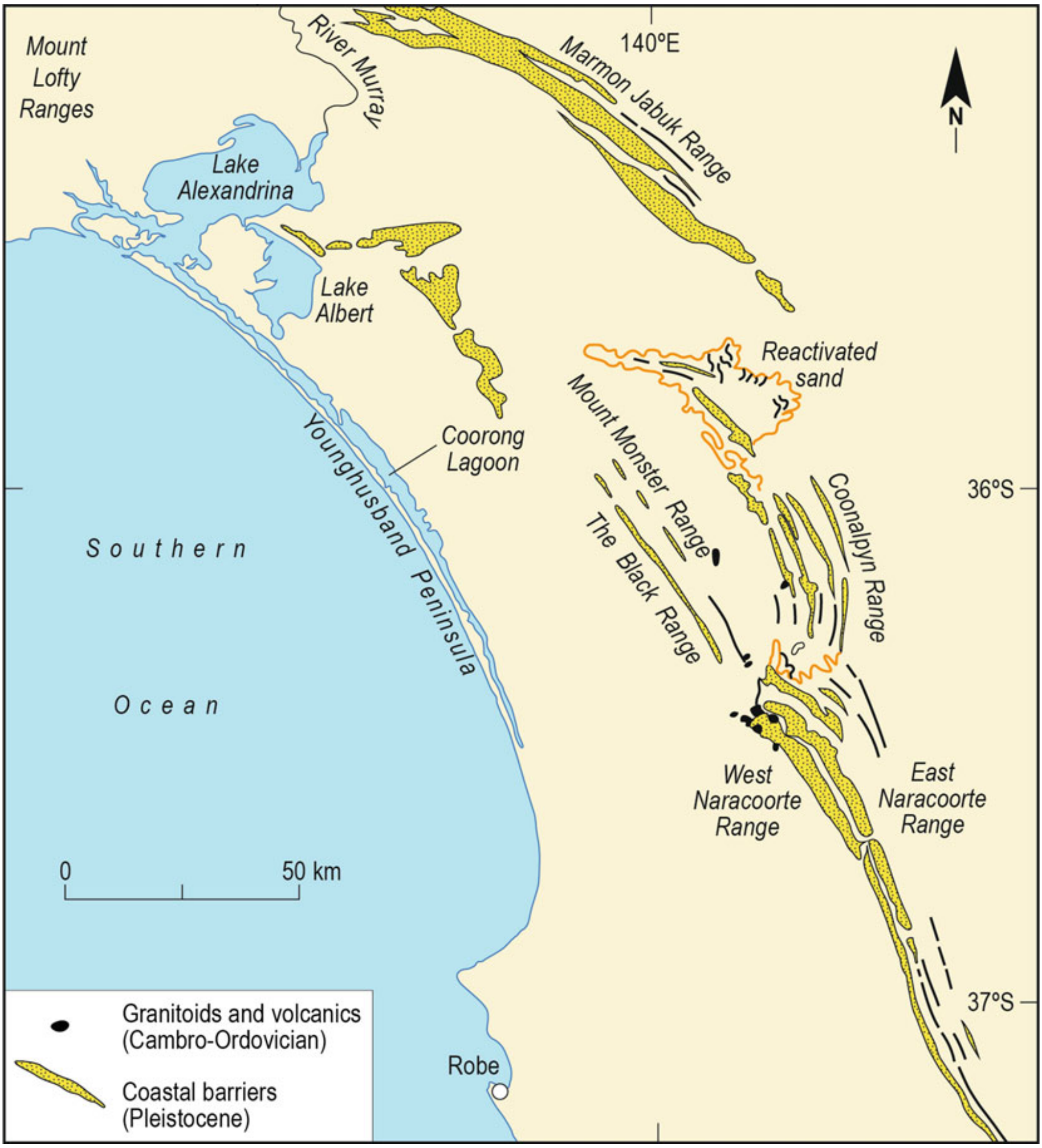


Fig. 2.8 Line drawing of the structure of the Early Pleistocene Coonalpyn Range and its relation to other barriers of late Early to Middle Pleistocene age as inferred from SRTM imagery available from the U.S. Geological Survey

some 16 km north-east of Tailem Bend and its southern limit 35 km north-east of Coonalpyn (Fig. 2.1a, b). The range is up to 80 km inland from the present coastline and is broadly an arcuate shape in plan-view. The sedimentary succession pre-dates the deposition of the Bridgewater Formation. The sediments are strongly indurated and preserve multiple calcrete profiles. The Marmon Jabuk Range is situated on, and defines the western margin of the Pinnaroo Block, an area of up-faulted higher relief. The escarpment of the Marmon Jabuk Range has been described as an Early Pleistocene erosional coastline with a surface relief of 40 m (Rogers 1980b). Low angle alluvial fans drape the western escarpment of the Marmon Jabuk Range.

2.6.2 Cannonball Hill Range

The Cannonball Hill Range is the oldest barrier of the Pleistocene Bridgewater Formation (Bowler et al. 2006). It is situated up to 5 km landward of the Coonalpyn Range and accordingly represents an older relict shoreline feature. Its name is derived from the large siliceous clasts within the sediments of diagenetic origin. The Cannonball Hill Range signifies a major change from the deposition of siliciclastic sediments of the Loxton-Parilla Sands to the prolific formation of bioclastic sedimentary carbonates of the Bridgewater Formation. The Cannonball Hill Range has not been directly dated. Bowler et al. (2006) correlated the succession with MIS 43 or 47 (c. 1.3–1.4 Ma) based on a linear interpolation of coastal barrier ages for the Pleistocene Bridgewater Formation and the previously inferred age of MIS 25 for the East Naracoorte Range (Murray-Wallace et al. 2001).

2.6.3 Coonalpyn Range

The Coonalpyn Range (Tintinara Bay and Keith Beach of Sprigg 1959) is similar to, but appears to be a morphologically more complex Early Pleistocene barrier shoreline than the Naracoorte Range in SRTM imagery (Figs. 2.7 and 2.8). Due to its pronounced arcuate shape, part of the barrier structure is situated up to 30 km inland from the Naracoorte Range. Tindale (1959) considered the flats on the seaward side of the barrier to represent a former lake. Coonalpyn Range is some 10 km wide in cross-section. The dune range comprises at least three physically distinct barrier features (Ryan 2015) although the mapping by Rogers (1980a) suggested the presence of seven separate barriers rather than superposed structures forming composite barriers as evident in the Naracoorte Range to the south. The southern portion of the Coonalpyn Range merges with the northern-most part of the West Naracoorte Range, in an area of outcropping residuals of Cambro-Ordovician granite, that have locally influenced sedimentation and coastal configuration. Tate (1898) described a 74 m thick succession of shelly limestone from Tintinara Railway Bore seaward of the Coonalpyn Range that extended from 13 m APSL to 61 m BPSL. Apart from three shells, all the species are extant. The age of the Coonalpyn Range has not been determined.

2.6.4 Mount Monster Range

Mount Monster Range is a broadly linear barrier structure situated up to 18 km seaward (west) of the Coonalpyn Range (Fig. 2.8). The more linear form of the Mount Monster Range reflects a declining influence of the basement of granitoid and volcanic rocks of the Padthaway Ridge in constraining coastal sedimentation. The barrier is a subdued landform up to 1 km in cross-section and can be traced up to 50 km along its strike on SRTM imagery. It is named after a large quartz porphyry inselberg that bears the same name situated 4 km to the east in the lee of the barrier. The feature was erroneously termed the Hynam Range by de Mooy (1959a) and Ryan (2015) based on a miscorrelation with the Hynam Range as mapped and defined by Sprigg (1952) which is actually situated on the landward side of the East Naracoorte Range. Although the age of Mount

Fig. 2.9 Casts of the fossil pelagic janthinid gastropod *Hartungia* (*dennanti) chavani* within the East Naracoorte Range at Henschke Quarry, Naracoorte. *Hartungia* sp. is an important index fossil in the Early Pleistocene successions of southern Australia (*Photograph* Murray-Wallace 1994)

Monster Range has not been geochronologically determined, it may correlate with MIS 21 (Ryan 2015).

2.6.5 The Black Range

The Black Range is a more distinct linear barrier structure than its older counterpart the Mount Monster Range (Fig. 2.8). The structure can be traced clearly in SRTM imagery for over 48 km as a linear structure 5 km west (seaward) of the Mount Monster Range. The Black Range has not been directly dated but may relate to MIS 19 based on its relative position to the younger succession of barriers across the coastal plain.

2.6.6 Hynam–Koppamurra Range

The Hynam–Koppamurra Range is situated 6 km inland from the East Naracoorte Range and accordingly predates the latter (Sprigg 1952). The barrier is a linear structure, up to 1 km in cross-section and can be traced laterally for up to 30 km (Fig. 2.1a, b). The dune crests of the barrier are up to 20 m above the general level of the coastal plain. Although no geochronological investigations have been undertaken for this barrier dune range, as the feature predates the East Naracoorte Range, it is likely to be older than MIS 21 or MIS 25 based on correlation of barrier structures with oxygen isotope records (Lisiecki and Raymo 2005).

2.6.7 East Naracoorte Range

The East Naracoorte Range is the youngest barrier of Early Pleistocene age on the coastal plain. The East Naracoorte Range is situated on an up-thrown block of Oligo-Miocene Gambier Limestone and occurs immediately to the east of the Kanawinka Fault (Fig. 2.1a, b). The dune crests of this barrier complex are up to 120 m APSL and the adjacent back-barrier lagoonal flats are some 80 m APSL. Palaeomagnetic studies by Idnurm and Cook (1980) showed that the East Naracoorte Range is of reversed polarity, indicating a minimum age of 781 ka. The acquisition of remanent magnetization within aeolianite will significantly post-date the timing of aeolianite deposition. Based on the degree of reddening of siliceous sands to a depth of 2 m within 20,000 years, Idnurm and Cook (1980) inferred a time lag of approximately 30 ka between calcareous dune formation and the acquisition of chemical remanence. A similar time offset may accordingly apply to the Brunhes-Matuyama reversal recorded within aeolianites between the East and West Naracoorte Ranges. Huntley et al. (1993a) reported an age of 720 ± 70 ka for the East Naracoorte Range but acknowledged that this may underestimate the true age of the succession given the presence of the Brunhes-Matuyama reversal, and suggested that the barrier may have formed during the sea-level highstand event 60 ka before the magnetic reversal. Given the time lag between aeolianite deposition and the acquisition of chemical remanent magnetism, the East Naracoorte Range may have a minimum age exceeding 810 ka. Based upon the elevation and long-term uplift rate of the Coorong Coastal Plain, the East Naracoorte Range may be correlated with the MIS 25 sea-level highstand with an inferred age of 860 ka (Belperio and Cann 1990). A whole-rock AAR age of 935 ± 178 ka for aeolianite has been derived for the East Naracoorte Range suggesting a correlation with MIS 31 (Murray-Wallace et al. 2001).

Casts of the pelagic marine gastropod *Hartungia (dennanti) chavani* are a common fossil within shelly calcarenite facies associated with the East Naracoorte Range as seen at Henschke Quarry at Naracoorte, reaffirming the Early Pleistocene age of the East Naracoorte Range (Ludbrook 1978, 1984; Fig. 2.9). The elevation here is 85 m APSL but the coastal barrier range rises to over 120 m to the south. The biostratigraphical correlation with the Early Pleistocene, based on the presence of *Hartungia* sp., cannot, however, be more precisely correlated with Marine Isotope Stages until more detailed regional biostratigraphical information becomes available.

Within the Comaum Forest Reserve, excellent exposures of the East Naracoorte Range reveal multiple lenses of littoral gravel and sand with abundant shelly debris. The sand facies are also visible at the top of the Wrattonbully Road Quarry where coarse shelly and pebbly, trough cross-bedded littoral sediments directly overlie Gambier Limestone at an elevation of 90 m APSL. This site has yielded a TL age of 720 ± 70 ka (Huntley et al. 1993a) and is also the reversed magnetic polarity site of Idnurm and Cook (1980). The higher elevation here compared with similar littoral facies in sand quarries to the north of Naracoorte (55–60 m APSL; Keeling et al. 1985) and at Henschke's Quarry south of Naracoorte (85 m APSL) is attributed to enhanced uplift adjacent to the Kanawinka Fault.

2.7 Middle Pleistocene Coastal Sedimentation—Robe to Naracoorte Line of Section

The Middle Pleistocene commenced some 781 ka ago and its onset is internationally recognised with the geomagnetic polarity reversal heralding a change from the reversed magnetic polarity of the Matuyama Chron to normal polarity of the current Brunhes Chron (Pillans and Gibbard 2012). The Middle Pleistocene ended with the onset of the last interglacial maximum at approximately 132 ka ago, near the base of the Eemian Interglacial in Europe (Shackleton et al. 2002).

Through the combined processes of epeirogenic uplift, relative sea-level changes involving episodic transgressions and forced regressions, and high sedimentary carbonate bio-productivity on the adjacent Lacepede and Bonney Shelves, the coastal plain prograded up to 74 km during Middle Pleistocene time. This involved the development of successive high wave energy barrier shoreline complexes between the Kanawinka Fault scarp and seaward footslope of the East Naracoorte Range across to the seaward side of the West Dairy Range (Robe-Naracoorte line of section). Fourteen laterally persistent and physically well-defined barrier shoreline complexes developed during this period.

During the Middle Pleistocene evolutionary phase of the coastal plain, in the line of section from Robe to Naracoorte, in plan-view, barrier development was not significantly influenced by morphological irregularities in pre-Quaternary basement rocks. Accordingly the broadly linear form of the barriers reflect their wave-alignment adjacent a shallow-water, gently sloping inner-shelf environment. In contrast, the pronounced arcuate shape of Coonalpyn Range, farther north, and the northern portion of the Naracoorte Range, south of the Mount Monster and Black Ranges, were significantly influenced by outcropping residuals of Cambro-Ordovician granitic basement rocks (Fig. 2.1a, b). Accordingly, the barriers tend to be more linear in plan form along the central sector of the Coorong Coastal Plain as characterised in the line of section from Robe to Naracoorte. Up to 50 km south of the Robe–Naracoorte line of section, however, the barriers curve towards the Mount Burr Volcanic Complex in the form of a cuspate foreland (Mount Burr Peninsula sensu Sprigg 1952; Blakemore et al. 2015) revealing that the volcanic complex pre-dates the development of these shoreline complexes. This is a significant observation as the volcanics are highly weathered and not readily amenable to geochronological analyses. Accordingly, the ancient shoreline successions provide a minimum age for the volcanic complex.

The crests of the successive Middle Pleistocene barrier dune ranges and their associated back-barrier estuarine-lagoonal facies (Stewarts, Woolumbool, Baker, Ardune, East Avenue) show a progressive seaward decrease in elevation above present sea level associated with the seaward slope of the coastal plain. Coeval back-barrier, estuarine-lagoonal facies are poorly exposed because of the lack of deep drains and the masking effects of overlying lacustrine facies. Hence much of the palaeosea-level observations are derived from only the elevations of the back-barrier flats and therefore represent only a first-order approximation of Pleistocene sea level highstands (see further discussion in Chap. 7). Morphostratigraphical evidence from the last interglacial (MIS 5e) Woakwine Range, however, suggests that the inferred Middle Pleistocene sea levels represent a realistic first-order approximation of relative sea level.

The northern-most portion of the West Naracoorte Range as mapped on the Naracoorte 1:250,000 map sheet (Rochow 1969) shows that its plan-view shape is influenced by numerous residuals of Lower Paleozoic age granite that would have represented an archipelago during the formation of this coastal barrier. The residuals promoted sediment deposition locally within the region and longshore sediment transport to the north accounts for the development of the Coonalpyn Range and its connection with the West Naracoorte Range.

2.7.1 West Naracoorte Range

The West Naracoorte Range extends as a distinct linear shoreline for over 100 km in a south-south-easterly direction before it recurves in a tombolo-like arc and loses geomorphological form landward of the Mount Burr volcanic complex (Table 2.1). Along much of its length the seaward side of the range is defined by a consistent rectilinear slope (Fig. 2.10). The West Naracoorte Range occurs along the base of a fault-line scarp associated with the Kanawinka Fault (Sprigg 1952). In the north-western sector of the coastal plain closer to the Mount Lofty Ranges the feature is termed the Marmon-Jabuk Scarp (Rogers 1980b), which had previously been correlated with the Naracoorte and Hynam Ranges (Tindale 1959). As a regional structural feature, the Kanawinka Fault and Marmon Jabuk

Table 2.1 Geomorphological attributes of barrier landforms, Coorong Coastal Plain, southern Australia

Dune range	Cross-section width (km)	Traceable length[a] (km)	$\%CaCO_3$	$\delta^{18}O$ age[b]
Central and northern regions				
Robe I/Younghusband	1–3	194	71	1
Robe II/III	1–2	320	81	5a/5c
Woakwine I	1–3	340	81	5e
West Dairy	0.5–1	32	–	7a
East Dairy/Kongorong	0.5	19	–	9
Reedy Creek	1	162	55	7e
West Avenue	0.5–1	115	83	9
East Avenue	0.5–1	96	55	11
Ardune	0.5	50	–	11
Lucindale	1	34	–	13
Baker	0.5–1	50	73	13
Woolumbool/Peacock	1	160	–	15
Stewarts/Cave	0.5–1	135	–	17
Harper	1	67	58	17
West Naracoorte I	1–2	165	90	19
East Naracoorte	1–2	165	21	>25
The Black	0.5	48	–	19
Mount Monster	0.5–1	50	–	21
Hynam-Koppamurra	1	50	–	>25
Coonalpyn	14	75	57	>25
Cannonball Hill Range	1	69	–	>25
Marmon Jabuk	11	60	–	>25
Mount Gambier region				
Robe II/III (Canunda)	0.5–1	25	98	5a/5c
MacDonnell	0.5–1	13	96	5e
Burleigh	0.5–2	50	97	7
Caveton	0.5–2	45	92	9
Gambier	1–1.5	40	88	11
Glenburnie	0.5	5?	–	13
Compton I/II	1–3.5	30	90–66	15/17
Mingbool	1.5–3	45	96	17
Dismal	1	15	96	19

[a]As some of the barriers are masked in places by younger dunes of Last Glacial age, or merge with other barriers, the estimated barrier lengths represent approximations
[b]$\delta^{18}O$ age based on a 'count from the top approach' to sequential numbering of isotope stages, as well as geochronological evidence outlined in Chap. 6

Fault can be traced for over 600 km from near the Mount Lofty Ranges in South Australia to near Portland in western Victoria. The total offset on the fault is 40 m at Naracoorte based on the displacement of the top of the *Victoriella conoidea* foraminiferal zone of the Gambier

Fig. 2.10 Seaward foot slope of the West Naracoorte Range, approximately 20 km north of Naracoorte. The broad form of this hillslope extends uninterrupted for over 100 km along the length of the barrier (*Photograph* Murray-Wallace 1995)

Limestone (Cook et al. 1977). Although a morphologically subdued feature, the Kanawinka and Marmon Jabuk Fault represents one of the most laterally persistent relict sea cliffs in the world (Kenley 1971; Bourman et al. 2016). The abrupt change in surface elevation of the coastal plain associated with the fault complex explains the close proximity of the East and West Naracoorte Ranges. At the time of formation of the West Naracoorte Range, the fault-line scarp would have represented a sea cliff constraining the position of this dune range.

The West Naracoorte Range has been stratigraphically separated into five units, West Naracoorte Range I–V (Schwebel 1978; Prescott 1997). An undulating unconformity separating West Naracoorte Range I from II is evident in the eastern face of a small quarry now occupied by a prominent winery at Wrattonbully (Fig. 2.11). West Naracoorte Range I is of normal magnetic polarity, and hence younger than 781 ka, it has been correlated with MIS 19 highstand (Belperio and Cann 1990). Eastward dipping aeolian cross-bedding is well displayed within several road cuttings in the Naracoorte area where the elevation of the barrier ridge is 70–90 m APSL. The back-barrier flats at 60 m APSL provide a first approximation of relative sea level at the time of deposition, uncorrected for tectonic uplift. The back-barrier flats are 20 m below the level of equivalent landforms of the East Naracoorte Range signifying the magnitude of offset on the Kanawinka Fault. Volcanoes of the Mount Burr Volcanic Complex were near-shore islands at this time and open ocean 'reef facies' have been described up to 65 m APSL on the slopes of Mount Burr and Mount Graham, (Sprigg 1952). Shoreline facies are interpreted at lower elevations (55 m) for coarse sand in quarries north of Naracoorte (Belperio and Cann 1990).

Fig. 2.11 Unconformity surface separating West Naracoorte Range I from the underlying West Naracoorte Range II in Wrattonbully Quarry. The unconformity surface dips to the left of the photograph and occurs immediately above the person standing next to the quarry wall (*Photograph* Murray-Wallace 1993)

2.7.2 Harper Range

Harper Range is a significantly more subdued barrier located approximately 11 km seaward (west) of the West Naracoorte Range (Fig. 2.1a, b). The feature is up to a maximum of 1 km wide in cross-section and appears as a physically distinct, broadly linear landform for up to 67 km as mapped by Sprigg (1952) and reaffirmed by SRTM imagery. The relict coastal dune crests are less than 20 m above the general level of the lagoonal flats which are some 36 m APSL near the lee footslope of Harper Range in a line of section west of Naracoorte. The Mosquito Plains occur landward of the Harper Range and at the north-western extremity of the range, these lagoonal flats are at 29 m APSL reflecting the general north-westerly fall of the landscape. Dating of the aeolian dune facies has yielded a TL age of 585 ± 44 ka (Huntley et al. 1993a) and a leucine racemization whole-rock age on aeolianite of 693 ± 132 ka (Murray-Wallace et al. 2001) suggesting correlation with either MIS 15 or 17 respectively.

2.7.3 Stewarts/Cave Ranges

Stewarts Range occurs up to 3 km seaward of Harper Range. The barrier landform has also been termed 'Stuart Range' by Crocker and Cotton (1946, p. 76), who acknowledged that the former is 'probably more correct'. Cave Range, the south-easterly continuation of Stewarts Range, which occurs some 13 km west of Penola and 22 km west of the West Naracoorte Range is a more arcuate shaped feature in plan form and joins the higher relief of the Mount Burr Volcanic Complex (Fig. 2.1a, b1). Harper Range tapers out and does not occur between the Cave and West Naracoorte Ranges. Stewarts Range is on average 2 km wide in cross-section. The dune crests are up to 67 m APSL and the back-barrier lagoonal flats up to 49 m APSL in a line of section to the west of Naracoorte. Dating of the aeolian dune facies of the Stewarts/Cave Range (Cave Range according to the mapping of Sprigg 1952) by TL has yielded an age of 725 ± 100 ka suggesting a correlation with MIS 17 (Huntley and Prescott 2001).

2.7.4 Woolumbool and Peacock Ranges

Woolumbool Range is situated approximately 19 km west of the West Naracoorte Range and 4 km west of Stewarts Range (Fig. 2.1a, b). The regional mapping by Sprigg (1952) suggested that the Woolumbool Range is a complex structure that to the south merges with the Wattle Dune, which in turn joins the Cave Range. The SRTM imagery, however, reveals that Woolumbool Range can be traced along its strike for up to 160 km and that the southern-most portion of the dune range terminates with the higher relief of the Mount Burr Volcanic Complex as part of a large cuspate foreland complex comprising several barriers. The dune crests of Woolumbool Range extend up to 50 m APSL in a line of section to the west of Naracoorte, while the adjacent back-barrier lagoon flats are up to 39 m APSL. Dune blowouts have partially masked the cross-sectional width of Woolumbool Range. Where undisturbed the barrier is up to 2 km wide. The Peacock Range is a geographically closely related feature occurring 3 km to the west of Woolumbool Range. Although Peacock Range is a distinctive barrier, it merges on its landward side with the Woolumbool Range due to the presence of more recent dune blowouts. These two dune ranges have not been the subject of geochronological investigations.

2.7.5 Baker Range

Baker Range is a prominent dune range with a maximum cross-sectional width of 3.5 km. On average the barrier is up to 2.5–5 km seaward of Peacock Range (Fig. 2.1a, b). The dune crests of Baker Range reach up to 30 m above the adjacent back-barrier lagoon flats, which are 28 m APSL to the west of Naracoorte. Baker Range is situated 30 km west (seaward) of West Naracoorte Range in a line of section from Naracoorte.

Aeolian dune facies of Baker Range have yielded a TL age of 456 ± 37 ka on quartz grains (Huntley et al. 1993a) and a leucine racemization whole-rock age on aeolianite of 438 ± 83 ka (Murray-Wallace et al. 2001) both suggesting a correlation with MIS 11.

2.7.6 Lucindale Range

Lucindale Range is situated on the seaward side of Baker Range (Hossfeld 1950). SRTM imagery reveals that the barrier structure in the north occurs in close proximity to Baker Range, but bifurcates from Baker Range in a more southerly direction over a distance of some 34 km (Fig. 2.1a, b). Although Lucindale Range has not been directly dated it is likely to have formed later in MIS 11 given its proximity to Baker Range.

2.7.7 Ardune

The Ardune is situated approximately 37 km west (seaward) of the West Naracoorte Range. The Ardune is a single broadly linear barrier up to 1.6 km wide that extends for approximately 50 km N–S before merging in the north with the Baker Range on its leeward side and the younger East Avenue Range on its seaward side (Fig. 2.1a, b). The general trend (strike) of the Ardune is in greater sympathy with the younger interglacial barrier East Avenue Range than the older and more landward Baker Range. The latter barrier is more arcuate-shaped in plan form. Although the age of the Ardune has not been geochronologically determined, it has along with the geographically closely related East Avenue Range, been correlated with MIS 11 (Belperio and Cann 1990).

2.7.8 East Avenue Range

The East Avenue Range is a major dune range situated 40 km west (seaward) of the West Naracoorte Range. The barrier is larger than the younger West Avenue Range reflecting the large sediment input from the Lacepede and Bonney Shelves during the early stages of the interglacial. The barrier is up to 3–4 km wide and its aeolian dune crests reach up to 20 m above the surface of the adjacent back-barrier lagoon flats. East Avenue Range occurs 9 km east of the more seaward and younger West Avenue Range. The surface of the back-barrier lagoon flats is up to 25 m APSL. The East Avenue Range can be traced along its strike length as a single barrier for 96 km before it merges in the north with the Ardune Range and Baker Range. To the south, the East Avenue Range loses morphological expression approximately 20 km north of the Mount Burr Volcanic Complex. TL ages for quartz sand from the East Avenue Range of 414 ± 29 ka (Huntley et al. 1993a) and 404 ± 23 ka (Huntley and Prescott 2001) suggest a correlation with the sea level highstand of 405 ka of MIS 11. Therefore it would appear that Baker Range, Lucindale Range, Ardune Range, and East Avenue Range all developed during the 'super-interglacial' of MIS 11 which has been shown to be one of the longest interglacials in the Quaternary (Bradley 2015). The EPICA Dome C ice core record brackets MIS 11 between 424.6 and 392 ka (Masson-Delmotte et al. 2010), a duration of some 32.6 ka compared with approximately 11–12 ka for the last interglacial maximum (MIS 5e; Muhs 2002; Shackleton et al. 2002). During the formation of these four physically distinct barriers, the coastal plain advanced seaward by approximately 8 km during MIS 11.

2.7.9 West Avenue Range

West Avenue Range is a prominent, broadly linear barrier that can be traced northwards from Mount Graham (the northern-most volcano in the Mount Burr Volcanic Complex) along its strike length for up to 130 km where it then merges with the younger Reedy Creek Range. Geochemically sediments of the West Avenue and Reedy Creek Ranges differ to the more seaward and landward dune ranges in terms of their Mg, Sr, Y, Th and U-content, possibly suggesting a contrasting source area for their quartz and heavy mineral components (Huntley et al. 1993a; Prescott 1997). The quartz sands are also coarser grained. The West Avenue Range is situated 54 km west (seaward) of the West Naracoorte Range. The back-barrier lagoon flats (Avenue Flat), between the West and East Avenue Range are up to 10 km wide. The ridge crests of the highest dunes are 60 m APSL and the back-barrier lagoonal flats are around 25–29 m APSL in a transect from Robe to Naracoorte. A potential source for the sediment is from prior streams flowing to the west from Victoria (Hossfeld 1950; Blackburn et al. 1965). Hossfeld (1950) suggested that prior streams now forming the Glenelg River flowed to the sea at Kalangadoo, approximately 32 km north of Mount Gambier.

TL ages on quartz sand of 315 ± 25 ka (Huntley and Prescott 2001) and 342 ± 32 ka (Huntley et al. 1993a) have been reported for the West Avenue Range. A leucine racemization whole-rock age on aeolianite of 382 ± 73 ka has also been derived (Murray-Wallace et al. 2001) indicating a correlation with MIS 9. Thus, Marine Isotope Stage 9 highstand is represented by the West Avenue (central and northern coastal plain) and Caveton Ranges (in the south near Mount Gambier). The West Avenue Range displays seaward dipping littoral facies on its seaward side in the Drain L cutting near Robe as well as a lagoonal facies in the landward side. The elevation of the back-barrier flats, littoral facies and lagoon facies all corroborate an MIS 9 relative shoreline elevation of 24 m APSL uncorrected for tectonic uplift (Table 2.1).

2.7.10 Reedy Creek Range and East and West Dairy Ranges

Marine Isotope Stage 7, the penultimate interglacial multiple highstand events between 250 and 200 ka, is represented by Reedy Creek Range, West Dairy Range and possibly the East Dairy Range. In the southern-most portion of the coastal plain near Mount Gambier, the Burleigh Range is the equivalent barrier feature (Murray-Wallace et al. 1996; Fig. 2.1a, b).

Reedy Creek Range is a physically well-defined, broadly linear barrier landform that extends uninterrupted for 170 km from near Mount Burr, NNW to the east of Salt Creek (Fig. 2.1a, b). For approximately 60 km south of Salt Creek, Reedy Creek Range appears to merge with the seaward (western) side of the older West Avenue Range. Shelly, back-barrier lagoon facies of Reedy Creek Range occur at 18 m APSL. The fossils are poorly preserved and too degraded for amino acid racemization dating. Quartz-skeletal carbonate littoral sand facies at the same elevation on the seaward side of the barrier are 2–3 m thick and overlain by up to 20 m of large-scale trough cross-bedded dune sand. Reedy Creek Range is a more subdued feature than the younger and more seaward last interglacial (MIS 5e) Woakwine Range. The dunes of Reedy Creek Range are up to 20 m above the adjacent lagoon flats. The surface elevation of the back-barrier lagoonal flats of Reedy Creek is 22 m APSL.

Multiple beach ridges occur on the seaward side of Reedy Creek Range to the east of Kingston SE. The beach ridges, which can be traced laterally and parallel for up to 20 km with southern Lacepede Bay occur across a variably sloping beach ridge plain of between approximately 2° (inner ridges) and 5° (outer 16 more seaward ridges). Approximately 40 beach ridges occur across the 6 km wide beach ridge plain (Fig. 2.12). The sediments are capped by a calcrete precluding them from being interpreted as landforms of Holocene age. The troughs of the inner set of beach ridges occur between 11 and 8 m APSL and the outer set grade seaward from approximately 10 to 2 m APSL. Geochronological studies are required to determine if the beach ridge plain succession relates to a forced regression at the end of MIS 7 or whether they relate to MIS 5e.

During the course of preparing this book, an OSL sample was collected from the beach ridge plain on Bells Road (S36° 43.872′; E139° 54.720′), approximately 3.5 km east of Highway 1. The sample collected from the side

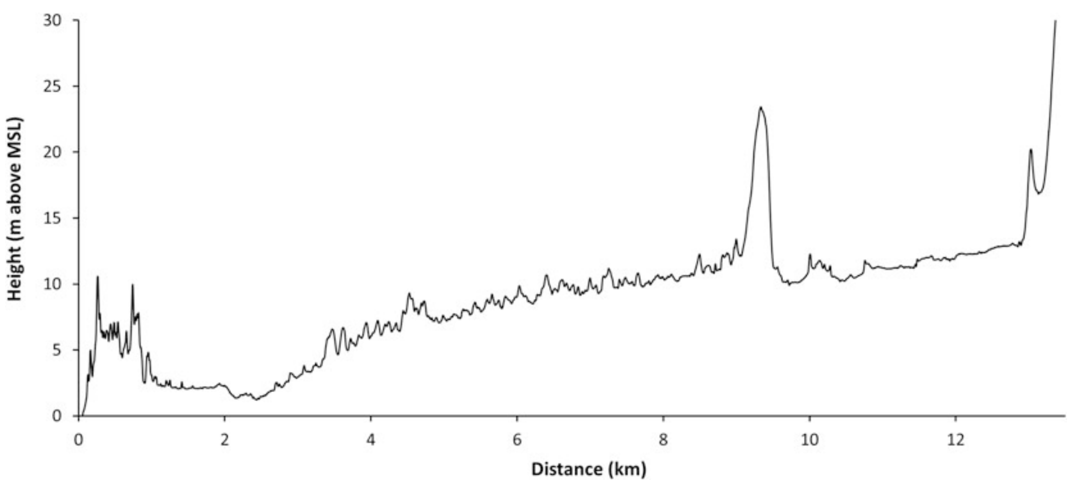


Fig. 2.12 SRTM-derived transect of Pleistocene beach ridges on the seaward side of Reedy Creek and Woakwine Ranges at Lacepede Bay. Reedy Creek Range is situated 13 km to the east of the modern coastline and is represented by the spike on the right-hand side of the image. The Woakwine Range occurs at 9.5 km inland from the modern coastline. A Holocene beach ridge plain occurs across the first 1 km inland from the modern coastline (*Source* SRTM data courtesy of the U.S. Geological Survey)

wall of a 100 m long borrow pit was obtained from a strongly indurated calcarenite beach ridge. The dose rate determined was 1.09 Gy/ka which is significantly higher than the average rate of 0.5 Gy/ka determined for the coastal plain (Huntley et al. 1993a). A considerable scatter in total dose was noted ranging between 20 and 70 Gy. A minimum age of 100 ka would apply if the De was 0.6 Gy/ka (Oliver, *pers. comm.* 2017).

The East and West Dairy Ranges are less prominent barriers that were first described as separate structures to the east of Robe in the mapping by Hossfeld (1950) and Sprigg (1952). The barriers occur within a major corridor between the Reedy Creek and Woakwine Ranges (Fig. 2.1a, b). To the east of Robe, the East Dairy Range occurs as a single linear barrier landform for approximately 19 km and the West Dairy Range as a similar, parallel structure for over 32 km. These dune ranges are more localised features than most of the barriers of the coastal plain. The two ranges are separated by a lagoonal flat approximately 1.5 km wide. The East Dairy Range records a relative sea level of between 6 and 8 m APSL (uncorrected for uplift). Biscuit Flat occurs in the lee of the East Dairy Range, a name derived from the biscuit-sized algal laminated muds that have formed through desiccation, as first noted by Woods (1862).

Luminescence dating of quartz sand from aeolianites within Reedy Creek Range has yielded ages of 220 ± 20 ka (MIS 7e) by OSL (Banerjee et al. 2003) and 258 ± 25 (MIS 7e) by TL (Huntley et al. 1993a). A leucine racemization (whole-rock) age on aeolianite of 251 ± 48 ka has also been derived for the Reedy Creek Range (Murray-Wallace et al. 2001). The East Dairy Range has yielded a TL age of 292 ± 25 ka (MIS 9; Huntley and Prescott 2001) and the West Dairy Range, a TL age of 196 ± 12 ka (MIS 7a; Huntley et al. 1994).

At face value the TL age for the East Dairy Range appears at variance with the TL ages for Reedy Creek Range and West Dairy Range (i.e. an MIS 9 age between two MIS 7 ages). The TL sample was collected from the Drain L cutting on the leeward (eastern) side of the barrier (Huntley and Prescott 2001). Schwebel (1978, 1984) suggested that the East Dairy Range correlated with MIS 9 while Belperio and Cann (1990) favoured a correlation with MIS 7. Schwebel (1983, 1984) noted that the East Dairy Range had been flooded during a younger marine transgression responsible for erosion of some of the aeolian facies of this dune range. On this basis, given that several of the dune ranges are composite structures representing more than one interglacial or interstadial, it is possible that the TL age of 292 ± 25 ka for the East Dairy Range is based on an older sedimentary component of this barrier (i.e. an erosional remnant from within the core of the range rather than a younger succession that physically gives rise to the landform).

Further evidence for the complexity of the stratigraphy of these coastal landforms is the fact that the back-barrier environment of the East Dairy Range was re-flooded during the Last Interglacial Maximum (MIS 5e) as attested by AAR results for the cockle *Katelysia rhytiphora* from the shelly facies at the margins of the barrier structure (Murray-Wallace and Belperio 1991). Thus, when the Woakwine Range formed during the last interglacial maximum (MIS 5e), its back-barrier lagoon facies also extended to the lee of the East Dairy Range and seaward of Reedy Creek Range (Fig. 2.1a, b). The region was therefore a major seaway during the last interglacial maximum, attaining a maximum width of 20–25 km, a water depth of several metres and shallow marine waters completely encircling the East and West Dairy Ranges.

2.7.11 Neville Range

Hossfeld (1950) identified erosional remnants of aeolianite of a presumed younger dune range seaward of Reedy Creek that he termed Neville

Range. The erosional remnants cannot be identified unambiguously on SRTM-imagery and the residuals have not been subject to geochronological investigation.

2.8 Late Pleistocene Coastal Sedimentation—Robe to Naracoorte Line of Section

The Late Pleistocene sedimentary record of the Coorong Coastal Plain is represented by the formation of two laterally persistent barrier shoreline complexes; the last interglacial (MIS 5e) Woakwine Range and Robe Range that formed during the warm interstadials (MIS 5c and 5a). Robe Range is also capped by unlithified Holocene coastal dunes that have formed since the attainment of present sea level some 7000 years ago.

During the Late Pleistocene the coastal plain prograded by up to 13 km in the transect from Robe to Naracoorte. This value takes into account the former extent of Robe Range and therefore includes an estimated maximum of 2 km of coastal erosion of Robe Range since the Holocene sea level highstand (i.e. the past 7000 years) as attested by numerous islands and erosional residuals of the dune range.

2.8.1 Woakwine Range

The name Woakwine Range is an Aboriginal term in reference to an ‘elbow or bent arm’ relating to the shape of a creek near Woakwine Homestead (Prescott 1997). The Woakwine Range was first described by Woods (1862), which he termed the Stone Hut Range. More detailed stratigraphical descriptions of this dune range were undertaken in the Robe area based on the examination of drainage cuttings such as Drain L (Hossfeld 1950; Sprigg 1952; Schwebel 1978, 1983, 1984) and the McCourt Cutting near Beachport (Murray-Wallace et al. 1999). In the Mount Gambier region the equivalent barrier feature was termed MacDonnell Range by Sprigg (1952), although he did not assign it to the Last Interglacial. Volumetrically the bulk of Woakwine Range and the associated Glanville Formation formed during the Last Interglacial Maximum (MIS 5e) (Fig. 2.13). The latter refers to a succession of shoreface and back-barrier estuarine-lagoonal facies that inter-finger with the aeolian dune facies, attesting to their contemporaneity. Apart from one well-defined break in its physical structure between Cape Jaffa and Kingston SE, the Woakwine Range extends as a continuous linear barrier complex for 340 km (Fig. 2.1a, b). It can be traced from northern Hindmarsh Island in the River Murray Mouth region adjacent to the Mount Lofty Ranges, south-east to near Mount Gambier (Fig. 2.1a, b). South of Mount Gambier, an equivalent age barrier landform termed MacDonnell Range by Sprigg (1952) can be traced laterally into western Victoria.

Between Cape Jaffa and Kingston SE the dune range bifurcates to form an easterly trending spit or ‘hook’ termed Benson’s Hook. The spit formed within a partially protected marine corridor between the Woakwine and Reedy Creek Ranges due to longshore drift in the lower wave energy, lee-side of the Woakwine Range at southern Lacepede Bay. At that time a 20–25 km wide marine corridor existed between the actively forming Woakwine Range and the older, more landward and consolidated Reedy Creek Range (Fig. 2.1a, b).

The break in the Woakwine Range coincides with a major change in the shape of the coastline at southern Lacepede Bay to the north-east of Cape Jaffa. The asymmetrically curved bay or zetaform beach (Chapman 1978) represented by Lacepede Bay and southern Younghusband Peninsula broadly coincides with the northern limit of the Gambier Embayment of the Otway Basin, in part defined by the Padthaway Ridge. Accordingly, the break in the Woakwine Range may be in part, structurally controlled by the shallow sub-surface basement rocks to the Quaternary successions. A calcreted beach ridge complex to the east of Kingston SE on the western (seaward side) of Reedy Creek Range has also restricted the formation of the Woakwine Range as a distinct barrier structure within

Fig. 2.13 View looking north-east, near Beachport, towards the higher relief on the seaward side of the Woakwine Range, a composite coastal barrier predominantly of last interglacial age (MIS 5e). (*Photograph* Murray-Wallace 2017)

this region (Fig. 2.12). It is likely, however, that the beach ridge plain is coeval with the Woakwine Range which is more prominently developed farther north, but detailed geochronological studies are required to confirm the age of this succession.

Carter (1985) suggested that to the north of Cape Jaffa, the discontinuation of the Robe and Woakwine Ranges was possibly due to erosional truncation. He suggested that these barriers may have formerly extended to either Cape Jervis on southern Fleurieu Peninsula or Cape Willoughby on the eastern tip of Kangaroo Island. His reasoning was in part based on the suggestion of Sprigg (1952) that Margaret Brock Reef, 7 km to the west of Cape Jaffa represented a continuation of Robe Range, and that accordingly the dune range continued across Lacepede Bay following the same north-west trend. To the north of Kingston SE, however, the Robe and Woakwine Ranges both follow the general trend, and actually define the modern coastline of Lacepede Bay. The Woakwine Range continues in a NNW direction with its beach facies cropping out on the landward margin of the Coorong Lagoon (e.g. at Salt Creek and at numerous sites in the northern Coorong Lagoon; Murray-Wallace et al. 1996, 2010; Bourman et al. 2016), and island remnants of Robe Range occur within the Coorong Lagoon (Cann and Murray-Wallace 2012; Fig. 2.14).

The older and more subdued Dairy Range complex (West and East Dairy Ranges, 8–10 km landward of the Woakwine Range respectively), would have been elongate islands during the Last Interglacial Maximum (MIS 5e) when they were flooded on both their former seaward and landward sides by the high sea level stand of that event. Estuarine-lagoon facies of the Glanville Formation with a distinctive molluscan faunal assemblage with abundant bivalve molluscs including *Anadara trapezia* and *Katelysia rhytiphora* record this marine flooding episode. Extensive areas in the lee of the Woakwine

Fig. 2.14 An elongate remnant of Robe Range in the southern Coorong Lagoon close to the Holocene barrier Younghusband Peninsula. The island predominantly comprises Late Pleistocene aeolianite and is capped by Holocene sand, in part derived from Younghusband Peninsula. Two small patches of Robe Range aeolianite are also visible to the right of the main island featured. (*Photograph* Murray-Wallace 2017)

Range and around the margins of the West and East Dairy Ranges are covered by shelly assemblages (coquina) over 1 m thick (Sprigg 1948, 1951, 1952).

For much of its strike length the Woakwine Range is 1–3 km wide in cross-section. The dune crests of the barrier complex typically extend up to 30 m above the level of the adjacent coastal plain and reach up to 60 m near Cape Jaffa and 80 m at Mount Benson. In the area of Mount Benson the Woakwine Range is up to 10 km wide in cross-section.

The facies architecture of the Woakwine Range is revealed by good exposures in the walls of deep drains (Fig. 2.15). In the McCourt Cutting near Beachport, littoral and back-barrier facies indicate a single major depositional event during the last interglacial maximum (MIS 5e) with a sea level that transgressed from 6.4 to 11.6 m APSL (uncorrected for uplift; Murray-Wallace et al. 1999). On entering the cutting from the western (seaward) side of the barrier landform, three distinctive facies are encountered. These are (1) shallow subtidal, (2) littoral and (3) foredune and dune facies that together make up the coastal sand barrier (Murray-Wallace et al. 1999; Fig. 2.16). The shallow subtidal facies are visible in the lower-most metre of the drain walls. They comprise consistently seaward dipping, parallel laminated, medium to coarse grained, moderately well-sorted bioclastic sand. Thin pebbly and shelly layers occur at intervals. The consistent seaward dipping laminae indicate a dominance of return-flow in the lowermost littoral to shallow subtidal zone. Littoral or beach facies occupy an interval from 1 to 3 m above the drain floor, rising eastwards to 6 m. They comprise bi-directional trough cross-bedded and tabular cross-bedded, medium to coarse grained, well-sorted bioclastic sand. Bedform wavelengths of about 2 m are evident. Pebbly and shelly lag horizons with calcrete clasts and reworked flint cobbles from the Oligo-Miocene Gambier Limestone are common, particularly towards the centre of the barrier where this facies merges with parallel-laminated wash-over fan deposits. The littoral facies indicate that the palaeo-shoreline elevation decreased from about 10 to 7 m (uncorrected for tectonic uplift) during construction of this barrier.

The foredune and dune facies overlie the lower two facies and rise up to 30 m above the former shoreface. They comprise slightly finer bioclastic sands in large sets of landward dipping cross-beds up to 10 m thick. Reactivation surfaces between sets are weakly cemented and may host palaeosols and rhizomorph concentrations.

A fourth facies, the back-barrier estuarine-lagoon facies is visible towards the eastern end of the McCourt Cutting. Flat lying shelly mud with abundant *Katelysia* sp., *Ostrea* sp., and small gastropods, and exposed for up to 1.5 m above the drain floor, laps on to the localised calcreted hardground. Transgressive dunes subsequently buried the lagoon sediment surface, locally asphyxiating the cockle population. Similar processes occur today on the landward side of Younghusband Peninsula where transgressive dunes are migrating into the Coorong Lagoon. *Katelysia* shells from a similar setting at Drain L and at the McCourt Cutting have been correlated with the last interglacial maximum (MIS 5e) based on amino acid racemization (Murray-Wallace et al. 1991). The lagoon facies indicates a palaeosea-level of about 10 m APSL uncorrected for tectonic uplift.

In Drain L of the Anderson Drainage Scheme (Williams 1964; 1977) 8 km to east of Robe, at least three successive depositional episodes are recognised within the Woakwine Range at between 5 and 10 m APSL (Hossfeld 1950; Sprigg 1952; Schwebel 1984; Belperio and Cann 1990: Fig. 2.17a, b). In the early mapping of Woakwine Range, Hossfeld (1950) identified four depositional components based on the succession exposed in the Drain L cutting (he termed in ascending order Woakwine A through to D; Fig. 2.17b). Woakwine A occurs beneath a marine abrasion surface. Woakwine B is capped

Fig. 2.15 View of the Woakwine Range looking west from the former observation platform at McCourt drainage cutting. At this locality the barrier is predominantly of last interglacial age (MIS 5e; Woakwine I) but includes a core of older aeolianite of penultimate interglacial age (MIS 7; Woakwine II) not visible in the photograph. Lake George and mobile transgressive dunes of Younghusband Peninsula are visible in the horizon. The maximum depth of the 1 km long cutting is up to 30 m in the central portion of the barrier (*Photograph* Murray-Wallace 1997)

by two cemented shelly units of differing ages based on their cross-cutting relationships (Horizons A and B; Hossfeld 1950). The interbedded aeolian unit Woakwine C occurs between shelly horizons A and B and appears to represent a shorter-term depositional episode. The bulk of the barrier is represented by Woakwine D aeolian facies. Sprigg (1952, p. 50) concluded that there were at least '… three complete or partial marine submergences', revealed in the Drain L cutting, and that the oldest aeolian unit must have been

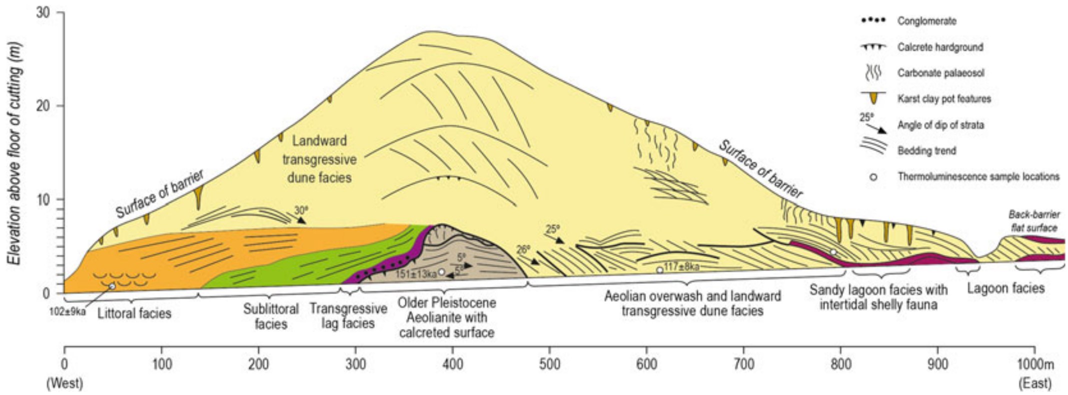


Fig. 2.16 Facies architecture of the Last Interglacial Woakwine Range as revealed within McCourt Cutting near Beachport, southern South Australia based on mapping reported by Murray-Wallace et al. (1999)

deposited on a cemented unit at the time of sea-level rise. Schwebel (1978, 1984) identified five depositional phases within the Woakwine Range in the Drain L cutting and from drill core.

The Robe–Penola Road traverses Lake Hawdon, a low-lying complex of contemporary ephemeral lakes with sediments comprising micro-gastropod-rich dolomitic marl. The Holocene cover, however, is relatively thin and the regional landscape morphology is essentially inherited from a more extensive last interglacial back-barrier lagoon precursor. The Glanville Formation was deposited in this lagoon landward of the Woakwine Barrier, and its waters lapped the seaward side of Reedy Creek Range, surrounded the Dairy Range and extended many kilometres southwards. *Anadara* sp., *Ostrea* sp., *Mytilus* sp., *Fulvia* sp., *Chlamys* sp, *Brachidontes* sp., and *Katelysia* sp., are conspicuous large fossil molluscs found in this sediment throughout the region. Palaeosea-level estimates for the Glanville Formation in this area have been estimated at 7 m APSL, uncorrected for tectonic uplift (Belperio and Cann 1990). At Lake Hawdon, the surface of the Glanville Formation is at 5 m APSL, indicating a water depth of some 5 m within the former Glanville lagoon.

The West and East Dairy Ranges are partially buried, older (MIS 7a) coastal barriers around which the Glanville sea lapped. At the Wilmot Drain on the landward (eastern) side of Reedy Creek Range, a typical oyster-cockle-scallop assemblage is exposed in the shallow cutting and in the drain spoil. Amino acid racemization dating of molluscs from this site has confirmed a last interglacial (MIS 5e) age and an unpublished OSL measurement on quartz sand from the lagoonal facies has yielded an age of 126 ka (Rhodes, *pers. comm.* 2007).

After exactly 3 km along the Robe–Penola Road (S37° 15′ 44.4″; E139° 56′ 10.7″) from the Beachport turnoff, fossiliferous shell beds of the last interglacial back-barrier lagoon facies are exposed in low, calcreted road-side cuts on the southern side of the road (Fig. 2.3a, b). Articulated *Katelysia rhytiphora* and *Fulvia tenuicostata* are extremely abundant in this exposure, their occurrence resembling a modern living assemblage of these cockles. Their presence signifies a shallow subtidal to intertidal marine setting which was subsequently buried by aeolian sands.

North of Kingston SE, the former shoreline of the Woakwine Range equivalent is situated immediately on the landward side of the Holocene Coorong Lagoon and can be traced parallel with Younghusband Peninsula as far as Lake Alexandrina where it forms a recurved spit on the south-eastern margin of Lake Albert (de Mooy 1959a, b; Blackburn et al. 1965). To the north-west of Lake Albert, the dune range extends across the northern-most portion of Hindmarsh Island (Murray-Wallace et al. 2010; Bourman et al. 2016). Along this coastal sector

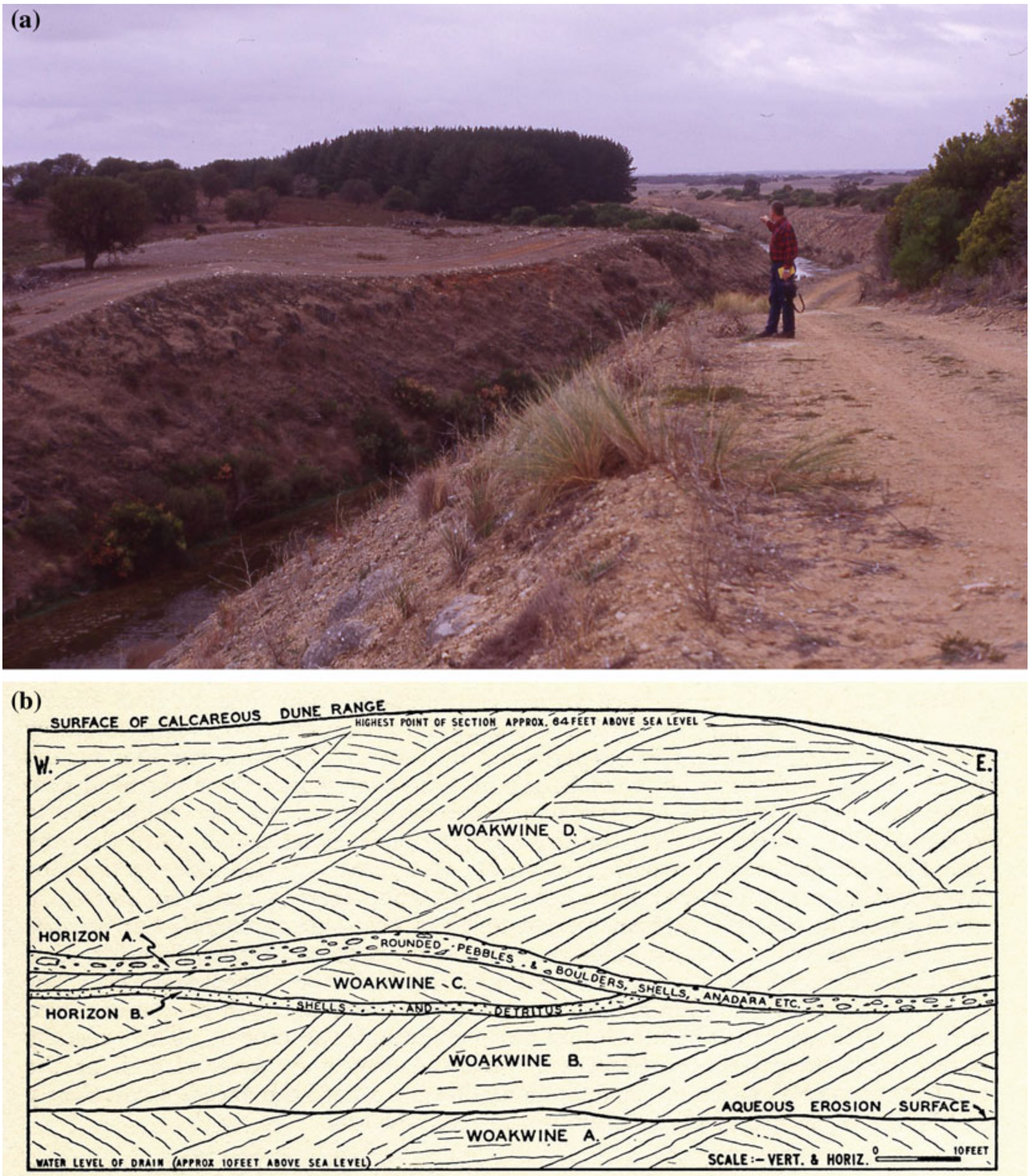


Fig. 2.17 **a** View looking east along the Drain L drainage cutting of the Anderson Scheme. The drain cuts across Bridgewater Formation aeolianites of the Last Interglacial age Woakwine Range (*Photograph* Murray-Wallace 1993); **b** schematic diagram illustrating four superposed components of Woakwine Range as seen within Drain L drainage cutting, based on the mapping of Hossfeld (1950) (Reproduced courtesy of the Royal Society of South Australia)

the Late Pleistocene successions represent a condensed section due to subsidence in some areas and a slower rate of neotectonic uplift elsewhere.

The elevation of the last interglacial (MIS 5e) shoreline and back-barrier lagoon facies associated with the Woakwine Range varies systematically along the 340 km length of this barrier.

Near Mount Gambier the lagoonal facies attain a maximum height of up to 18 m APSL (Murray-Wallace et al. 1996). At Salt Creek, consolidated low angle, planar cross-bedded beach-face sediments with abundant, storm-reconcentrated, disarticulated bivalves (*Anapella* sp.) occur up to 3 m APSL. Equivalent facies occur at just 1 m APSL some 80 km NNW before disappearing beneath Lake Alexandrina, a zone of subsidence in the River Murray mouth region, bounding the reversely faulted and uplifted Mount Lofty Ranges (Adelaide Fold-belt). In this latter region in the northern-most Coorong Lagoon (Pelican Point to Long Point), shoreface facies of the Last Interglacial define much of the landward shoreline of the lagoon. The moderately lithified sediments comprise low angle, planar and trough cross-bedded skeletal carbonate sands with abundant in situ bivalve molluscs *Donax deltoides* (Goolwa cockle) and *Spisula* (*Notospisula*) *trigonella* (Murray-Wallace et al. 2010).

The skeletal constituents of the barrier sands are similar to those of the modern open ocean beaches and barriers, reflecting a mixed and comminuted shallow inner continental shelf source. Typically the sediments include abraded and well-sorted tests of foraminifers, calcareous red algae, and comminuted molluscs, bryozoans and echinoids. Reworked skeletal aggregates, microids and pisoids are also common and quartz is the dominant silicate in a relatively small non-carbonate fraction. The calcium carbonate component is commonly up to 80% of the sediment. The sediments interfinger on their lee-side with cockle, scallop and oyster-rich lagoonal to intertidal shell beds (Glanville Formation), and dolomitic lacustrine facies that are extensively developed within interdune corridors south of Kingston, as far inland as the base of the Reedy Creek Range.

The last interglacial (MIS 5e) age of the bulk of the Woakwine Range barrier comprising predominantly dune facies is based on several TL ages on quartz sand from these sediments yielding ages of 120 ± 8.7 ka (Banerjee et al. 2003), 132 ± 6 ka (Huntley et al. 1993a), 118 ± 4 ka and 132 ± 9 ka (Huntley et al. 1994) and 117 ± 8 ka (Murray-Wallace et al. 1999). In addition, AAR results for fossil marine molluscs (*Katelysia* sp.) from coeval back-barrier estuarine-lagoon facies in the McCourt Cutting, as well as shoreface facies (*Anapella* sp.) at Salt Creek and *Donax deltoides* at Mark Point on the northern-most landward shoreline of the Coorong Lagoon in the Murray Lakes region, indicate an MIS 5e age for the Woakwine Range (Murray-Wallace et al. 1999, 2010).

2.8.2 Robe Range

Robe Range is the youngest barrier of Late Pleistocene age on the coastal plain (Schwebel 1978, 1983, 1984). Low relief (<15 m high APSL) outcrops of aeolianite of Robe Range occur within the Coorong Lagoon as small islands (<1 km long) and more extensively at Parnka Point and Hack Point some 25 km to the north of Policeman Point (Cann and Murray-Wallace 2012). In this northern region the Holocene sand dunes of Younghusband Peninsula mask much of the Late Pleistocene aeolianite of Robe Range (Fig. 2.18). More prominent outcrops of Robe Range aeolianite are exposed in well-developed sea cliffs reaching up to 20 m high along the 155 km sector of coastline from Robe, south-east to Port MacDonnell (Fig. 2.1). Along this coastal sector the barrier is a more distinctive landform. The higher rate of uplift along this portion of the coastline is responsible for the extensive outcrops of Robe Range above present sea level.

Eroded remnants of Robe Range typically occur up to 1–2 km offshore as small islands having formed in the past 7000 years by coastal erosion under present sea level conditions. The most extreme example is the island Margaret Brock Reef which occurs some 7 km to the west of Cape Jaffa. The accordant surfaces of shore platforms surrounding the islands corresponding with present sea level indicate that the only time they could have formed was during the past 7000 years of the Holocene sea level highstand (Fig. 2.19). Since the time of their formation, the two Late Pleistocene components of Robe Range

Fig. 2.18 Modern/Holocene coastal dunes of Younghusband Peninsula and the northern Coorong Lagoon near Narrung Peninsula (*Photograph* Murray-Wallace 2014)

(MIS 5c at 105 ka and MIS 5a at 82 ka) had remained above sea level until the attainment of the Holocene highstand some 7000 years ago.

Three stratigraphical units, correlative with the Late Pleistocene interstadials MIS 5c, 5a and draped by Holocene and modern dune sand (termed Robe III, II and I respectively) constitute Robe Range (Schwebel 1983, 1984). The toe (basal foot slope) of the two Late Pleistocene components of Robe Range occurs between 36 and 24 m below present sea level (BPSL; Sprigg 1979).

Basal sediments of Robe Range rest unconformably on Oligo-Miocene Gambier Limestone. The Robe Range aeolianite is exposed in a number of road cuttings, pits and eroding headlands within and near Robe Township, and forms prominent cliffs along portions of the coastline between Robe and Port MacDonnell. The TL dating site of Huntley et al. (1994) and Banerjee et al. (2003) for Robe III beneath a palaeosol, which yielded an age of 116 ± 6 ka, is exposed on the western headland at Glass Beach at Robe (Prescott 1997). On the eastern side of Robe harbour, particularly at Cape Dombey, excellent exposures of Robe Range aeolianite with large scale cross-bedding preserved with the original dune form structure of topset, foreset and bottom-set beds is still evident in the present landscape. Belperio (1995) inferred a current MIS 5c shoreline elevation of 2 BPSL m for this region (9 m BPSL when corrected for tectonic uplift). Calcrete palaeosols on Robe Range are limited to soft carbonate illuviation with minor development of blocky calcrete and excellent preservation of primary bedding.

A thermoluminescence (TL) age 95 ± 6 ka for aeolianite at Policeman Point indicates a correlation with MIS 5c for part of the dune facies (Huntley and Prescott 2001) equating with Robe III. Robe III was also assigned to MIS 5c (c. 100 ka) by Schwebel (1978, 1983, 1984). Using quartz extracts, Huntley et al. (1994) obtained a TL age of 116 ± 6 ka for Robe III

Fig. 2.19 Erosional remnants of Robe Range aeolianite near Robe, rimmed by shore platforms that have formed in the past 7000 years under present high sea level conditions (*Photograph* Murray-Wallace 2014)

sediments cropping out at Glass Beach, the type locality near the township of Robe. Using feldspar inclusions within quartz grains, Huntley et al. (1993b) also determined an IR-OSL age of 107 ± 36 ka for this dune. Using the single-aliquot regenerative-dose (SAR) procedure, Banerjee et al. (2003) reported ages of 100 ± 6.7 ka and 61 ± 3.6 ka for Robe III and II respectively, from sites near the township of Robe. Taken at face value, the SAR-OSL age from Robe II is considerably younger than the 82–85 ka age commonly associated with MIS 5a and may imply that the succession dated at this locality is unrelated to this interstadial sea level highstand, and represents an isolated phase of dune reactivation during the Last Glacial Cycle. This may indicate that some of the aeolian successions within the Robe Range complex were locally reworked during younger stadials and do not have a specific sea level connotation as foreshadowed by Kirkey (1988), and as noted in other stratigraphically complex aeolianite successions such as the Swan Coastal Plain in Western Australia (Brooke et al. 2014). An OSL sample from the base of an eroded residual of Robe Range aeolianite cropping out within the Robe-Woakwine corridor approximately 1 km north of Lake St Clair yielded an age of 75.5 ± 3.9 ka (Ayling 2005) suggesting a correlation with MIS 5a. A TL sample collected from the unconsolidated Holocene sands of Robe I yielded an age of 1.2 ka (Prescott 1997).

2.9 Coastal Plain Sedimentation—Mount Gambier Region

The southern-most portion of the Coorong Coastal Plain occurs in the Pleistocene-Holocene volcanic region of southern South Australia and extends into western Victoria (Fig. 2.20). Up to nine morphologically distinct barriers occur across this sector of the coastal plain including the warm interstadial Robe Range which occurs

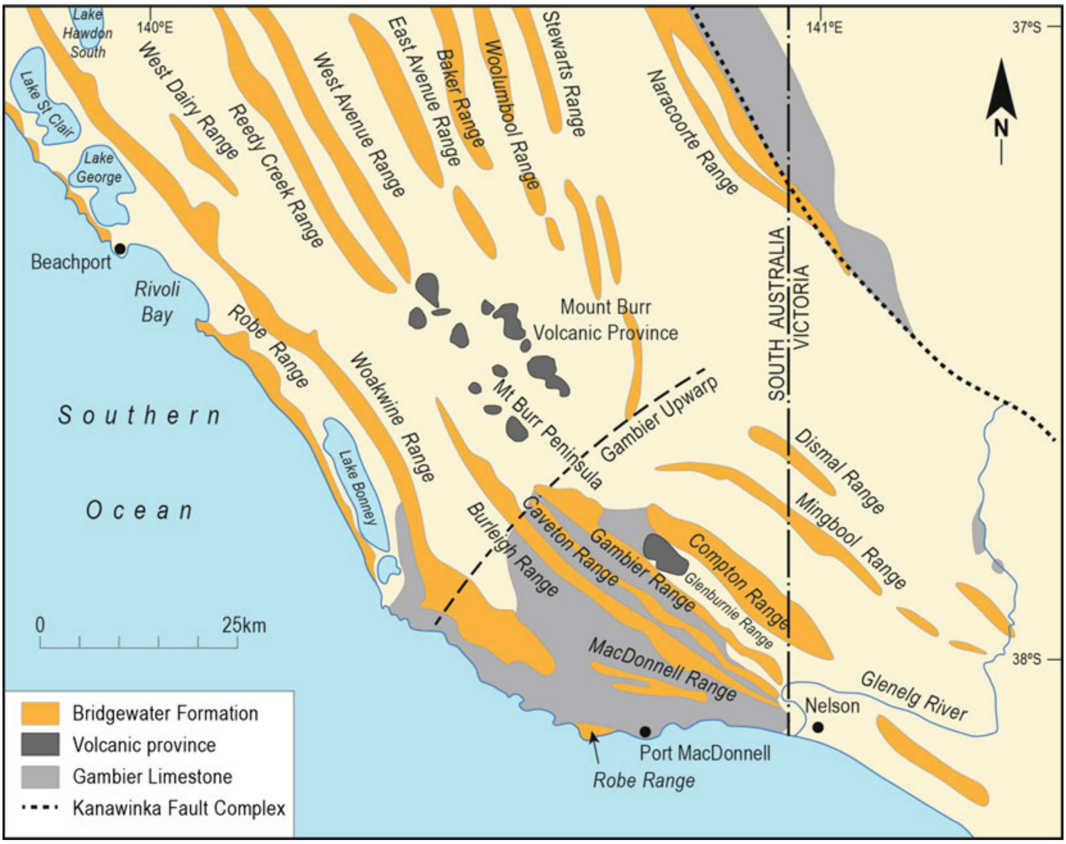


Fig. 2.20 Map illustrating the spatial distribution of the coastal barriers of the Mount Gambier region, southern South Australia based on SRTM data available from the U.S. Geological Survey and mapping of Sprigg (1952) and Blakemore (2014)

at the modern coastline (Sprigg 1952; Blakemore et al. 2015). The barrier sediments have principally been derived from the adjacent Bonney Shelf. With the exception of the Glenelg River to the far east of this sector of the coastal plain, the absence of rivers has resulted in these barriers having a higher percentage of calcium carbonate grains. Average percentage of $CaCO_3$ is $90 \pm 10\%$. Percentages of calcium carbonate sediment for each barrier are provided in Table 2.1.

The barriers were deposited on a subaerially-exposed and karstified marine abrasion surface that formed on the Oligo-Miocene Gambier Limestone by multiple transgressive—regressive episodes during Pleistocene time. The marine abrasion surface slopes in a seaward-direction and in detail, is stepped in the form of a series of benches of contrasting relative heights above present sea level. The shape of the individual barriers in plan-view is related to crustal doming of the Gambier Limestone associated with the emplacement of magma during multiple episodes of volcanism. The oldest barriers such as the Dismal, Mingbool, and Compton Ranges curve seawards towards the higher relief of the Pleistocene Mount Burr Volcanic Complex indicating that these barriers post-date the volcanic complex (Fig. 2.20). In contrast the Glenburnie, Mount Gambier, Caveton and Burleigh Ranges in plan-view are linear in form and trend broadly parallel with each other. The MacDonnell and Robe Ranges both trend obliquely to each other and to the Burleigh Range

(Fig. 2.20). The different orientations of these latter barriers highlight the influence of the domed upper surface of the Gambier Limestone on controlling the regional configuration of the coastline during successive interglacials.

Trending NE–SW between Mount Burr and Mount Gambier, the 'Mount Gambier Upwarp' (Sprigg 1952), also termed the Mount Burr Peninsula (Sprigg 1952; Blakemore et al. 2015), refers to a region of the highest surface relief of the Gambier Limestone (marine abrasion surface) reaching over 80 m APSL (Murray-Wallace et al. 1998). To the northwest of the Upwarp, the coastal plain dips gently in that direction and conversely to the southeast dips towards Mount Gambier. These gentle slopes also influence the shape of the barriers in plan-form.

With the exception of the Gambier Range, the majority of the barriers are morphologically smaller structures than the majority of barriers in the line of section from Robe to Naracoorte. This observation and the absence of major unconformities within these barriers imply that each barrier equates with a single interglacial and also reflects the smaller sediment supply from the Bonney Shelf compared with the Lacepede Shelf. In the following discussion some of the key attributes of the barriers in the Mount Gambier region are reviewed. The barriers are described from the oldest, most landward to the younger more seaward structures.

2.9.1 Dismal Range

Dismal Range is the oldest and most landward barrier in the Mount Gambier sector of the Coorong Coastal Plain. It is situated 40 km inland from the coastal town of Port MacDonnell. Excluding the Late Pleistocene warm interstadial barrier of Robe Range (MIS 5c and 5a) which is exposed along the modern coastline in spectacular outcrops in cliff sections from Carpenter Rocks to Port MacDonnell, Dismal Range is the eighth interglacial barrier within the region, and based on the notion of each barrier equating with a separate interglacial sea level highstand within the region is provisionally correlated with MIS 19. AAR analyses on the benthic foraminifer *Elphidium crispum* yielded a numeric age of 933 ± 145 ka suggesting a correlation with MIS 23 (Blakemore et al. 2015).

2.9.2 Mingbool Range

Situated some 33 km inland from Port MacDonnell, Mingbool Range is the seventh interglacial barrier within the region and at face value would correlate with MIS 17 based on a 'count from the top' approach for inferring age. An exposure of Mingbool Range within Don's Quarry, near Dartmoor, western Victoria reveals a subaqueously deposited succession of horizontally and trough cross-bedded, dominantly fine grained skeletal carbonate sand with entire and fragmented oyster shells (*Ostrea angasi*) and the foraminifers *Elphidium crispum*, *Discorbis dimidiatus* and *Ammonia beccarii* (Blakemore 2014). Coarser grained trough cross-bedded inter-beds occur within the succession indicating episodic pulses of higher energy deposition possibly related to storm deposition. The presence of the oyster *Ostrea angasi* indicates shallow water deposition of several metres water depth (Ludbrook 1984). AAR analyses on the benthic foraminifer *Elphidium crispum* yielded a numeric age of 788 ± 118 ka suggesting a correlation with MIS 19 (Blakemore et al. 2015).

2.9.3 Compton Range

Compton Range is the sixth barrier inland from the present coastline and situated some 23 km from Port MacDonnell. As a distinct landform the upper surface of the barrier is on average up to 20 m above the karstified marine abrasion surface on the Oligo-Miocene Gambier Limestone that defines the regional landscape and the highest point of the barrier is 68 m APSL. In cross-section the barrier is up to 3.5 km wide with two parallel components.

The Compton Range succession is well exposed in Baxter's Quarry in the township of Mount Gambier. The exposure reveals that this barrier is a composite structure representing more than one interglacial. The deep quarry section reveals laterally persistent aeolian dune facies with well-developed tabular cross-beds resting unconformably on a succession of subaqueously-deposited skeletal carbonate sands mapped as Compton II (Blakemore 2014). A partially eroded protosol, which separates the two successions, has formed on the top of the subaqueously deposited unit. The upper succession of aeolian sands (Compton I) is capped by a calcrete of irregular thickness with numerous rhizomorphs. Both sedimentary components of Compton Range are truncated by solution pipes up to 75 cm wide and 3.5 m deep infilled with *terra rossa* soil. AAR analyses on the foraminifer *Elphidium crispum* suggest that Compton II is of MIS 15 age (538 ± 102 ka) and an OSL age of 390 ± 35 ka suggest an MIS 11 age for the stratigraphically superposed Compton I (Blakemore et al. 2015).

2.9.4 Glenburnie Range

Glenburnie Range is a particularly subdued barrier that trends NW–SE immediately to the east of Mount Gambier (Sprigg 1952). The feature is difficult to identify in the field due to the irregular and undulating topography of the karstified Gambier Limestone and Bridgewater Formation in this region. As mapped by Sprigg (1952) the barrier can be traced as a linear structure for only 2.4 km. The extensive cover of volcanic ash associated with the Holocene volcano Mount Gambier has also frustrated studies of this barrier. Given the indistinct physical nature of this barrier, it may relate to a short-term highstand associated with an interstadial in the Middle Pleistocene. The feature is also indistinct on SRTM imagery. The age of this barrier has not been resolved.

2.9.5 Gambier Range

The Gambier Range is a morphologically prominent landform and represents the fourth barrier inland from the modern coastline (Fig. 2.21). The barrier attains a maximum height of 80 m APSL, occurs up to 30 m above the surrounding plains and is situated some 20 km inland from the modern coastline. In cross-section the barrier is up to 1.5 km wide. Morphostratigraphically, the Gambier Range would appear to be correlative with the East Avenue Range in the region between Robe and Naracoorte and therefore of MIS 11 age between 424.6 and 392 ka (Masson-Delmotte et al. 2010). This is consistent with the geographic position of the barrier as the fourth barrier inland from the present coastline. An AAR age of 581 ± 90 ka on the foraminifer *Elphidium crispum* would imply a correlation with MIS 15 (Blakemore et al. 2015).

2.9.6 Caveton Range

Named by Crocker and Cotton (1946), the Caveton Range represents the south-eastern continuation of the West Avenue Range to the south-east of the Mount Burr volcanic complex. Near Mount Burr the dune structure losses definition as noted by Sprigg (1952) and is morphologically more distinct closer to Mount Gambier and Mount Schank. The higher level landscape of the Mount Burr Volcanic Complex appears to have experienced marine erosion of its SW margin which may equate with periods of erosion both at the time of formation of the Gambier and Caveton Ranges. The Caveton Range is situated approximately 2 km inland from the younger Burleigh Range and up to 25 km from the present coastline.

Back-barrier lagoon facies of the Caveton Range are exposed in road cuttings and a small silage pit adjacent to Rabbitors Road and about 100 m north on the eastern side of the road (S37° 53′ 56″; E140° 46′ 27.7″; Fig. 2.22a, b). The pit exposure reveals pale yellowish grey, fine

Fig. 2.21 View looking south towards the Holocene volcanic centre of Mount Schank in the horizon, taken from the southern rim of Mount Gambier. In the middle distance are the coastal barriers of the Gambier and Caveton Ranges. (*Photograph* Murray-Wallace 2017)

to medium grained skeletal carbonate-quartz sands, containing the fossil molluscs *Anapella cycladea*, *Spisula* (*Notospisula*) *trigonella*, *Tellina deltoidalis*, *Katelysia rhytiphora* and *Fulvia tenuicostata*. Collectively, the fossil molluscs indicate a low energy, intertidal to shallow subtidal estuarine-lagoonal environment with fully marine salinities (Ludbrook 1984). Juvenille *Anapella cycladea* and *Spisula* (*Notospisula*) *trigonella* are particularly abundant in the upper 30 cm calcreted portion of the exposure reflecting a transition from normal marine salinities to more brackish conditions. Pristine *Ammonia beccarii* is the only observed species of foraminifer present within these sediments (n = 276 individuals counted) indicating a restricted lagoonal depositional environment equivalent to the modern Coorong Lagoon (Murray-Wallace et al. 1996). Palaeosea-level (uncorrected for tectonic uplift) was determined to be 38 m APSL from the intertidal lagoonal indicators.

TL dating of quartz sand associated with the marine molluscs yielded an age of 320 ± 22 ka indicating a correlation with MIS 9 of the marine oxygen isotope record (Murray-Wallace et al. 1996). TL dating of the West Avenue Range to the north-east of Beachport yielded ages of 342 ± 32 ka and 315 ± 25 ka (Huntley et al. 1993a; Huntley and Prescott 2001) demonstrating its time equivalence with the Caveton Range.

2.9.7 Burleigh Range

Located 10 km south of Mount Gambier, the Burleigh Range (Fig. 2.23) is a prominent shoreline barrier that trends in a NW–SE direction. The Holocene volcano, Mt. Schank erupted on the seaward side of the Burleigh Range, and basaltic pyroclastics from the volcanic centre are draped over this dune range. The Burleigh Range can be traced for over 50 km from the Mt. Burr

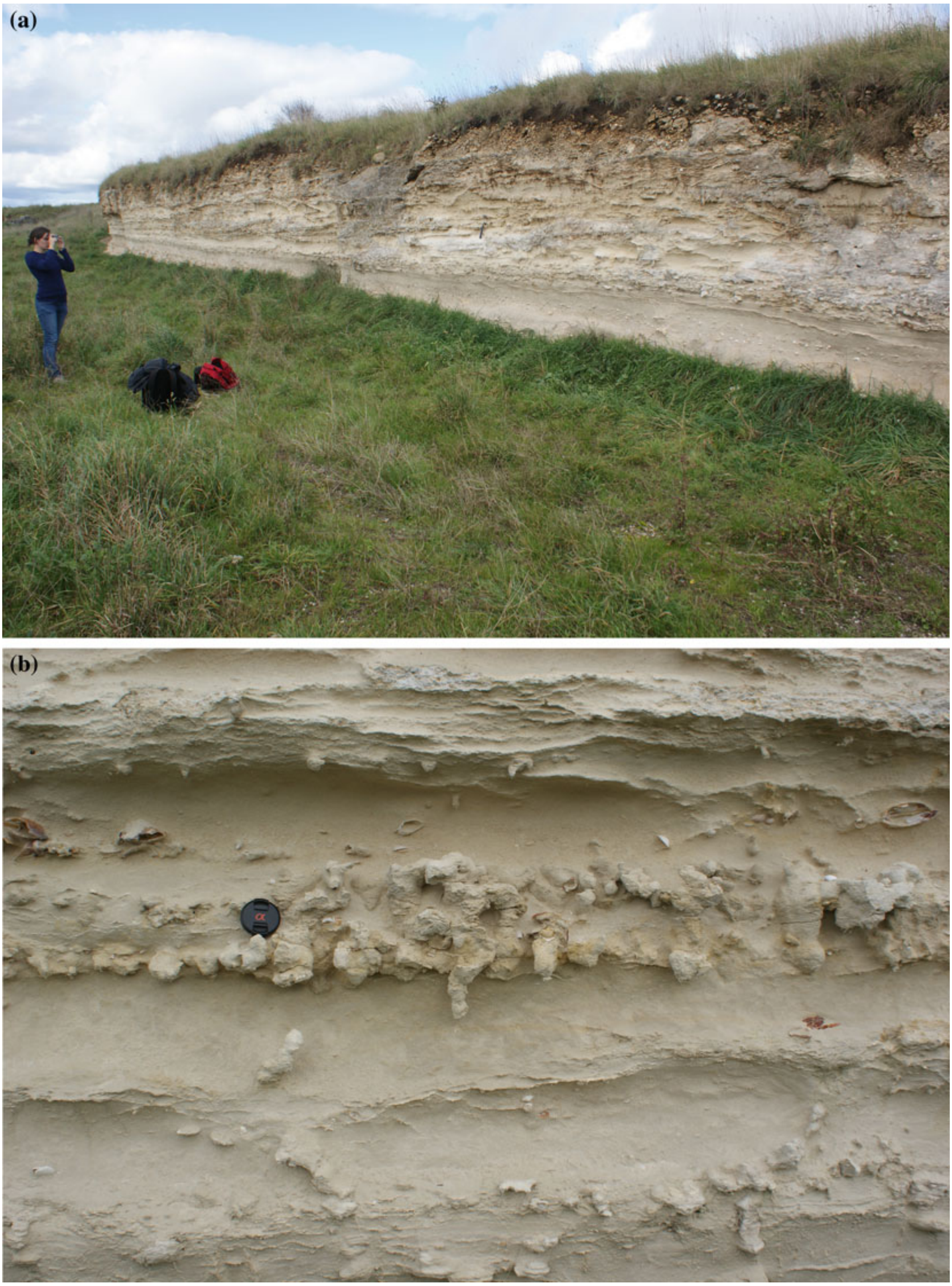


Fig. 2.22 **a** Back-barrier lagoon facies of the Antepenultimate Interglacial (MIS 9) Caveton Range south of Mount Gambier; **b** detail of back-barrier lagoon facies showing isolated articulated and disarticulated bivalve molluscs in the upper portion of the image and discrete zones subject to bioturbation. Lens cap for scale. (*Photographs* Murray-Wallace 2014)

Volcanic Province to the Glenelg River at the border of South Australia and Victoria, where it merges with a number of older dune ranges.

Approximately 2 km due east of Mt. Schank a small road cutting on Rabbitors Road reveals three lens-shaped, tightly-packed seaward dipping gravel beds that occur within planar and trough-cross-bedded calcarenites of Burleigh Range (Fig. 2.24). The gravel consists predominantly of rounded, oblate to equant flint clasts, and is interpreted as high energy shoreface cobble beach deposits. Although similar in broad form to the flint-dominated cobble deposits on the modern beaches near Port MacDonnell (see Chap. 3), the framework clasts are smaller suggesting a more distal source. The flint, a diagenetic feature, is derived from coastal erosion of the Oligo-Miocene Gambier Limestone. Medium to coarse grained skeletal carbonate sand occurs within the gravel matrix together with 1–2 cm sized fragments of the cockle *Katelysia rhytiphora*. The gravel beach deposits and their relation to the back-barrier depression imply that a former coastal lagoon 2 km wide and over 20 km long with a water depth of up to 4 m existed in the lee of the Burleigh Range.

TL dating of quartz sand grains extracted from the sandy matrix of the shoreface gravels of the Burleigh Range yielded an age of 237 ± 16 ka (Murray-Wallace et al. 1996). In a similar manner, the extent of racemization of several amino acids, within fragments of the cockle *Katelysia rhytiphora* from the gravel units indicates a penultimate interglacial age (MIS 7) (Murray-Wallace et al. 1996).

Near Mount Schank, the Burleigh Range palaeoshoreline is elevated to 34 m APSL. TL ages of 258 ± 25 ka and 237 ± 16 ka for the Reedy Creek and Burleigh Ranges respectively (Huntley et al. 1993a; Murray-Wallace et al. 1996) confirm an MIS 7e correlation whereas the West Dairy Range correlates with MIS 7a. AAR

Fig. 2.23 View of the seaward side of Burleigh Range barrier of Penultimate Interglacial (MIS 7) 2 km east of the volcanic centre Mount Schank (*Photograph* Murray-Wallace 1996)

Fig. 2.24 High wave energy, seaward dipping shingle beach facies of the Penultimate Interglacial (MIS 7) Burleigh Range. The sediments comprise flint clasts derived from the coastal erosion of the Oligo-Miocene Gambier Limestone (*Photograph* Murray-Wallace 1996)

analyses on the foraminifer *Elphidium crispum* yielded an age of 218 ± 35 ka for the Burleigh Range (Blakemore et al. 2015).

2.9.8 MacDonnell Range

The MacDonnell Range is located 16 km south of Mount Gambier. The trend of the barrier is sub-parallel to the modern coastline and is traceable as a distinct linear feature over a distance of approximately 27 km (Fig. 2.20). The barrier bifurcates into to two parallel linear structures 4 km east of Allendale East and attains a maximum cross-sectional width of up to 1 km. The dune crests of the barrier are up to 20 m above the general level of the surrounding coastal plain and the aeolian successions rest unconformably on the marine abrasion surface that has formed on the Oligo-Miocene Gambier Limestone. A series of low relief beach ridges occurs on the seaward side of the MacDonnell Range and most likely represent a forced regression at the end of the Last Interglacial Maximum. An OSL age of 124 ± 10 ka was determined on quartz sand from the aeolian facies of this barrier succession (Blakemore et al. 2014).

The MacDonnell Range is not as laterally persistent as the older and more landward Burleigh Range. The dune range loses morphostratigraphical expression over a distance of some 13 km between Allendale East and Kongorong (Fig. 2.20). It is most likely a correlative feature of the Kongorong Range mapped by Sprigg (1952) and the OSL age confirms its correlation with the Woakwine Range of MIS 5e age in the northern sector of the coastal plain.

2.9.9 Robe Range (Canunda Range)

Robe Range, also termed Canunda Range by Hossfeld (1950), is the youngest Pleistocene barrier of the Coorong Coastal Plain. In the Mount Gambier region the barrier succession crops out sporadically along the modern coastline from Carpenter Rocks to Port MacDonnell as vertical coastal cliffs up to 20 m APSL. Directly offshore from the settlement of Carpenter Rocks occur a series of islands that bear the same name. Some 53 islands representing erosional residuals of Robe Range occur up to 1.5 km offshore from the present coastline. The final phase of the development of these islands is associated with the post-glacial rise in sea level and the attainment of present sea level some 7000 years ago. The accordant surface elevations of the minor shore platforms that rim the islands can only have formed in the current, Holocene interglacial as sea level remained below present from the time of formation of Robe Range (MIS 5c and 5a) to the present sea level highstand. Along the sector of coast from Carpenter Rocks north to Robe several hundred small residuals of Robe Range occur as small islands up to 2 km offshore.

At Port MacDonnell, Robe Range occurs as a stacked succession of aeolianites with interbedded palaeosols and protosols. As with the prominent outcrops of this dune range near Robe, coastal outcrops of Bridgewater Formation aeolianite at Port MacDonnell show large scale tabular cross-beds representing the former slip faces of landward migrating coastal dunes capped by topset beds. At least three phases of dune deposition are evident. Equivalent outcrops of aeolianite occur at Cape Northumberland, the southern-most point on the coastline of South Australia (Fig. 2.2).

Evidence for the regional uplift of the Late Pleistocene Robe Range is shown by the presence of a strongly indurated flint conglomerate beach facies with interstratified shell within a well-cemented calcrete matrix on the surface of an actively eroding shore platform at Port MacDonnell. The consolidated shelly unit rests unconformably on an erosion surface on the Oligo-Miocene Gambier Limestone and stratigraphically below an aeolianite unit of Robe Range (Blakemore et al. 2014). The exhumed shelly gravel facies crops out on the upper reaches of the modern shore platform resulting from the erosional retreat of the overlying aeolianite. The overlying aeolianite was dated at 53 ± 4 ka by OSL and AAR analyses on the operculum of the gastropod *Turbo undulatus* from the conglomerate yielded a numeric age of 102 ± 16 ka and a minimum, finite radiocarbon age of 47,905 ± 2106 year BP (Wk-34733; Blakemore et al. 2014). Given the regional tectonic stability of Australia at a continental scale, the flint conglomerate is the first identified example of a subaqueously-deposited warm interstadial coastal facies above present sea level in Australia. Based on a previously determined rate of uplift of 0.13 mm year^{-1} in the Mount Gambier region (Murray-Wallace et al. 1996), a minimum sea level of −14 m is inferred for MIS 5c for this region based on this sedimentary unit.

2.10 Coastal Plain Sedimentation—River Murray Mouth Region

The aeolianite barrier successions of the River Murray Mouth region are time equivalent features of the rest of the Coorong Coastal Plain, but represent a foreshortened and condensed sequence (de Mooy 1959a, b; Sprigg 1959; Bourman and Murray-Wallace 1991; Murray-Wallace et al. 2010). The successions have been deposited in a region of gradual basin subsidence adjacent to the up-faulted margin of the eastern Mount Lofty Ranges (Adelaide Foldbelt). Gradual basin subsidence over the Middle and Late Pleistocene has resulted in barriers of this region being less widely separated and in several instances, the superposition of interglacial barriers of different ages (e.g. Narrung Peninsula). This is in contrast to the southern portions of the coastal plain near Robe and Mount Gambier where faster rates of uplift have resulted in the wider spacing of the barriers so that they are physically well-separated and morphostratigraphically distinct structures. The widespread occurrence of desert dunes of last glacial age that blanket the aeolianite successions in the River Murray mouth region, represents an added complexity in assessing the relative age relationships of these barriers (Sprigg 1959; Murray-Wallace et al. 2010; Ryan 2015). Last glacial age desert dunes are largely absent in the central and southern-most portions of the coastal plain.

The River Murray mouth region is the seaward edge of Australia's largest drainage basin that reaches the sea, the Murray-Darling drainage basin covering an area of 1,062,530 km^2 and 1/7th of the Australian continent. Two prominent coastal lakes occur in the terminal region of the River Murray (Fig. 2.25). Lakes Alexandrina and Albert are shallow lakes with maximum water depths of 3 and 2 m respectively. Lake Alexandrina is 39 km (east-west) by 20 km (north-south) and Lake Albert is 13 km (east-west) by 18 km (north-south). The River Murray debouches into Lake Alexandrina and has produced a small digitate delta in the NE sector of the lake. These lake basins were most probably excavated at times of low sea level stands during Pleistocene glacial cycles by the ancestral River Murray.

The modern landscape of the River Murray Mouth region has resulted from the combined effects of Holocene coastal landscape changes and geological inheritance. Sir Richard and Younghusband peninsulas are coastal barriers of Holocene age having formed in the past 7000 years following the onset of the sea level highstand at the culmination of the post-glacial marine transgression (Bourman and Murray-Wallace 1991; Bourman et al. 2000). The evolution of these coastal landforms is discussed further in Chap. 3. Younghusband Peninsula is a substantial barrier up to 194 km long, representing Australia's longest beach. The width of the barrier ranges between 0.5 and 3 km. Massive transverse, parabolic dunes and dune blow out depressions are common on Younghusband Peninsula and in places well-developed beach ridge plains (relict coastal foredunes) have also formed (Fryberger et al. 2001).

Early geological and geomorphological investigations of the River Murray mouth region identified three distinct shoreline complexes (de Mooy 1959a). The modern coastline de Mooy termed the Younghusband Association after the principal Holocene landform, Younghusband Peninsula. De Mooy also identified two Pleistocene dune ranges which he termed the Bonney Coastline situated on the landward shoreline of the modern Coorong Lagoon and the Alexandrina dune range, a more landward feature now represented by Sturt Peninsula and including the northern-most portion of Narrung Peninsula. In a study of the regional landscapes of the River Murray mouth region, Sprigg (1959) introduced the terms Lake Albert Beach and Loveday Bay Beach (Fig. 2.25). Defined by its arcuate shape and series of coastal dunes, the Lake Albert Beach refers to the northern portion of coastline of Lake Albert which he correlated with the Naracoorte Range to the south-east. The Loveday Bay Beach, a younger inferred strandline extending across the central portion of Narrung Peninsula to Loveday Bay was correlated with the Avenue Ranges of the central sector of the coastal plain (Robe to Naracoorte transect; Sprigg 1959).

Given ongoing subsidence within the River Murray mouth region, the locations of older barrier structures have influenced the spatial distribution of younger coastal landforms. The modern coastline of Encounter Bay and Younghusband Peninsula in particular, is in part defined by the position of present sea level, available accommodation space and the location of erosional remnants of Late Pleistocene sediments representing equivalents of the Woakwine Range. On the landward side of the Coorong Lagoon, richly fossiliferous (Goolwa cockle *Donax deltoides*) seaward dipping foreshore facies of the last interglacial Woakwine Range crop out representing the former location of the shoreline during the Last Interglacial Maximum (MIS 5e). Southeast from Goolwa, sediments of the Woakwine Range extend across the northern-most portion of Hindmarsh Island as a relict barrier dune complex with associated back-barrier, estuarine-lagoon and open ocean beach facies. The highly eroded Woakwine Range barrier complex sediments also extend

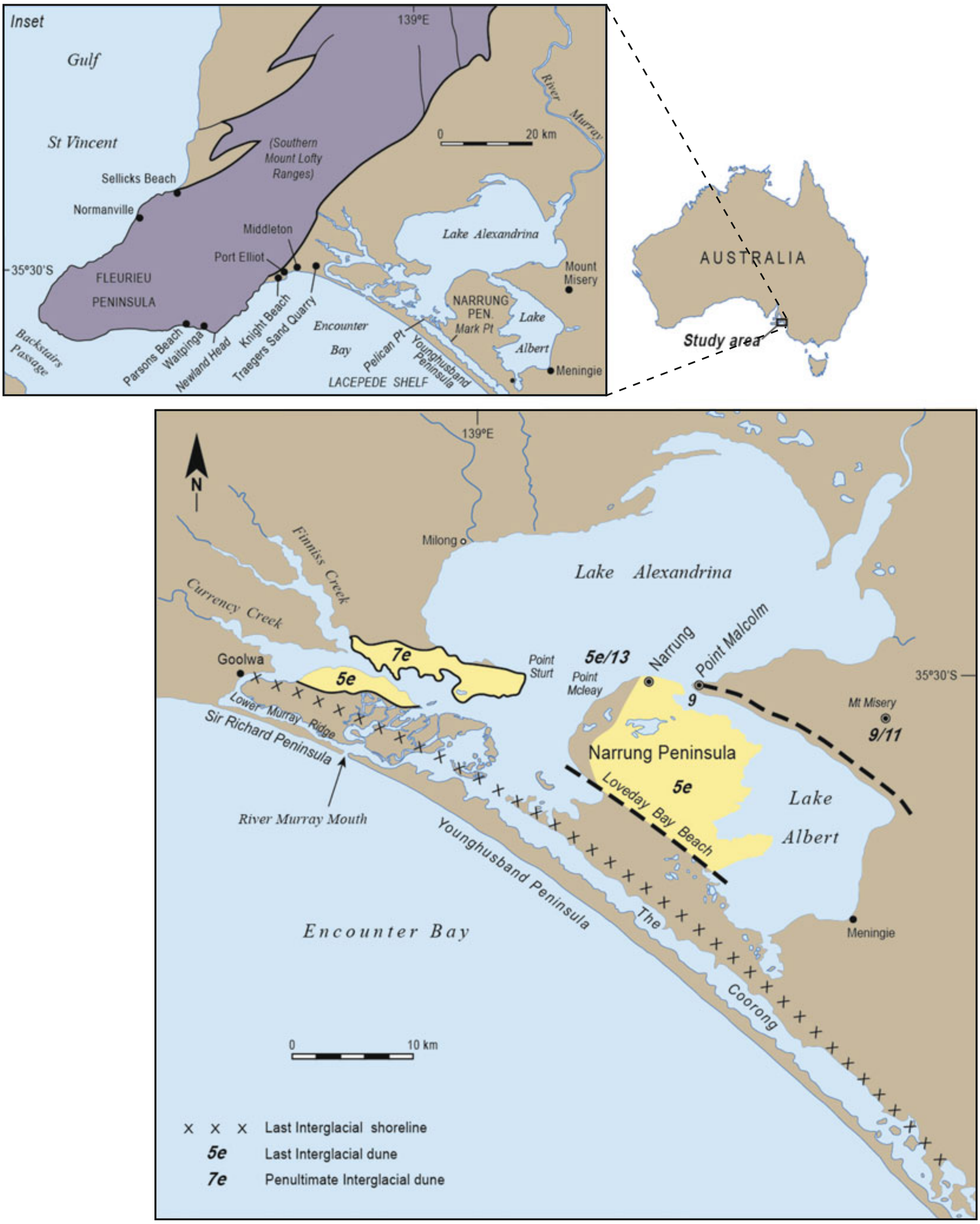


Fig. 2.25 Map of the River Murray Mouth and lower lakes region, southern Australia showing the spatial distribution of the last interglacial (MIS 5e) Woakwine Range based on mapping by Murray-Wallace et al. (2010) and Bourman et al. (2016)

across Mundoo Island, Ewe Island and Tauwitchere Island to Long Point in the northern-most Coorong Lagoon (Fig. 2.25). The successions have been correlated with the Last Interglacial Maximum based on aminostratigraphy and a TL age of 140 ± 15 ka on barrier dune sediments from northern Hindmarsh Island (Murray-Wallace et al. 2010).

A barrier dune complex of penultimate interglacial age (MIS 7) occurs up to 1.5 km landward of the Woakwine Range in the present site of Sturt Peninsula on the western margin of Lake Alexandrina (Fig. 2.25). TL ages for aeolianite at Point Sturt (230 ± 50 ka) and Clayton Water Tower (215 ± 35 ka) indicate a correlation with MIS 7 (Murray-Wallace et al. 2010). The aeolianites of Sturt Peninsula are therefore correlatives of Reedy Creek Range and Burleigh Range of the central and southern-most portions of the Coorong Coastal Plain respectively.

2.11 Summary and Conclusions

Since the Middle Pleistocene transition involving a change from the 41 ka to approximately 100 ka orbital forcing insolation cycles, the Coorong Coastal Plain and adjacent Lacepede and Bonney Shelves have been a region of prolific temperate sedimentary carbonate production and have been instrumental in providing sediment for the formation of a series of high wave energy coastal barrier successions of the Bridgewater Formation. The coastal barriers formed during Pleistocene sea level highstands during interglacials and interstadials. Through the combined processes of epeirogenic uplift, relative sea-level changes involving episodic transgressions and forced regressions, and high sedimentary carbonate bio-productivity, the coastal plain prograded up to 90 km since late Early Pleistocene time from the Naracoorte Range and Kanawinka Fault complex (MIS 25 or MIS 31). Twenty morphostratigraphically distinct barrier forms and erosionally truncated barriers representing composite structures have been identified across the coastal plain. Uplift of the Coorong Coastal Plain has resulted in a clear physical separation of barrier shoreline successions. The plan-form geometry of the laterally-persistent barriers has been directly influenced by an irregular antecedent topography with outcropping granite residuals, epeirogenic uplift and episodes of volcanism. The Mount Burr Volcanics acted as a near-shore archipelago and several barriers nucleated on to this volcanic complex. This remarkable record of coastal landscape change has been preserved by the combined processes of epeirogenic uplift, regional aridity and calcrete development.

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3 Holocene Coastal Sedimentary Environments of the Coorong Coastal Plain, Southern Australia

Abstract

The Holocene sedimentary environments and coastal landforms of Younghusband Peninsula and its back-barrier Coorong Lagoon are the present day equivalent of the relict barriers (dune ranges) that traverse the Coorong Coastal Plain. These modern landforms, together with their associated ephemeral carbonate precipitating lakes and distinctive marine, lagoonal and lacustrine shelly faunas, provide an interpretive model for the geomorphology, stratigraphy and palaeoenvironments of the Pleistocene coastal successions. Younghusband Peninsula progressively developed as a coastal beach-dune barrier complex following the culmination of the post-glacial marine transgression approximately 7000 years ago, so forming the narrow, shallow water lagoon in its lee that now extends some 150 km along the coast from the mouth of the River Murray to slightly northeast of Kingston SE. The present location of the peninsula relates to the shallow accommodation space associated with the emergence of the Late Pleistocene aeolianite barrier complexes of Robe and Woakwine Ranges. The Coorong Lagoon and its associated ephemeral lakes are the sites of distinctive mineral associations including the formation of dolomite. The beach and dune sands are predominantly of inner-continental shelf derived bioclastic calcium carbonate, comprising the comminuted remains of molluscs, bryozoans, coralline algae, echinoderms and foraminifers. The southern Australian continental margin has hosted such biota since the separation from Antarctica some 43 Ma ago. The region has thus been a major carbonate province since early Paleogene time. Within the corridor between the Late Pleistocene Robe and Woakwine Ranges, regional uplift, together with upward shoaling sedimentation has greatly modified the original environment and illustrates the sequential changes in coastal sedimentary environments during an interglacial highstand event, an analogue for the Pleistocene successions. To the south of Mount Gambier, in an area of faster neotectonic uplift and more restricted sediment supply, the coastal landscapes are dominated by rocky outcrops of Robe Range and cobble flint beaches.

Keywords

Coorong Lagoon · Younghusband Peninsula St Kilda Formation · Holocene coastal evolution

Photos by the author, if not indicated differently in the figure/photo legend.

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3.1 Introduction

The most recent evolutionary phase of the Coorong Coastal Plain has occurred during the Holocene epoch and involved the formation of Younghusband and Sir Richard Peninsulas, well-defined barriers with transverse and parabolic dunes. The Coorong, a back-barrier lagoon, formed along the northern sector of the coastal plain in the lee side of Younghusband Peninsula. To the south, strand plains comprising multiple series of beach ridges (relict foredunes) have formed along parts of the open ocean coastline near Kingston SE and within rocky coastal embayments (e.g. Guichen and Rivoli Bays). Along other coastal sectors such as Admella and Canunda Beaches, extensive dune sheets with actively migrating transverse and parabolic dunes have formed mantling the consolidated Late Pleistocene barrier of Robe Range. Flint cobble beaches and coastal cliffs on aeolianite of Robe Range dominate other portions of the coastline such as from Port MacDonnell to the Glenelg River in western Victoria.

Since the attainment of present sea level some 7000 years ago, the Holocene shoreline of Younghusband Peninsula has prograded a maximum of about 5 km in the region to the immediate north of Salt Creek (i.e. seaward from the position of the Last Interglacial shoreline of the Woakwine Range on the landward shoreline of the Coorong Lagoon; Fig. 3.1). In the southern section of the coastal plain between Robe and Port MacDonnell, in the region of faster uplift, the spatial distribution of Holocene coastal sediments has been constrained by the emergence of the Late Pleistocene warm interstadial barrier, Robe Range (MIS 5c and 5a) giving rise to a cliffed coastline on consolidated aeolianite. The Holocene sedimentary successions and coastal landforms represent a critical analogue for understanding the Pleistocene evolution of the coastal plain. As with the Pleistocene barrier and lagoonal successions, a distinctive element of the Holocene successions and landforms is their vast spatial scale. Younghusband Peninsula for example extends uninterrupted along its length for up to 194 km and is the longest beach in Australia (Short 2004).

In southern Australia sea level rose rapidly from about 18,000 years ago after the Last Glacial Maximum (MIS 2), and transgressed the continental shelf of the southern margin, defining the present coastline by approximately 7000 years ago (sidereal years) (Thom and Chappell 1975; Belperio et al. 1983; Belperio et al. 2002; Lewis et al. 2013). This major geomorphological change resulted in the landward advance of the shoreline from near the edge of the continental shelf across the Lacepede and Bonney Shelves by up to 180 km. Loading of the continental shelf by the rising sea resulted in different degrees of coastal warping (hydro-isostatic compensation) and a geographically variable relative sea level history (apparent regression) around the coastline of southern Australia over the past 7000 years (Belperio et al. 2002; Lewis et al. 2013). The combined effect of these changes in relative sea level and, in places, high rates of coastal sedimentation heralded significant changes in the position of the Holocene shoreline. At the head of the Cooke Plains embayment to the east of Lake Alexandrina, for example, the early Holocene highstand shoreline is stranded by up to 20 km inland from the present Lake Alexandrina shoreline (von der Borch and Altmann 1979; Figs. 3.1 and 3.2). The surficial sediments and soils in this region, termed the Malcolm Combination by de Mooy (1959a, b) are black, fine-textured in character, containing up to 70% clay. During the highest recorded flood of the River Murray in 1956, the flood waters within Lakes Alexandrina and Albert (3.3 m) did not fully inundate the former marine embayments such as the Cooke Plains Embayment (de Mooy 1959a, b; Fig. 3.2).

Holocene coastal sediments of the St. Kilda Formation sensu Cann and Gostin (1985) comprise a diverse range of sedimentary facies deposited by coastal and marine processes. The St Kilda Formation refers to coastal sediments of Holocene age that were deposited since the culmination of the marine transgression following the Last Glacial Maximum (Belperio 1995).

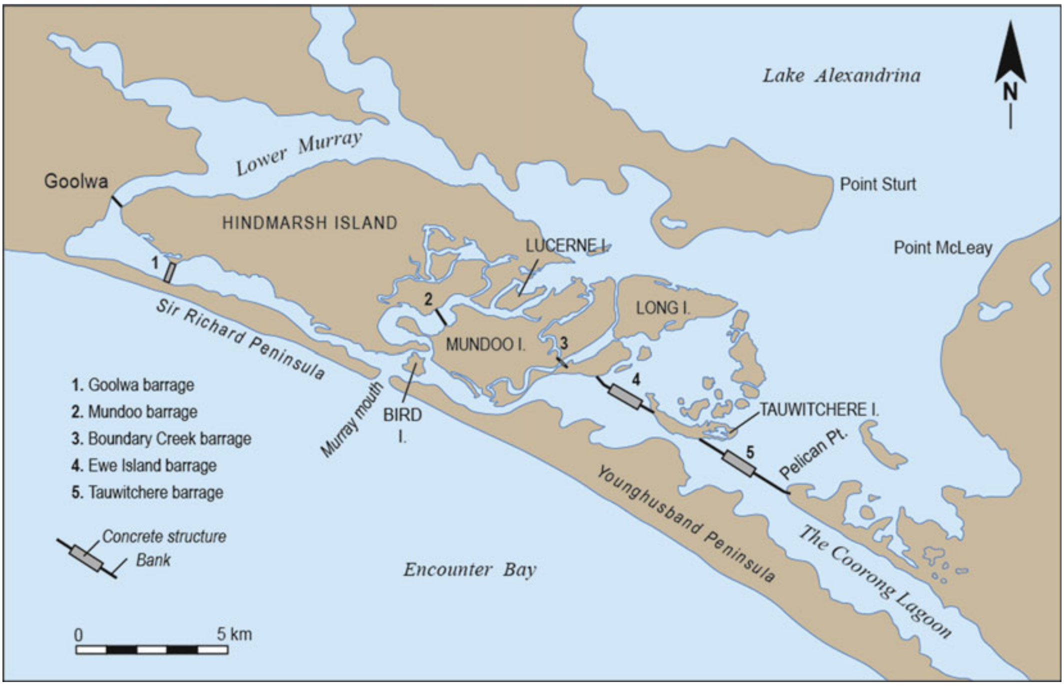

Fig. 3.1 General location map of the Murray Lakes area including Sir Richard and Younghusband Peninsulas, Hindmarsh and Mundoo Islands and the Coorong Lagoon, southern Australia

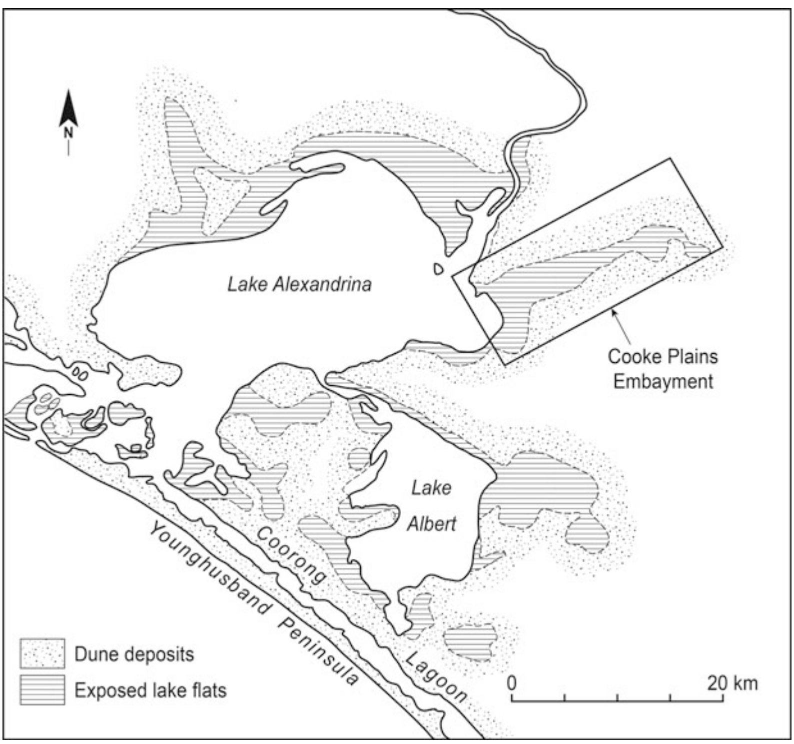

Fig. 3.2 General location and setting of the Cooke Plains Embayment, Murray Lakes area, southern Australia (modified after Von der Borch and Altmann 1979)

The base of the St Kilda Formation is clearly defined, as it disconformably overlies pedogenically modified Late Pleistocene marine and terrestrial sediments, and its upper surface may be one of active sedimentation. Cann and Gostin (1985) and Belperio and Rice (1989) provide a practical breakdown of the various facies of the St. Kilda Formation as encountered in the tidally-dominated shallow gulf waters north of Adelaide.

3.2 Physical Processes in the Modern Shelf and Coastal Environments

The modern coastline of the Coorong Coastal Plain defines the landward margin of the Lacepede and Bonney Shelves. The Lacepede Shelf (30,000 km^2) is situated to the southeast of Kangaroo Island, Fleurieu Peninsula and to the south of the River Murray Mouth, Sir Richard and Younghusband Peninsulas. The Lacepede Shelf is broadly triangular in shape and up to 180 km wide in cross-section from the River Murray mouth to the 100 m isobath. Its shelf edge is delimited by a series of submarine canyons, some of which are the largest in the world (Sprigg 1947; Hill et al. 2009; Murray-Wallace 2014). To the south-east the shelf narrows and merges with the Bonney Shelf (c. 6150 km^2). The Bonney Shelf is a narrow, 30–80 km wide, un-rimmed shelf trending south-east between Cape Jaffa and Cape Northumberland.

The modern coastline of the Coorong Coastal Plain experiences the full force of the dominant south-westerly waves of the Southern Ocean, with swell at Cape Northumberland exceeding 2 m for 68% of the year. Modal deep-water wave heights are typically >2.5 m, and long-period swell waves (>12 s) have wavelengths of 200 m (Short and Hesp 1984). The south-westerly derived swell has been estimated at 0–2 m (31%), 2–4 m (62%) > 4 m (6%) with calm conditions only experienced for about 1% per annum. The modern beach of Younghusband Peninsula is dissipative in character with more than 75% of incident wave energy reaching the shoreline and waves breaking up to 500 m offshore over physically distinct offshore bars (Short and Hesp 1982; Fig. 3.3). The resultant landform characteristics of the peninsula are a low-gradient subaerial beach, relatively stable shoreline and a back-beach setting characterised by topographically high dune forms including a high foredune due to abundant sand supply. The shallow sea floor in this region is less than 20 m deep with a gradient of 1:150. Semidiurnal tides are microtidal with a range consistently <1 m. Storm surges and longer period oscillations of sea level have amplitudes of up to 1.5 m and there is marked winter to summer change in mean sea level of up to 1 m.

The region experiences a Mediterranean-style climate with hot, dry summers and cool, wet winters. The highest rainfall is concentrated from May to August. Mean annual rainfall recorded at Robe Post Office is 635 and 712 mm at Mount Gambier Airport (Climatic Averages Australia: http://www.bom.gov.au/climate/map/climate_avgs/clim_avg1.shtml). Mean annual temperature at Robe is 14.7 and 13.3 °C at Mount Gambier Airport (Climatic Averages Australia).

The modern Lacepede Shelf is a storm-influenced, temperate, bioclastic to biolithic, palimpsest carbonate ramp with bryozoan, coralline algae, molluscs and foraminifers representing the dominant sedimentary constituents (Bone and James 1993; James and Bone 2011). Hardgrounds and rocky surfaces host rich encrusting communities of sponges, algae, ascidians, bryozoans, crinoids, molluscs and serpulid worms. Bioclastic debris from these local carbonate factories, together with winnowed lithoclasts are generally redistributed as patchy, coarse to medium-grained bioclastic grainstone sheets or as larger isolated sand banks. Offshore from the River Murray Mouth, fine quartz sand is an important sedimentary component (James et al. 1992). Along the outer shelf, thicker deposits of coarse-grained bioclastic sands result from the increased bryozoan productivity associated with oceanic upwelling (Li et al. 1998).

Ocean currents influence the nature of sediment constituents and rates of bioproductivity.

Fig. 3.3 A representative example of the dissipative beach characteristics of northern Younghusband Peninsula, southern Australia (*Photograph* Murray-Wallace 1993)

The warm southerly flowing Leeuwin Current brings warmer (17°–19 °C) lower salinity (35.7–35.8‰) ocean surface waters sourced from the Indonesian Archipelago and eastern Indian Ocean, along the coastline of Western Australia. The current changes its course at Cape Leeuwin and crosses the Great Australian Bight where it may influence the Lacepede Shelf. In summer, the Flinders Current travels in a westerly direction along the Bonney and Lacepede Shelves.

3.3 The Terminal Lakes to the River Murray—Lakes Alexandrina and Albert

Lakes Alexandrina and Albert are the terminal lakes to the Murray-Darling drainage basin. Lakes Alexandrina and Albert are shallow lakes with maximum water depths of 3 and 2 m respectively. Lake Alexandrina is 39 km (east-west) by 20 km (north-south) and Lake Albert is 13 km (east-west) by 18 km (north-south; Fig. 3.1). The River Murray debouches into Lake Alexandrina and has produced a small digitate delta in the NE sector of the lake. These lake basins were most probably excavated at times of low sea level stands during Pleistocene glacial cycles by the ancestral River Murray.

Lake Alexandrina, into which the River Murray flows, has been extensively modified by human intervention and a system of barrages now restricts saltwater incursion from the sea (Bourman and Barnett 1995; Bourman et al. 2000, 2016; Fig. 3.1). Before the construction of the barrages, the estuary was dominantly a freshwater environment. Lakes Alexandrina and Albert were freshwater, the Lower Murray Channel and Goolwa Channel were marine with a fluctuating brackish zone between. During severe droughts, salt water may have penetrated further upstream, but this was a relatively rare event. It was only after the pronounced abstraction of water from upstream for irrigation that saltwater became more common within the lower lakes system of barrages designed for freshwater retention.

Lake level within Lake Alexandrina is approximately 1 m above summer mean sea level, and little different to winter levels. The margins of the lake contain extensive low-lying areas which are former embayments now infilled with sediment and elevated up to 2 m above lake/sea level. Studies by Altmann (1976), Spagnuolo (1978) and von der Borch and Altmann (1979) have confirmed that these marginal deposits are of Holocene age (Fig. 3.2). They contain a consistent lithology, characterised by a basal eutrophic lagoon facies, a main lacustrine facies and a regressive lake facies. The eutrophic facies (sapropel and diatomite), dated at 6930 ± 145 year BP (GAK-6718), was attributed to the early Holocene development of Lake Alexandrina as a result of rising sea levels and lake damming (von der Borch and Altmann 1979). A relative sea level highstand of 1 m APSL some 6.5 ka ago was responsible for significant lake expansion and marginal lacustrine deposition (Fig. 3.2). Commercial gypsum deposits are associated with this marginal facies at Cooke Plains.

3.4 Younghusband Peninsula—A Holocene Analogue for the Pleistocene Barrier Successions

Younghusband Peninsula is a Holocene barrier complex with coastal dunes that extend uninterrupted for 194 km (Short 2004). The barrier is backed by the Coorong Lagoon, a shallow back-barrier lagoon with a marine connection at the River Murray Mouth. The modern barrier is longer than the Coorong Lagoon (c. 150 km long) as the southern-most portion of the lagoon has changed to a spatially restricted lacustrine system of isolated lake and wetland environments through progressive sedimentation and subtle tectonic uplift. The slightly faster rate of uplift in the southern portion of the Coorong Lagoon has resulted in the partial emergence of the Late Pleistocene Robe Range aeolianite barrier complex. This is expressed by outcrops of aeolianite forming elongate islands within the Coorong Lagoon (Cann and Murray-Wallace 2012), and may explain the physical location of the peninsula in this region (i.e. the coexistence of present sea level and shallow subsurface occurrence of aeolianite, reducing accommodation space for Holocene sediments). The northern portion of the peninsula comprises unconsolidated Holocene sand, and Late Pleistocene aeolianite is not permanently exposed. Accounts of episodic exposure of aeolianite by dune deflation imply the presence of Late Pleistocene successions at shallow depth (Bourman and Murray-Wallace 1991).

There are systematic longshore variations on Younghusband Peninsula in beach width, sediment particle size, foredune stability and transgressive dune activity. Away from the River Murray mouth, the calcium carbonate content of both the beach and dune sands of the peninsula progressively increases and particle size decreases (Chappell 1991). Carbonate grains include benthic foraminifers, coralline algae, echinoids, molluscs and limited bryozoans, the latter, preferentially selected against by mechanical abrasion as sediment is transported from the inner shelf to the back-beach dune systems (Joury et al. 2018). Transgressive dune systems are characterised by un-vegetated active dune sand sheets, large-scale parabolic and transverse dunes reaching 30–40 m APSL, coppice mounds, and deflation basins or blowouts that extend down to sea level (Fryberger et al. 2001). Much of the Holocene barrier complex that makes up Younghusband Peninsula consists of former transgressive dune sand sheets now stabilized by vegetation. Where dunes are stable the vegetation includes *Acacia* (coastal wattle), *Leptospermum* (tea tree) and *Melaleuca* (paperbark) as well as numerous exotic species introduced since European settlement. On the seaward side of the barrier, numerous areas of active erosion have provided sources of sand for the landward translation of portions of the barrier, a phenomenon termed 'barrier rollover' (Fryberger et al. 2001).

The early history of Younghusband Peninsula immediately preceding the culmination of post-glacial sea-level rise is most likely as a series of barrier islands comprising sand from the inner Lacepede Shelf. Middens that include oysters on Hack Peninsula (Fig. 3.1) within the Coorong Lagoon on the central portion of the peninsula indicate a protected back-barrier environment with fully marine salinities implying a local opening to the sea in that area at 5910 ± 70 year BP (Wk-8173; Harvey et al. 2006; Bourman et al. 2016).

Palaeosol horizons exposed in modern dune blowouts indicate periods of former dune stability, vegetation and soil development. Fragile rhizomorphs (plant root replacement features also termed rhizocretions) are exposed by shallow deflation and reveal that calcite precipitation and replacement of plant root organic matter occurs relatively quickly during early diagenesis (Fig. 3.4). Aboriginal remains, including middens composed largely of the cockle *Donax deltoides* harvested from open ocean foreshore environments are commonly associated with the palaeosols (Cann et al. 1991; Cann and Murray-Wallace 1999). Radiocarbon dating of humus extracted from palaeosols, or associated bioclastic or cultural remains, indicate repeated episodes of dune transgression and stabilization dating from the present back to 6000 years ago (Ohmori et al. 1987). Similar processes of dune remobilisation and deposition with associated cultural remains are inferred for Sir Richard Peninsula, a coastal barrier to the north of the River Murray mouth (Bourman and Murray-Wallace 1991; Bourman et al. 2000).

The evolutionary development of Younghusband Peninsula after the culmination of sea-level rise following the Last Glacial Maximum is most likely to have initially involved barrier island development on shallowly submerged calcreted Pleistocene aeolianite of the Bridgewater Formation (Harvey et al. 2006). As additional sand was supplied from the Lacepede Shelf in this high wave energy environment, the progressive growth of barrier islands would have amalgamated to form a more continuous barrier structure. Beach ridge development and the formation of extensive aeolian dunes (transverse and parabolic dune systems) would have enhanced the development and stabilization of the Younghusband Peninsula barrier. The hydro-isostatic response following the culmination of the post-Glacial sea-level rise, involving a fall of relative sea level of about 0.5 m, and more recent sea-level rise associated with human-induced global warming will have seen the seaward and subsequent landward advance of the barrier illustrating the dynamic nature of this coastal landform. The landward shoreline translation of the barrier is attested to by the episodic exposure of back-barrier estuarine-lagoon facies on the seaward side of the barrier (Bourman and Murray-Wallace 1991). These changes suggest a more complex origin for Younghusband Peninsula than the sequential northwest-ward growth of the peninsula as suggested by Howchin (1929).

3.5 The Coorong Lagoon and Associated Saline Lake Environments

The Coorong is a back-barrier saline lagoon, 150 km long that has formed landward of Younghusband Peninsula and represents the longest coastal lagoon in Australia (Figs. 3.1 and 3.5). Its name is derived from the Aboriginal word 'Karanj' or 'Kurangh' in reference to a long neck of water (Cockburn 1908; Warren 1990). It comprises nine interconnected basins up to 4 km wide and 4 m deep that are increasingly restricted, hypersaline and ephemeral towards their southern end.

The substrate to the Holocene sequences of the Coorong Lagoon is a calcreted, hard-ground surface developed on earlier dune calcarenites. On the landward side of the Coorong Lagoon, the calcreted surface is developed on the last interglacial (MIS 5e) Woakwine Range and shelly beach-face facies can be seen at several sites at, and to the north of Salt Creek. Calcrete capped

Fig. 3.4 Rhizomorphs (rhizocretions), plant root replacement features, in a partially deflated Holocene sand dune, Younghusband Peninsula, illustrating that calcareous rhizomorphs can form relatively quickly during the early stages of diagenesis (*Photograph* Murray-Wallace 1993)

aeolianite, which occurs as small islands within the Coorong Lagoon are inferred as equivalents of Robe Range (Cann and Murray-Wallace 2012). Thus two distinct aeolianite barrier complexes occur in close proximity within the Coorong Lagoon and are capped by a continuous calcrete profile, although of differing ages. This stratigraphical relationship reaffirms the difficulty of using calcretes as a framework for lithostratigraphical correlations. The calcreted surface is commonly exposed around the Coorong margins and the internal facies architecture is visible in eroding coastal profiles. A representative profile is exposed in the coastal road cut south of Halite Lake (S36° 09′ 30.4″; E139° 38′ 46.3″). Here solution pipes, rhizomorphs and a soft calcareous earthy profile, associated with the carbonate palaeosols extend down several metres into the underlying strata beneath the surficial carbonate hardpan.

Average water depth in the North Lagoon in summer is 1.2 ± 0.1 m (Noye and Walsh 1976). Waters are derived from the ocean via the River Murray mouth, from the River Murray, from seasonal rainwater and from unconfined groundwater. Distinct seasonal fluctuations are superimposed on the marked salinity gradient. There is also a pronounced seasonal oscillation of water level of approximately 1 m that results in part from higher winter sea levels, alternating dominance of winter rainfall and summer evaporation as well as lake level setup by winds across the lagoon (Noye 1973; Paton 2010). Superimposed on this is up to 1 m of tidal oscillation and a further 1–1.5 m winter to summer fluctuation of mean sea level.

Before significant human impacts to the region in the form of an extensive network of drainage channels to drain the back-barrier depressions (Williams 1964, 1977; Taffs 2001),

Fig. 3.5 View of the modern Coorong Lagoon from the Loop Road in the Coorong National Park approximately 7 km south of Salt Creek. Actively migrating dunes are encroaching on the lagoon. (*Photograph* Murray-Wallace 2017)

waters were introduced to the Coorong Lagoon from Salt Creek (England 1993). Before the widespread upstream extraction of freshwater from the River Murray and construction of the barrages in the terminal lakes area (Lakes Alexandrina and Albert), the salinity varied widely in the Coorong Lagoon depending on river flow, local rainfall and regional groundwater flow. Since the barrages were built, and large drainage schemes constructed, a much more stable salinity gradient has resulted, varying from normal marine salinity at the Murray Mouth to hypersaline conditions (>5%) in the southern ephemeral reaches of the Coorong Lagoon.

Sediments of the Coorong Lagoon consist of fetid bioclastic magnesian calcite and aragonite sand and pelletal mud derived from molluscs, bryozoans, ostracods and foraminifers (Brown 1965). The small (c. 1 cm long-axis) gastropod *Coxiella striata*, the foraminifer *Ammonia beccarii* and various ostracods, characteristic of a restricted marine lagoon, are common, as well as the marine molluscs *Spisula* (*Notospisula*) *trigonella*, *Anapella cycladea*, *Tellina* (*Macoma*) *deltoidalis* and *Katelysia* sp. Serpulids and bryozoans are present in less restricted parts of the Coorong Lagoon. Around the lagoon margins, a prominent winter storm beach of comminuted shell debris and summer strandline of *Coxiella* sp., remains are clearly discernible. Cores indicate that the protected marine lagoon became increasingly restricted as sedimentation progressed, and hypersaline conditions subsequently developed in the southern half of the lagoon (von der Borch et al. 1976a). Pelletized aragonitic mud characterises the seasonally exposed ephemeral lagoon floor. Drainage channels constructed to the south of the Coorong Lagoon have stopped the overflow from swamps reaching the lagoon in years of heavy rainfall, and may thus have accentuated the trend towards hypersalinity.

More recently this has been partially addressed by modifications to the inlet channel into the Southern Coorong Lagoon at Salt Creek.

Evidence from foraminiferal assemblages for enhanced aridity during the Holocene manifested by a reduction in surface water runoff from the River Murray has been examined from the Coorong Lagoon (Cann et al. 2000; Lower et al. 2013). A core collected from the Goolwa Channel revealed a decline in fluvial discharge from the River Murray expressed by the dominance of marine sedimentation as attested by the increasing percentages of foraminiferal species from inner continental shelf environments such as *Discorbis dimidiatus*, *Elphidium macelliforme* and *Elphidium crispum*. The increasing marine influence is constrained by radiocarbon dating of foraminifers and ostracods to between 5255 ± 60 year BP and 3605 ± 70 year BP (uncalibrated radiocarbon years; Cann et al. 2000). Corroborative evidence for regional drought manifested by a salinity event approximately 3500 years ago is indicated by the combined presence of the foraminifers *Ammonia becarrii*, *Elphidium excavatum*, the ostracod *Osticythere baragwanathi* and the oogonia of charophytes in an additional core (Coorong#5) from the northern Coorong Lagoon near Narrung Peninsula (Lower et al. 2013).

The combined effects of hydro-isostasy and neotectonic uplift has resulted in about 1 m of relative sea-level fall in the Coorong area over the past 7000 years, a factor that has compounded the restrictive effects of regressive sedimentation. As a result, at its southern end, the Coorong Lagoon is now a seasonally exposed ephemeral body and a number of isolated, ephemeral lacustrine depocentres have formed. These are now largely isolated from marine influence and are dominated by the groundwater regime. These ephemeral lakes and the ephemeral lagoon precipitate a variety of fine-grained carbonate minerals during their annual evaporative phase (Alderman and Skinner 1957; von der Borch 1976a; Warren 1988; Rosen et al. 1988, 1989). These include partially ordered dolomite and poorly crystallized protodolomite, magnesite and hydromagnesite, magnesian calcite, aragonite and monohydrocalcite. The assemblages reflect meso- and macro-scale variations in geography, topography and water level, and the relative roles of marine to meteoric groundwater mixing, plant abundance, alkalinity and water chemistry (von der Borch and Lock 1979; Warren 1990).

The ephemeral lagoon and proximal ephemeral lakes are alkaline (pH 8–10), have high Ca/Mg ratios (1–20) and reflect mixed seawater-groundwater sources. Evaporite minerals precipitated during summer months are flushed out during the annual winter freshwater cycle. Aragonite sediment is precipitating under these conditions at the southern ephemeral end of the Lagoon where it is rapidly pelletized by biota (von der Borch 1965). Dolomite also precipitates in inland lakes and swamps well away from contemporary marine influences, within broad interdune corridors (von der Borch 1981), but much less is known of the hydrogeochemical parameters controlling this process. Most of the dolomite-bearing lakes are situated where mean annual rainfall is between 500 and 700 mm and the annual desiccation cycle appears to be a necessary pre-requisite. They also have in common a prolific flora of algae and higher aquatic plants (e.g. *Ruppia* sp.) during their less saline winter stage (2–5%), but summertime evaporation causes extreme salinity variations to over 18%. Lithified crusts with their associated polygonal and tepee structures commonly form around the lake margins during the summer months.

In addition to pavements cemented by desiccative and capillary processes, algal-related cemented pavements (stromatolites, oncolites, thrombolites, cauliflower tufa) also form around a number of lakes where conditions are conducive to active algal nucleation and binding of sediments. Algal stromatolites, including stratiform, crenulate and globular forms are associated with hydromagnesite-bearing ephemeral lakes near Salt Creek. Thrombolitic microbialites and calcareous tufas are found in marine-influenced saline lakes closer to Robe, whilst in higher rainfall areas closer to Mount Gambier, only freshwater lakes and swamps are found. Burne et al. (1980), Cann and De Deckker (1981) and Burne and Ferguson (1983) described the distinctive biota and sediments of the seasonally hypersaline lakes, including oncolites, stromatolites, ostracods, foraminifers and charophyte oogonia. In many cases, desiccation of the ephemeral lake margins produces fenestral and laminar crusts, polygonal cracks, tepee structures and intraclastic mud chip breccias that have direct analogues in ancient carbonate depositional environments (Muir et al. 1980).

A series of ephemeral, alkaline, saline lakes extends southwards from the main Coorong Lagoon towards Kingston SE. These reflect the progressive infilling and shoaling of a formerly more extensive, earlier Holocene lagoon, with concomitant change to groundwater-dominated lacustrine environments. These lakes are actively precipitating a variety of carbonate muds including dolomite, magnesite, aragonite and magnesian calcite. Modern dolomite precipitation in Kingston Lake and Lake Hawdon, first reported by Mawson (1929), was later amplified and extended by Alderman and Skinner (1957), Alderman (1959, 1965) and von der Borch (1965, 1976a) to many other sites. Modern dolomite formation on the coastal plain only occurs where shallow groundwater lakes pass through an annual desiccation phase (i.e. north of latitude 37.5°S where annual rainfall is <700 mm: von der Borch and Lock 1979). These lakes have comparatively high pH and Ca/Mg ratios.

Five unique lakes are located in close proximity within the Coorong National Park near Salt Creek (Fig. 3.6). These display the range of mineralogical and sedimentological processes that are present in these carbonate-dominated lakes, reflecting subtle differences in the degree of continental groundwater influence. The lakes annually fill with groundwater in winter and spring to depths up to 2 m. Carbonates precipitate in spring and summer aided by an increase in pH due to aquatic plant growth and evaporitic concentration. Four of the lakes (North Stromatolite Lake, Pellet Lake, Dolomite Lake and Halite Lake) were once connected to the Coorong Lagoon through a marine corridor (Rosen et al. 1989). This marine connection is now infilled with sediments. Milne Lake had no former marine connection and its sedimentary history is dominated purely by groundwater processes.

At various times, the tar-like remains of Coorongite can be observed washed up on the Coorong beaches (Brown 1908; McCourt and Mincham 1987). These are the weathered remains of cyanobacterial and botryococcus algal blooms that occur sporadically. Coastal Bitumen has been found along the ocean beaches and is unrelated to Coorongite. The Coastal Bitumen has originated from a variety of local and remote sources such as Indonesia, drifting to southern Australia with the Leeuwin Current, as well as being sourced from shipping within the region (Edwards et al. 2016).

3.5.1 North Stromatolite Lake

North Stromatolite Lake is an elongate NE–SW-trending lake approximately 1 km long by 0.5 km wide (Fig. 3.6). A low-lying corridor of Holocene coquina marks the former-marine connection between North Stromatolite Lake and the Coorong Lagoon (Fig. 3.6). The shell beds are exposed in bulldozer scrapes and include both cemented and unconsolidated variants. The cemented shell beds pass down into finer grained and better sorted shelly quartz sands. Shell remains are dominated by *Spisula* (*Notospisula*) *trigonella* sp., with fewer *Tellina* sp., and *Katelysia* sp., attesting to a setting similar to the modern Coorong Lagoon. Along the margins of the corridor, a gradation up into gastropod coquina (*Hydrococcus brazieri* and *Coxiella striata*) reflects increasing restriction and hypersalinity. Cementation of Holocene marine sediments is not common in southern Australia and is here locally developed from groundwater discharge from adjacent dune areas.

North Stromatolite Lake is an ephemeral, groundwater dominated lake reflecting the final phase of upward shoaling and isolation from the marine system. Seasonal exposure results in cementation and formation of marginal carbonate crusts. The cemented crusts show excellent

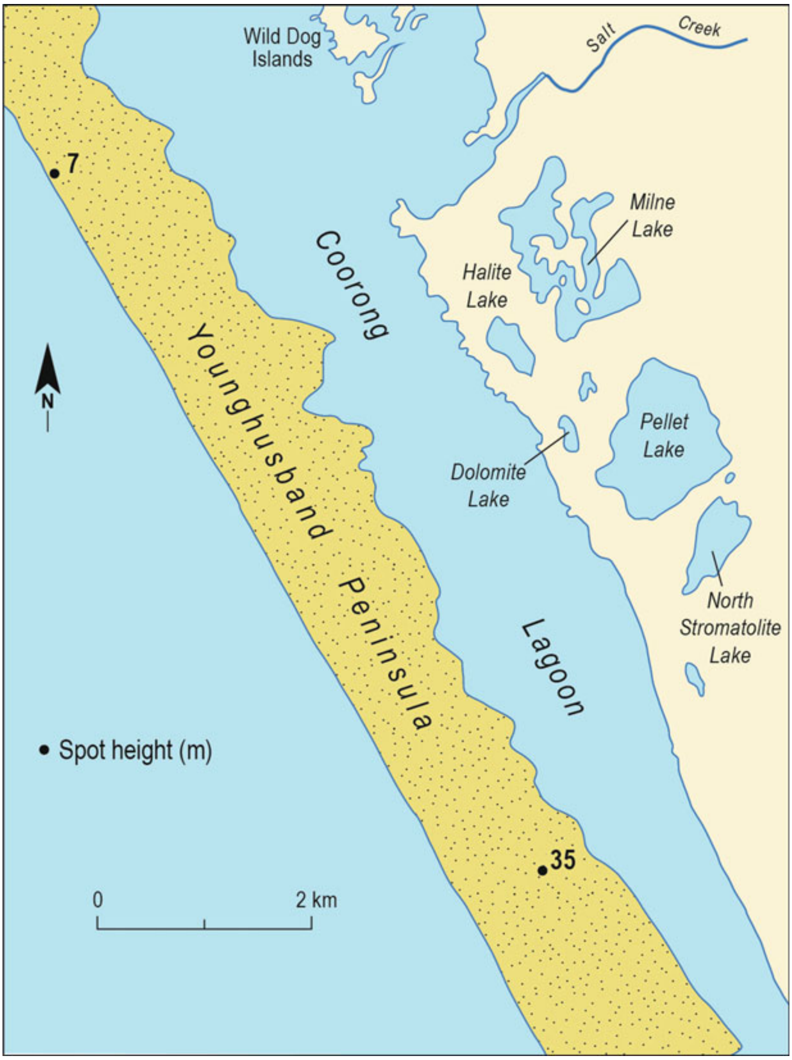

Fig. 3.6 Map illustrating the network of lakes in the Coorong National Park, south of Salt Creek. The region formerly represented a southerly, landward extension of the Coorong Lagoon and has progressively changed to a lacustrine/saline lake environment due to sediment aggradation. The former connection to the main Coorong Lagoon is attested by the presence of Holocene coquina at shallow depths

development and preservation of classic teepees, polygonal structures, mudcracks and footprints. *Coxiella striata* and ostracod marl and rubbery pustular algal mats are well-developed over the surface of the exposed lake floor.

Algal mats are particularly well-developed around the margins of North Stromatolite Lake associated with aragonite—hydromagnesite surficial sediments. Microlaminae are preserved in the subsurface, but the mats also dry, crack and break up towards the end of summer. True stromatolitic bioherms (up to 3 m in diameter) are found in more permanently saturated parts on the north side of North Stromatolite Lake. Small globular and crenulate forms are found around the southern margins of the lake (von der Borch 1976b).

Cores from within North Stromatolite Lake confirm an earlier marine phase characterised by the shallow-subtidal to intertidal mollusc *Katelysia* sp., passing upwards into a restricted marine lagoon and ephemeral saline lake facies with the gastropod *Coxiella* sp., and the foraminifer *Ammonia beccarii*. This latter ephemeral saline lake phase of precipitated carbonate mud (hydromagnesite, aragonite, calcite, dolomite), algal laminated sediments and marginal carbonate crusts characterises the modern setting.

The waters of North Stromatolite Lake are invariably milky and consequently free of significant aquatic flora (von der Borch 1965). Seepage of marine water and mixing with continental-derived groundwater with a significantly higher bicarbonate ion concentration, lead to precipitation of hydromagnesite and aragonite within the main body of the lake.

3.5.2 Dolomite and Pellet Lake

Located approximately 1 km to the south of Milne Lake, Dolomite Lake (c. 400 by 300 m) and Pellet Lake (c. 1.5 by 1 km) are significant for the precipitation of dolomite (Fig. 3.6). Magnesian-rich dolomite 'yoghurt' and polished pellets of micro-crystalline dolomite characterise the uppermost sedimentary unit of Dolomite and Pellet Lakes (Fig. 3.6) to a depth of up to 60 cm below the lake floor. Calcian-rich dolomite is present around the margins. Magnesian calcite, aragonite, quartz and hydromagnesite are also present as is opaline silica (replacement chert). Cores through the lake reveal a regressive sequence up to 5 m thick that records similar hydrogeological changes to North Stromatolite Lake (i.e. a marine phase transitioning upwards to a restricted lagoon phase and subsequent ephemeral saline lake phase). Pelletization of the carbonate sediment by organisms maintains clearer water, allowing prolific growth of aquatic vegetation and greater alkalinity. The dolomite pellets are similar in appearance to the unconsolidated faecal pellets from the southern end of the main Coorong Lagoon (von der Borch 1965). Radiocarbon ages for Coorong dolomites (von der Borch 1965) indicate virtually modern ages for the uppermost sediments, increasing to about 2000 years BP at 35 cm depth, or a sedimentation rate of about 2 mm/year.

3.5.3 Halite Lake

Covering an area of some 250 m^2, Halite Lake is situated approximately 200 m landward from the main Coorong Lagoon (Fig. 3.6). The formation of gypsum and an annual halite crust develops from the evaporation of marine waters introduced to the lake through groundwater seepage. The marginal carbonate crust includes reworked *Spisula* (*Notospisula*) *trigonella* and *Katelysia* sp., shells and thus implies a former marine connection. The halite crust forms in summer and dissolves in winter with the higher watertable. Underlying sediments comprise laminated gypsum and hydromagnesite mud. The waters are too saline for *Coxiella striata*, and algal blooms occur during summer months.

3.5.4 Milne Lake

Milne Lake, also termed Pipe Clay Lake, is the most elevated and removed from marine influence and has always been separated from the main Coorong Lagoon (Fig. 3.6). The lake is approximately 1.7 km long by 1 km wide. The lake fills with water each winter and, around November, a milky turbid suspension forms adding to the annual cycle of dolomite and magnesite precipitation. Surface sediments consist of approximately equal proportions of magnesite and dolomite, but the proportion of magnesite decreases with depth until only dolomite is present from 30 cm. From 50 cm below the surface, a dark laminated fetid pelletal sand is present in cores. The slightly higher elevation of this lake results in more extreme desiccation above the lowered summer water table and greater development of brittle indurated crusts around the lake margin. Magnesite and dolomite crusts and intraclastic breccias occur with well-developed tepees, polygonal structures, mud cracks and animal tracks. The polygons, tepees and related breccias form from groundwater breakout during the early winter rising groundwater phase. Progressive infilling of the cracks by carbonate muds leads to progressive separation of polygonal plates (Muir et al. 1980). Smaller intraclastic breccias result from deflation of partially lithified 'yoghurt' muds and algal laminae. Pustular algal mats and large ostracods are also ubiquitous over the surface.

3.6 Soft Sediment Deformation Structures in Lagoonal Muds

Landward advancing coastal dunes on Younghusband Peninsula, across from Salt Creek, have resulted in the deformation of back-barrier lagoonal muds on the western side of the Coorong Lagoon forming a series of small *en échelon* fold structures such as anticlines with sinuous crests, flattened culminations and steeply dipping limbs (Brown 1965, 1969; Bourman et al. 2016). The fold structures, which have been traced for over 4 km along the seaward side of the lagoon, have formed from the load imposed by coastal dunes encroaching on the unconsolidated lagoonal muds (Brown 1969). Individual folds are commonly up to 0.5–2 m above the lagoon surface, 2–3 m wide, with fold axes up to 130–200 m long, parallel with the main trend of the Coorong Lagoon (Fig. 3.7a–c). Many of the ridges are arcuate-shaped in plan-form and at their widest occur in a belt 150 m wide. Normal faults with steeply dipping fault planes towards the lagoon have been observed within the dune sands at the margin of the lagoon due to subsidence of the lagoonal muds (Brown 1965, 1969). The intensity of deformation is greatest near the dunes closest to the centre of maximum loading. These features were termed 'mudlumps' by Townsend (1974) who noted that these mud anticlines and diapiric structures are similar to, but smaller than features observed in a major distributary channel of the Mississippi River.

From Salt Creek south to 'The Granites' the Coorong Lagoon becomes increasingly restricted, breaking up into a number of isolated depocentres, which dry out by the end of summer. The multiple blowouts with landward migrating sand sheets that characterise northern Younghusband Peninsula gradually diminish southward, changing to a lower, more stable barrier structure. At 'The Granites' the sand barrier comprises a beach ridge plain with several distinct relict foredune crests and a relatively stable modern beach-foredune. The extreme, high wave energy dissipative surf zone of northern Younghusband Peninsula systematically diminishes southward towards the protective lee of Cape Jaffa (Fig. 1.1).

3.7 Holocene Lake Environments Near Robe

3.7.1 Lake Fellmongery

Approximately 1 km east of Robe, Lake Fellmongery (c. 300 by 200 m) is a permanent body of water isolated from the sea. Like other lakes in the Coorong corridor, this lake is strongly alkaline with a high Mg/Ca ratio, although its waters essentially reflect seawater diluted by local groundwater. This lake does not pass through a desiccative phase but the annual cycle of evaporation and groundwater dilution favours the precipitation of calcium carbonate such as monohydrocalcite (Taylor 1975). Around the perimeter of the lake occurs a prominent platform of cemented pelletal carbonate or 'cauliflower travertine' (Fig. 3.8). This platform is exposed at the end of summer and wholly submerged beneath 0.5 m of water in winter and spring. Rapid encrustation is inferred from deposition of carbonate (monohydrocalcite) veneers over recent debris such as broken bottles. The seasonally emergent platform hosts a veneer of mucilaginous matter including photosynthetic blue-green and green algae. This form of calcification can be compared with microbial thrombolites found at Fresh Dip and Woolley Lakes south of Robe. These more isolated organo-sedimentary accumulations comprise magnesium calcite and aragonite precipitates with a characteristic clotted fabric formed from similar cyanobacterial processes in evaporative saline lacustrine environments (Mazzoleni 1993; Bullock 1994).

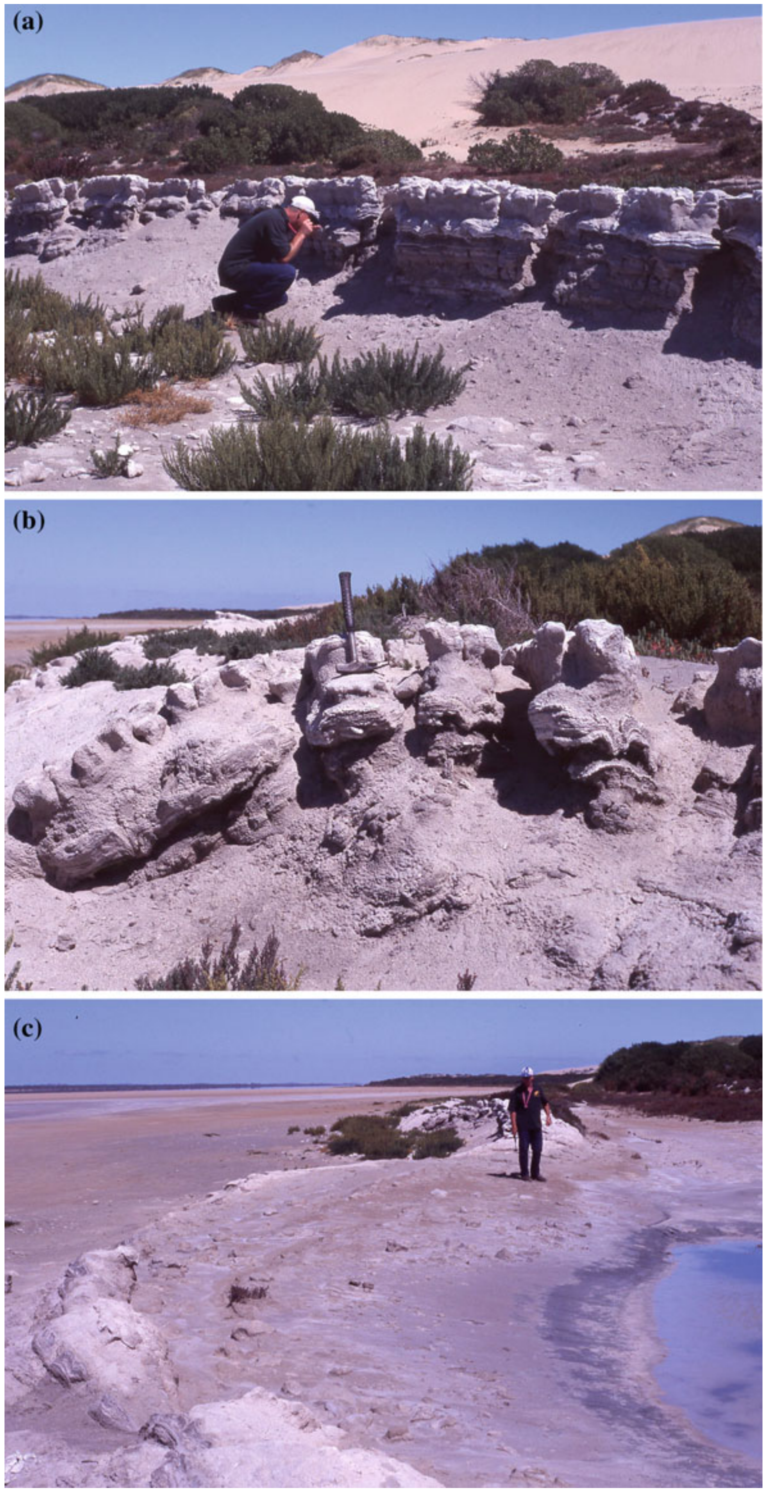

Fig. 3.7 **a** Deformed back-barrier muds of the southern Coorong Lagoon resulting from the load imposed by actively migrating coastal parabolic dunes, visible in the middle distance; **b** Detail of the deformed back-barrier muds of the Coorong Lagoon; **c** Longitudinal view looking south along the eastern margin of (left-side of photograph) the deformed back-barrier lagoonal muds of the southern Coorong Lagoon. (*Photographs* Murray-Wallace 1996)

Fig. 3.8 A platform of cemented pelletal carbonate (cauliflower travertine) at Lake Fellmongery, at Robe, South Australia (*Photograph* Murray-Wallace 1994)

3.7.2 Lake Robe and Fresh Dip Lake

Lake Robe is one of a number of larger (2 km N–S by 1.5 km E–W) ephemeral, saline lakes that now remain after the progressive infilling of a large Holocene marine lagoon landward of Robe Range (see also Sect. 3.9). The waters of the lake, rise and fall from winter to summer and the gastropod *Coxiella striata* and large ostracods characterise the present day saline lacustrine environment. *Coxiella* is euryhaline, but requires a salinity close to that of seawater to ensure reproduction. Fossil shells of oysters, scallops, mussels and cockles are exposed on the partially deflated lake floor, and coring indicates in excess of 2 m of marine shelly sands and coquina beneath the lake floor (Fig. 3.9). Radiocarbon dating of the oyster *Ostrea angasi* and articulated *Katelysia rhytiphora* yielded ages of 3890 ± 200 years cal BP (SUA-3026) and 4600 ± 200 years cal BP (SUA-3027) respectively (2σ-uncertainty terms) (Cann et al. 1999). Also from within the Lake Robe corridor, younger radiocarbon ages have been obtained on shells from stratified coquina indicative of intertidal shell bank deposition at least up to 2 ka ago (Cann et al. 1999). Closure of the marine corridor resulted from beach ridge progradation at Guichen Bay and Rivoli Bay.

A former excavation adjacent to an access track to Fresh Dip Lake revealed an upward shoaling succession of Holocene bioclastic sediments. At the base of the section subtidal oysters and echinoids occur, which in turn are overlain by intertidal sediments containing *Katelysia* (articulated valves) and other species of bivalves and gastropods (Cann et al. 1991, 1999). The uppermost comminuted shell and sand signify a high energy intertidal sand flat depositional environment. Amino acid racemization and radiocarbon dating have revealed mid-Holocene ages for these shelly accumulations. Fresh Dip Lake, a small (300 by 250 m) perched freshwater lake, represents the uppermost freshening phase in this regressive sequence. The waters of the lake today are only slightly brackish, but deposits

Fig. 3.9 View looking SW across Lake Robe revealing the partially exposed lake floor with in situ Holocene fossil assemblage of oysters (*Ostrea angasi*) and the cockle *Katelysia* spp. Partially stabilized Holocene dunes of Robe Range (Robe Range I) are visible in the horizon (*Photograph* Murray-Wallace, April 1993)

of 'cauliflower travertine' contain fossils of the gastropod *Coxiella striata*, indicating an earlier more saline lacustrine phase. Charophyte plants are abundant in this and other lakes of the region. Oogonia, the calcified reproductive bodies of these plants, provide another diagnostic microfossil for non-marine saline lakes.

Collectively, these observations imply a gradual infilling and shoaling of the former, Holocene marine corridor between the Late Pleistocene barriers Woakwine and Robe Range with complete closure occurring by about 2 ka ago (Cann et al. 1999). The prograded beach ridge plains at Guichen and Rivoli Bays are the seaward expression of this blockage, whilst surficial, saline to brackish lacustrine environments are the inland expression of these coastal landscape changes.

3.8 Holocene Beach Ridge (Relict Foredune) Deposition

Beach ridges, also termed relict foredunes (Hesp 1984) are low relief, aeolian-derived accumulations of sand that form in the immediate back-beach environment as a result of sand, supplied by on-shore winds, being trapped by vegetation (Oliver et al. 2017). Beach ridges are characteristically shore-parallel structures that can be traced laterally over considerable distances, at the scale of kilometres, depending on the configuration of a coastline. In plan-view they may occur as distinct sets of ridges and show evidence for erosional truncation reflecting major storm events and readjustment and reorientation of the coastline. On the Coorong Coastal

Plain several beach ridge plains have formed during Holocene time since the onset of high sea level conditions some 7000 years ago. At The Granites north of Kingston SE, and to the south, at Guichen and Rivoli Bays, multiple episodes of beach ridge formation have occurred signifying progradation of the strandplains in the Holocene (Sprigg 1952; Murray-Wallace et al. 2002; Bristow and Pucillo 2006; Fig. 3.1).

The Holocene embayment fill succession at Guichen Bay formed during the latest phase of coastal deposition within the temperate carbonate complex of the Coorong Coastal Plain (Fig. 3.10). The landward limit of the embayment is bounded by the western, seaward side of the Late Pleistocene (MIS 5e) Woakwine Range (Fig. 3.10). Guichen Bay is an erosional re-entrant through Late Pleistocene Robe Range (MIS 5c and 5a). The sedimentary succession within the embayment is 10 km long (north-south) and up to 4 km in shore-normal cross-section. The individual relict foredunes (beach ridges) are laterally persistent features and mostly extend uninterrupted and parallel to Long Beach, the modern beach, for distances up to 10 km. The ridges typically stand up to 2 m above the intervening interdune depressions. Although the spacing of the ridge crests varies slightly, they are typically 50 m apart. Equivalent features occur at Rivoli Bay some 45–55 km to the south-east of Guichen Bay (Fig. 3.11).

Sprigg (1952) first described the relict foredunes at Guichen Bay, noting the presence of 80 well-defined ridges in an east-west cross-section from the seaward side of Woakwine Range to the modern shoreline at Long Beach (Fig. 3.10). He also discussed the origin of these features suggesting the possibility of long-term (11 year) tidal variations as a possible mechanism for the origin of the ridges (i.e. greater aeolian entrainment of sand landwards at times of unusually low tides). Similar sequences of relict foredunes occur at Rivoli Bay approximately 50 km southeast of Guichen Bay near Beachport, where the Robe Range has also been breached. Others occur in the interdune corridor between the Robe and Woakwine Ranges north of Kingston (Fig. 3.1).

Thom et al. (1981) undertook a drilling transect across the central portion of the Guichen Bay embayment fill and reported radiocarbon ages on marine shells from the littoral facies underlying the beach ridges. The radiocarbon ages (corrected here for the marine reservoir effect and calibrated to sidereal years) ranged from 8110 ± 210 cal year BP (SUA-1374) on shell hash (coarse grained skeletal carbonate fragments) underlying one of the most landward ridges to 180 ± 180 year cal BP (SUA-1367) on shell hash from the littoral facies beneath the modern foredune (Fig. 3.12).

Murray-Wallace et al. (2002) reported several optically stimulated luminescence (OSL) ages on quartz sand sampled from the relict foredune facies across the Guichen Bay embayment fill succession. The advantage of optical dating is that it uniquely defines the time of deposition, whereas radiocarbon ages on shell fragments will pre-date the depositional event, dating the cessation of radiocarbon uptake, rather than the death of the marine invertebrates or their incorporation within sedimentary landforms. The OSL ages ranged between 5400 ± 230 years for one of the most landward relict foredunes to 51 ± 5 years for a sample 1 m below the modern foredune surface (Fig. 3.12). The OSL ages reveal an extremely rapid initial phase of sedimentation. Up to 1.6 km of coastal progradation occurred within a few hundred years, approximately 5 ka ago, signifying the geologically rapid transfer of sediment from the inner Bonney Shelf to the embayment. This was followed by a constant (linear) rate of coastal progradation (c. 0.39 m/year) from about 4000 years ago to the present day. An average rate of dune development of one dune every 80 years from 3900 years ago to the present is evident. The OSL ages for the late Holocene indicate that the present state of Long Beach is largely in equilibrium with sediment supply, with the modern foredune yielding an OSL age of 51 ± 5 years (Murray-Wallace et al. 2002).

Bristow and Pucillo (2006) applied ground penetrating radar (GPR) to the succession of beach ridges at Guichen Bay to examine the internal facies architecture of the Holocene

Fig. 3.10 Aerial photograph of the series of beach ridges (relict foredunes) within Guichen Bay (Photography supplied copyright by Mapland, Department of Environment, Water and Natural Resources, South Australia)

embayment fill succession. They identified over 100 ridges in six distinct sets based on ridge orientation and lateral continuity. The larger number of ridges includes sets of ridges that formed between the Robe and Woakwine Ranges to the south of the previously studied transect (Thom et al. 1981; Murray-Wallace et al. 2002). Ground penetrating radar analyses revealed evidence for multiple erosional truncations within the beach—near-shore facies than evident in plan-view from the cross-cutting relationship of the beach ridges. The foreshore seaward dipping clinoforms steepened in a seaward direction from 2.9° to 7.5° associated with an inferred increase in wave energy associated with the progradation of the beach ridge plain

Fig. 3.11 Photograph showing the characteristic form of the beach ridges at Rivoli Bay near Beachport, southern Australia. The road highlights the undulating nature of the landscape (*Photograph* Murray-Wallace 2017)

(strandplain) into deeper water. The GPR study also revealed that the reduction in the rate of coastal progradation related to an increase in sediment accommodation space as the coastline fronted increasingly deeper water. This also coincided with more time for beach ridge development resulting in larger dunes.

3.9 Holocene Biogenic Carbonate Productivity: The Robe—Woakwine Marine Corridor

South of Cape Jaffa to the Glenelg River in western-most Victoria, a highly irregular shoreline morphology in plan-view has resulted from exposure of Late Pleistocene calcarenites (Robe Range) and Oligo-Miocene Gambier Limestone to the high wave energy of the Southern Ocean. This has resulted in pocket or repressed beaches alternating with a rocky calcarenite coastline partially blanketed by Holocene dune sands.

An elongate, low-lying depression south of Guichen Bay and to the north of Rivoli Bay, between the Late Pleistocene coastal barriers of the Robe (MIS 5a and MIS 5c) and Woakwine (MIS 5e) Ranges, was a shallow-water seaway during the early Holocene immediately after the culmination of the post-glacial marine transgression some 7000 years ago (Cann et al. 1999). During the Holocene highstand the low-lying land between these two consolidated barriers was flooded, creating a linear marine corridor up to 30 km long, 6–10 km wide and 4 m deep (Fig. 3.13). As Guichen Bay and Rivoli Bay progressively infilled due to the coastal progradation of beach ridges, the former seaway progressively changed from an open, shallow-water, marine corridor to a more restricted environment of several lakes characterised by seasonally fluctuating salinities.

Marine shell beds that record the progressive infilling of the seaway between the Woakwine and Robe Ranges from 7 to 2 ka ago are exposed

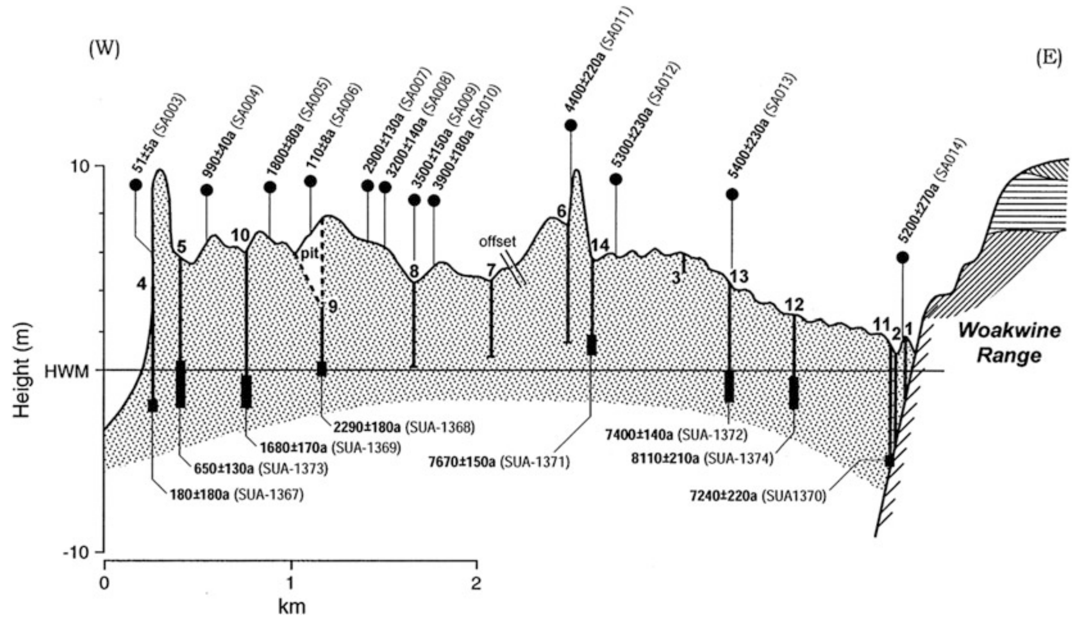

Fig. 3.12 Shore-normal cross-section across the Holocene embayment fill (beach ridge plain) at Guichen Bay showing the OSL ages on quartz sand from the relict foredunes and radiocarbon ages on coarse grained skeletal carbonate sand and larger shell fragments from the underlying littoral facies. The transect was undertaken along the central portion of the embayment fill adjacent the two offset roads in the upper middle portion of the photograph (*Source* Murray-Wallace et al. 2002)

Fig. 3.13 Holocene coquina exposed in a roadside borrow pit 1 km north of Lake St Clair (field site SE#44 of Cann et al. 1999). The site is now completely overgrown by *Acacia* (coastal wattle) (*Photograph* Murray-Wallace 1993)

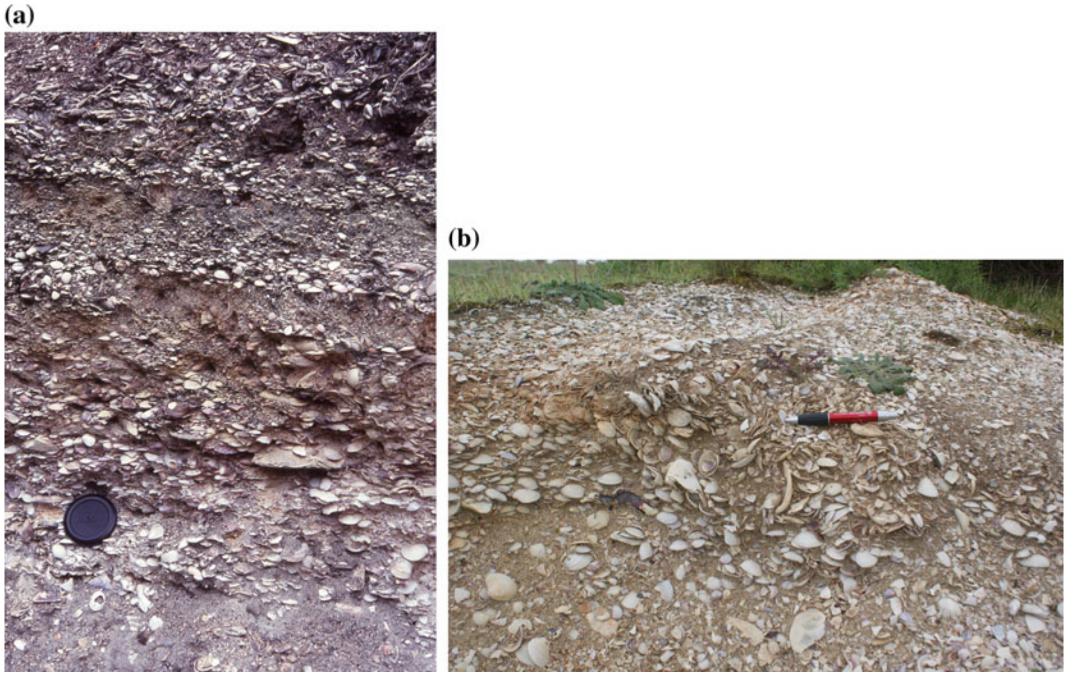

Fig. 3.14 **a** Holocene coquina at Little Dip Conservation Park, near Robe that is part of the shoaling-upward succession of carbonate sands that has formed by marine flooding of the Robe—Woakwine Corridor (*Photograph* Murray-Wallace 1993). **b**. Holocene coquina dominated by the cockle *Katelysia rhytiphora* 9 km ESE of Robe (*Photograph* Murray-Wallace 2017)

at various sites around Lakes Robe, Eliza and George, as well as within borrow pits and road cuttings (Cann et al. 1999; Fig. 3.14 a, b). These lakes now have no direct connection to the sea. Water quality varies from fresh to hypersaline depending on the balance between marine and continental groundwater infiltration, evaporation, rainfall and artificial drainage measures.

Holocene sedimentation within the marine-corridor was characterised by autochthonous and allochthonous shelly assemblages particularly the shallow water Venerid bivalve species *Katelysia scalarina* and *K. rhytiphora* and the gastropod *Batillaria* (*Zeacumantus*) *diemenensis* and the smaller individual *B*. (*Batillariella*) *estuarina* both characteristic of intertidal sand and mud-flats. *Katelysia scalarina* tends to frequent intertidal to shallow subtidal environments, while *K. rhytiphora* is more common in shallow subtidal waters immediately below the low water limit of the intertidal zone to approximately 1 m below low tidal datum (Nielsen 1964; Roberts 1984). The basal portion of the marine corridor succession is characterised by in situ coquina, dominated by articulated *Katelysia* sp, which pass upwards into 1–2 m of transported, disarticulated shells, convex upwards (Cann et al. 1999). Overall, the coquinas within the Robe–Woakwine Corridor represent a shoaling-upwards sequence as the molluscan-dominated faunas have slowly aggraded and reduced sediment accommodation space producing a 3–4 m thick succession of coquina within the entire 30 km long corridor, illustrating prolific carbonate productivity.

In the early Holocene depositional history of the Robe–Woakwine marine corridor, the seaward barrier Robe Range would have acted like a seawall and led to the formation of a tombolo comprising sand and mud flats radiating out from the more landward Woakwine Range. The initial marine incursion post-dates the formation of a basal peat dated at 7870 ± 210 year cal BP (Wk-5191) on which the shelly successions unconformably overlie. A radiocarbon age 7530 ± 170 year cal BP (Wk-4184) on a pioneering assemblage of *Katelysia rhytiphora* defines the onset of shallow marine sedimentation within the Robe–Woakwine Corridor (Cann et al. 1999) and is coincident with the culmination of the post-glacial sea-level rise as documented for other coastal sites in Australia (Sloss et al. 2007; Lewis et al. 2013).

At Lake Robe extensive shell beds of the oyster *Ostrea angasi* and associated *Katelysia* spp., are exposed in the modern lake floor at times of low water levels. Radiocarbon ages of 3890 ± 200 year cal BP (SUA-3026) on *Ostrea angasi* and 4600 ± 200 year cal BP (SUA-3027) on *Katelysia rhytiphora* indicate that the Lake Robe area had an unrestricted marine connection at this time and that the transition to more restricted lacustrine conditions post-dated these shelly assemblages. At this time Guichen Bay had only infilled to just under half its current beach ridge sequence (Murray-Wallace et al. 2002), allowing the continued exchange of marine waters by tidal flushing and incident waves. The later phase of coquina sedimentation in the Robe—Woakwine Corridor is characterised by increasing accumulations of transported shells expressed as disarticulated valves convex upwards, culminating in coarsely comminuted shelly debris similar to the surfaces of modern intertidal flats. The final phase in the evolutionary development of this coastal landscape was the formation of lacustrine and wetland environments in the absence of marine influence.

3.10 Holocene Coastal Sedimentation, Mount Gambier Region

3.10.1 Flint Shingle Beach Deposits, Port MacDonnell to Racecourse Bay

The coastline and adjoining Bonney Shelf from Carpenter Rocks to the Glenelg River in western-most Victoria is partially sediment starved and accordingly, Holocene coastal dunes have not formed along this coastal sector to the same magnitude as the vast accumulations of Holocene dunes on Younghusband Peninsula to the north (Fig. 3.1). The coastal sector from Carpenter Rocks to the Glenelg River is characterised by a faster rate of neotectonic uplift and the emergence of Late Pleistocene Robe Range as seen in numerous coastal cliffs and near-shore islands of eroded aeoliante. Coastal emergence in this region since the Middle Pleistocene has also exposed the Oligo-Miocene Gambier Limestone at sea level. During multiple interglacial highstands a regionally extensive marine abrasion surface has formed on which the successions of interglacial barriers of the Mount Gambier region have been deposited. The Gambier Limestone also crops out along the modern shoreline to the east of Port MacDonnell giving rise to well-developed shore platforms backed by flint shingle beaches.

To the east of Port MacDonnell numerous small pocket beach embayments (50–100 m wide) between small calcarenite headlands of Robe Range (Late Pleistocene Bridgewater Formation) and Gambier Limestone (1–3 m high), have infilled with cobbles and pebbles of flint and represent the only flint beaches in Australia. Farther east at Racecourse Bay a sinuously crested cobble beach deposit up to 2 km long has formed (Fig. 3.15). The asymmetrically shaped ridge crest attains a maximum height of 3 m APSL and is characterised by steep seaward facing slopes and lower angle back-beach slopes reflecting storm wave deposition. In detail the slope angles of this deposit vary along the structure in relation to the direction and magnitude of incident wave energy (Blakemore 2014). It has been estimated that over a beach-parallel distance of 20 km, occur up to 1000 tonnes of flint pebbles (Willington 1954).

The flint is derived from the Oligo-Miocene Gambier Limestone and is of diagenetic origin, largely from the dissolution of siliceous sponge spicules and re-precipitation as amorphous silica (Flint et al. 1989). In restricted places within the Gambier Limestone, the silica has nucleated to

Fig. 3.15 Sinuous crested shingle beach comprising flint cobbles and pebbles at Racecourse Bay, 5 km east of Port MacDonnell (*Photograph* Murray-Wallace 2015)

form complex 'box work' structures or branching networks, reminiscent of the trace fossil *Thalassinoides* as revealed in plan-view on upper bedding surfaces of the Gambier Limestone, which are initially exposed through differential weathering of the surrounding limestone (Fig. 3.16). These features are subsequently broken through mechanical abrasion by high wave energy resulting in the formation of flint cobbles and pebbles. Easterly trending long-shore drift has resulted in the concentration of these clasts to form high angle cobble beach deposits that have principally formed under storm conditions (Fig. 3.15). The cobble beach successions are typically up to 2–3 m thick and extend landwards for over 30 m, backed by a low relief swampland environment. These cobble beaches have been 'hand-mined' intermittently since 1909 as a source of flint for grinding in ball mills in the mining and paint industry and as high-grade silica cements (Willington 1954; Flint et al. 1989).

The flint was used as stone tools by Aboriginal people, and the remains of flake-scrapers with convex, concave and straight cutting edges have been found between Robe in South Australia and Portland in Victoria (Mulvaney and Kamminga 1999). The anthropologist and archaeologist Norman Tindale termed it the Gambieran Flint Industry. The archaeological occurrences are typically of Mid-Holocene age, which accords with the initial formation of these flint beach concentrations following the culmination of the post-Glacial sea-level rise and the beginning of the Holocene highstand.

3.11 A Dynamic Coastline—Coastal Erosion and Holocene Sediment Budgets

The high wave energy of the open ocean coastline of the Coorong Coastal Plain and the friable nature of the Pleistocene aeolianite successions

Fig. 3.16 Branching network of flint of diagenetic origin formed within the Oligo-Miocene Gambier Limestone and exposed on the landward limit of a modern shore platform to the west of Port MacDonnell. The flint has been exposed by differential weathering of the more erosionally susceptible Gambier Limestone (*Photograph* Murray-Wallace 1996)

renders them highly susceptible to erosion and the reincorporation of sediment into younger depositional systems. However, once the relict barriers have been uplifted and removed from the influence of wave attack they remain well-preserved in the geological record particularly due to their protective calcrete capping. The composite structure of several of the Pleistocene barriers which have formed in more than one interglacial illustrates the significance of wave attack in the geomorphological development of these features. The Woakwine Range, for example is represented by at least two depositional episodes during the penultimate (MIS 7) and the Last Interglacial Maximum (MIS 5e) as shown by geochronological evidence (Murray-Wallace et al. 1999), and possibly up to four or five phases of deposition as originally suggested by Hossfeld (1950); Sprigg (1952) and Schwebel (1978, 1984).

Studies of the composition and age of Holocene sediment particles provides further insights into the nature of sediment budgets and the role of erosional processes in providing inherited (reworked) sedimentary carbonate grains to younger sediments. The aeolianites of Robe Range have undergone considerable erosion since the formation of this barrier in the Late Pleistocene warm interstadials MIS 5c and 5a. Between 0.5 and 2 km of coastal erosion and horizontal shoreline recession has occurred, mostly during Holocene time, and in particular, since the attainment of present sea level some 7000 years ago (Fig. 3.17). The barrier would not have been subjected to wave attack for the entire interval from the end of MIS 5a some 82 ka ago to the attainment of present sea level. Minimal erosion is likely to have occurred during the last glacial cycle given the enhanced phase of aridity during this period (Sprigg 1952, 1979)

Fig. 3.17 View of an erosional remnant of Late Pleistocene Robe Range offshore from Long Gully, 8 km SE of Robe. Shore platforms are evident in the left-hand (western) side of the erosional residuals of Robe Range. The original arch-shape of the aeolian landforms is also clearly evident. (*Photograph* Murray-Wallace 2017)

which favoured pervasive calcrete development that effectively armours the original dune forms of the barrier. The coastal erosion of Robe Range is expressed as a linear series of near-shore islands parallel with the main structure of Robe Range. Many of the islands are rimmed with minor shore platforms several metres wide attesting to their more recent origin under present sea level conditions (Fig. 3.17). The skeletal carbonate sands derived from the erosion of Robe Range has been a major sediment source nourishing the beach ridge plains and Holocene dune complexes along the coastline (e.g. Guichen and Rivoli Bays).

AAR analyses by the 'whole-rock' method for sediments from Guichen Bay have shown that a substantial proportion of the sediment deposited in the late Holocene comprises relict carbonate grains as shown by the high extent of racemization which indicates that the carbonate grains are of Late Pleistocene age and derived from the erosion of the Robe Range (Murray-Wallace et al. 2001). A leucine D/L value of 0.317 ± 0.003 was obtained on sand from the most landward beach ridge at Guichen Bay (sample SA014 of Murray-Wallace et al. 2002) compared with a D/L value of 0.453 ± 0.005 for in situ skeletal carbonate sand from Robe Range III, dated by TL at 116 ± 6 ka (Huntley et al. 1994). In a similar manner, modern sand from the beach face at Long Beach, Guichen Bay, comprises a significant proportion of inherited carbonate grains as illustrated by a high leucine D/L value (0.225 ± 0.002). A leucine D/L value of 0.03 is commonly recorded in modern shells alive at the time of collection.

3.12 Aboriginal Settlement and Coastal Landscape Interactions

Aboriginal people lived in coastal communities on the Coorong Coastal Plain since the culmination of the post-glacial marine transgression some 7000 years ago as attested by radiocarbon ages on a variety of marine shells and charcoal from middens draping Holocene dunes on Sir Richard and Younghusband Peninsulas (Luebbers 1978; Bourman and Murray-Wallace 1991; Cann et al. 1991; Fig. 3.18). In addition, middens have been identified within incipient palaeosols and on erosion surfaces on the Late Pleistocene Robe Range (Tindale 1957; Luebbers 1978; Cann et al. 1991). Tindale (1957) reported an uncalibrated radiocarbon age of 8700 ± 120 year BP on charcoal from a hearth within a *terra rossa* palaeosol draping Robe Range at Cape Martin, approximately 1 km south of Beachport. Numerous stone tools and fragments of flint derived from the Oligo-Miocene Gambier Limestone, as well as marine molluscs including the gastropod *Turbo undulatus* were associated with the hearth.

Cann et al. (1991) reported calibrated radiocarbon ages on charcoal (8270 ± 80 year cal BP; ANU-7448) and the cockle *Katelysia* spp. (7910 ± 140 year cal BP; SUA-2613) from a midden that accumulated on a subaerially-exposed *terra rossa* palaeosol capping the Late Pleistocene successions of Robe Range near Robe. This midden equated with the Early Horizon, a cultural horizon chronicling the early human settlement of the region (Luebbers 1978). This age—event relationship implies that following the culmination of sea-level rise and the attainment of the Holocene highstand, people were living within a region subject to major coastal landscape changes. A Late Horizon was also identified by Luebbers (1978), found on unconsolidated Holocene dune sand, and contains *Turbo* sp., shells and flint fragments, the

Fig. 3.18 Middens comprising solely the Goolwa cockle *Donax deltoides* on Holocene dunes, Younghusband Peninsula (*Photograph* Murray-Wallace 1993)

Fig. 3.19 A midden consisting of the rocky shore gastropod *Turbo* sp., within a Holocene dune which covers the Late Pleistocene Robe Range at Nora Creina Bay. The in situ portion of the midden is visible as a single layer of *Turbo* sp., shells in the lower right-hand side of the photograph beneath the small vegetated knoll of sand. Late Pleistocene Robe Range is actively eroding at this locality with large residuals of the dune range present at the entrance to Nora Creina Bay (*Photograph* Murray-Wallace 2017)

latter which most notably would have come from up to 80 km farther south such as Racecourse Bay to the east of Port MacDonnell.

Aboriginal middens, marked by food remains such as shells and bones, flint tools and charcoal, also record the progressive changes in coastal palaeogeography, environments and associated biota (Cann et al. 1999). At Nora Creina, an Aboriginal midden draping a Holocene coastal parabolic dune dominated by the rocky shore gastropod *Turbo (Subninella) undulatus* was dated at 740 ± 130 cal years BP (Beta-104422) (Cann and Murray-Wallace 1999; Fig. 3.19).

Two superposed middens are present at Little Dip, 7 km north of Nora Creina Bay. These are stratotype equivalents of the time-cultural Early and Late Horizons of Aboriginal occupation in this region during Holocene time as identified by Luebbers (1978);

Late Horizon midden: At Little Dip a poorly vegetated coastal dune immediately overlooks the rocky foreshore on which the large gastropod *Turbo* sp. is extant and easily collected. The seaward side of the dune has been subjected to wind deflation and a lag deposit of abundant shells and opercula of *Turbo*, together with numerous fragments of flint are scattered across the land surface. Some opercula are chipped or fractured and are more numerous in some areas than others, as if sorted by some selective process. Above the lag deposit there are numerous conspicuous *Turbo* shells in a greyish, poorly consolidated horizon of the dune. The shell and flint materials appear to have been derived from this layer. Radiocarbon ages reveal that this site was occupied several hundred years ago when the geomorphological setting was essentially similar to that of today.

Early Horizon midden: On the landward side of the dune at Little Dip the Holocene sand sharply overlies a well-consolidated red-brown *terra rossa* soil on the Bridgewater Formation of Robe Range. Embedded within this palaeosol are numerous shells of the bivalve *Katelysia* sp., and fragments of charcoal. Thus far, no flint fragments have been observed, nevertheless, a human origin is also proposed for this material, based on the following evidence:

- The shells are disarticulated, lack any preferred orientation and many are severely broken. The fabric is inconsistent with known sedimentary processes.
- None of the shells have been observed to have "drill" holes inflicted by predatory gastropods.
- The *terra rossa* matrix enclosing the shells is barren of foraminifers or other microfossils that might be expected in natural sediment.
- The topographic setting and elevation of the *Katelysia* deposit at the crest of Robe Range makes natural sedimentation implausible if these shells are to be correlated with those undisputedly deposited by natural processes in the Holocene lagoon landward of the dune range. Radiocarbon ages on shell and charcoal, supported by amino acid racemization D/L values for shell, confirm that this site was occupied in the early to mid-Holocene (Cann et al. 1991).

Well-preserved shells of the Goolwa cockle *Donax deltoides*, a species that frequents shallow water foreshore sands are commonly found in large numbers within middens on Sir Richard and Younghusband Peninsulas (Bourman and Murray-Wallace 1991). On Sir Richard Peninsula, middens are confined to the proximal half of the peninsula and their ages range between 2240 ± 130 year cal BP (SUA-2880) and 270 ± 70 year cal BP (SUA-2885) (Bourman and Murray-Wallace 1991). The rocky shoreline species *Turbo (Subninella) undulatus* is also common within middens close to rocky shorelines, particularly on Holocene coastal dunes on Robe Range (Cann and Murray-Wallace 1999).

As outlined earlier in this chapter (Sect. 3.9) between the present locations of the coastal towns of Robe and Beachport, a major seaway existed between the Robe and Woakwine Ranges. At the culmination of post-glacial sea-level rise some 7000 years ago, a shallow seaway between 6 and 10 km wide, characterised by fully marine salinities with clear tidal and wave flushing, existed between these two consolidated Late Pleistocene dune ranges. The early Holocene radiocarbon ages cited above imply that people used water craft to get to Robe Range, which would have been an elongate island some 45 km long and up to 4 km wide. With the passage of time, coastal progradation of the beach ridge plains at Guichen and Rivoli Bays partially closed the seaway, resulting in a change in the shelly faunas and reducing the availability for harvesting of some shell species such as *Katelysia* spp., and *Ostrea* sp. Ultimately the seaway closed necessitating a change in Aboriginal food gathering practices for marine resources and explains the basis for the Early and Late Horizon middens identified by Luebbers (1978) based on radiocarbon ages of shelly materials.

Tindale (1983) described the occurrence of Aboriginal artefacts attributed to the Kartan phase of stone implements (a presumed Late Pleistocene cultural phase, since shown to be of Holocene age; Mulvaney and Kamminga 1999) scattered on the land surface on the seaward side of Woakwine Range and assumed that these artefacts were coeval with Late Pleistocene barrier development. However, the now well-established last interglacial age (MIS 5e; 125 ka) of this coastal landform significantly pre-dates the currently accepted minimum age for the arrival of Humans in Australia at 65 ka (Clarkson et al. 2017). The loose, unconsolidated and surface context of the artefacts also argues against a Last Interglacial age for these features, given that they have not been found within the indurated calcrete that mantles the dune range.

3.13 Post-European Settlement Human Impacts on the Coastline

The presence of areas of un-vegetated active dunes on Sir Richard and Younghusband Peninsulas has been known since the early observations of Nicolas Baudin and Matthew Flinders in 1802 of the Encounter Bay coastline (Flinders 1814; Baudin 2004). George French Angas in his travels from Adelaide to Mount Gambier in 1844 also noted the presence of extensive areas of active dunes on Younghusband Peninsula (Angas 1847). Sir Richard and Younghusband Peninsulas experienced renewed phases of aeolian dune reactivation with landscape deflation and dune blowout development, resulting from European settlement and the introduction of livestock for grazing on coastal vegetation and the uncontrolled spread of rabbits (Bourman and Murray-Wallace 1991). Bush fires, drought and plant diseases also exacerbated coastal landscape instability and increased the likelihood of dune reactivation (James 2004).

On the north-western margin of Lake George 30 km south-east of Robe, drift sand has been migrating at a rate of 15 m/year on the slip faces of parabolic dunes and 7.4 m/year into the lake as a larger, advancing body of sand since 1945 (Armstrong 1977). The region of actively migrating dune sand, locally known as '10 Mile Sandhill' covers an area of 225 ha and comprises a series of sinuous-crested sand ridges trending approximately 60°–80° reflecting the dominant wind directions. The advance of the sand has encroached on Lake George and obscured a road. Grazing of stock following early European settlement in the 1840s and the use of restricted supplies of timber for fence construction are considered responsible for dune reactivation, which has been exacerbated by recreational use of four-wheel drive vehicles in the 1960s.

In south-eastern Rivoli Bay, extensive dune reactivation was caused by the combined effects of overgrazing and bush fires in the early-mid-twentieth century. A series of dune blowouts and landward migrating dunes was mapped by Sprigg (1952) along the south-eastern portion of Rivoli Bay. The area of landward migrating dunes extends over 3.6 km along the south-eastern sector of the Rivoli Bay coastline and up to 1.2 km inland. More recent coastal dune landscape degradation has resulted from the use of off-road vehicles. Off-road vehicle tracks from across modern foredunes have mobilised sand and has formed conduits in which onshore winds have transported sand landwards. The slow recovery times of the coastal vegetation and soil disturbance has rendered these landscapes particularly vulnerable to coastal erosion.

3.14 Summary and Conclusions

Coastal changes during the Holocene represent the penultimate chapter in the complex evolutionary history of the Coorong Coastal Plain. Ongoing and future coastal landscape changes will constitute the final chapter yet to be written. The most profound coastal landscape changes accompanied the culmination of post-glacial sea-level rise from approximately 18,000 to 7000 years ago. At that time post-glacial sea-level rise led to the landward translation of the shoreline and concentration of barrier sands from the inner shelf environment resulting in the broad outline of the modern coastal landscapes. From 7000 years ago the coastal environments slowly adjusted to an essentially stable phase of relative sea level, notwithstanding a minor relative fall of approximately 1 m related to the hydro-isostatic adjustment of the Lacepede and Bonney Shelves and neotectonic uplift of the southern portion of the coastal plain. During the period of the Holocene highstand the coastal barriers Younghusband and Sir Richard Peninsulas became consolidated structures. In the back-barrier shallow-water, protected sedimentary environments of the Coorong Lagoon and Robe-Woakwine Corridor, the prolific growth of marine invertebrate faunas, particularly molluscs such as the cockle *Katelysia* sp., formed thick successions of coquinas. Vertical accretion (aggradation) of these shelly accumulations ultimately led to a major transition in sedimentary environments with the formation of ephemeral saline lake environments subject to fluctuating salinities.

Human-landscape interactions are a distinguishing characteristic of the Holocene evolution of the coastal plain, not evident in the Pleistocene record. Coinciding with the earliest development of the coastline in the Holocene sea level highstand, Aboriginal people harvested shellfish. This is attested by middens of the Early Horizon dating back to about 7000 years ago. The presence of a well-established seaway between the Robe and Woakwine Ranges and the presence of early Holocene (7000 years old) middens on Robe Range indicate that Aboriginal people used watercraft to reach the former island of Robe Range, as the width of the seaway would have precluded people safely swimming.

The most recent and on-going phase of coastal change was initiated by human impacts following European settlement of the region. The magnitude of coastal dune reactivation increased significantly following the introduction of livestock as well as the introduction of feral animals including the rabbit. These changes have been manifested by large areas of active dune sheets with landward advancing parabolic dunes, deflation of portions of the landscape and coastal erosion along some sectors of the coastline. Other environmental impacts relate to the water quality and the flow directions of surface water runoff. The construction of a wide network of drainage channels to drain the lee side of the barrier landforms that would otherwise flood during winter resulted in a significant change in water quality of the Coorong Lagoon.

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4 Pleistocene and Holocene Volcanic Activity and Neotectonism

Abstract

A series of volcanic eruption centres in southern South Australia is genetically related to the Newer Volcanics of western Victoria. Volcanism occurred during the Pleistocene (Mount Burr Volcanic Group) and middle Holocene (Mount Gambier and Mount Schank). The age of the Mount Burr Volcanic Group is poorly constrained due to the highly weathered nature of the volcanic lithologies, but the spatial arrangement of several coastal barrier shoreline complexes that connect with the volcanic complex in a tombolo-like form reveals that it is older than Middle Pleistocene in age (>781 ka). Mount Gambier and Mount Schank are basaltic cones (maars) in which explosive phreatomagmatic eruptions occurred, resulting from the interaction of CO_2-enriched magmas with aquifers within the porous and highly permeable Oligo-Miocene Gambier Limestone. The volcanic products are thus mostly air-fall pyroclastics, with only minor lava flows. Thermoluminescence dating of Pleistocene beach sands reset by transient heat flow from overlying basalts, and radiocarbon dating of charcoal beneath volcanic ash indicate middle Holocene ages for the eruptions of Mount Gambier and Mount Schank. The emplacement of magma within the upper crust has deformed the Oligo-Miocene Gambier Limestone into a regional dome structure resulting in the differential uplift of the Quaternary barrier shoreline successions.

Keywords

Newer volcanics · Intraplate volcanism
Phreatomagmatic eruptions · Neotectonics
Epeirogenic uplift

4.1 Introduction

A series of volcanoes and lava fields, initiated some 100 Ma ago, formed predominantly during the Cenozoic along the 4000 km-long eastern margin of Australia from northern Queensland to Tasmania, particularly in the region of the Great Dividing Range (Wellman and McDougall 1974; Sutherland 1983). The volcanism relates to hot-spot trails and in general terms the ages of the volcanic edifices young in a southerly direction reflecting the northward movement of the Indo-Australian Plate (Sutherland et al. 2012, 2014). The volcanic plume system is related to

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the failed Coral Sea spreading centre. As an example of the general younging trend in the age of volcanism with latitude, the volcanic events range from 32 Ma at Mount Dukes along the central northern Queensland coast to 6 Ma at Mount Macedon in central Victoria (Wellman and McDougall 1974; Sutherland et al. 2014). An $^{40}Ar/^{39}Ar$ age of 7 ± 2 ka for a 55 km long basalt flow at Kinrara in north-eastern Queensland (Cohen et al. 2017) shows that the progressively younging trend in the age of Quaternary volcanic activity with more southerly latitudes is more complex than traditionally appreciated. The extensive belt of volcanoes in western Victoria termed the Newer Volcanics, geologically represent the most recent phase of this volcanism and include at least 704 eruption points from a minimum of 416 volcanic centres (Price et al. 2003; Boyce 2013).

In contrast to much of the Cenozoic volcanism of eastern Australia, the origin of the Newer Volcanics is more problematic (Boyce 2013). The Newer Volcanics extend over a longitudinal distance of some 410 km from near Melbourne to the Mount Burr Volcanic Complex in southern South Australia. Accordingly they do not define a specific hotspot. In a similar manner, they span approximately 100 km of latitude but Australia moved north over 300 km during the 5 Ma time of their formation. Several hypotheses have been raised for the origin of the Newer Volcanics that include hotspot activity, continental extension and post-rift diapirism, reactivation of regional extensional faults and asthenospheric upwelling. The southern limit of the Newer Volcanics is defined by the Colac Lineament which extends east-west from Port Phillip Bay to south of Cape Nelson in western Victoria. Genetically related episodes of volcanism to the Newer Volcanics of western Victoria extend into southern South Australia in two distinct groups.

The basis for the intraplate volcanism responsible for Mounts Gambier and Schank, as well as the Mount Burr Volcanic Province remains problematic. Asthenosphere upwelling associated with rapid northward movement of the Indo-Australian Plate and thinning of the lithosphere was favoured by Demidjuk et al. (2007). In contrast van Otterloo et al. (2013) considered that melting occurred within zones of transtension in an overall transpressive lithospheric regime.

4.2 Pleistocene Volcanism—Mount Burr Volcanic Group

Situated between 20 and 46 km to the north-west of Mount Gambier in three linearly trending groups, the Mount Burr Volcanic Group comprises 17 volcanic centres in a range of forms including composite domes, tuff rings and maars (Firman 1973; Sheard 1995; Fig. 4.1). The NW-SE trend of the eruption centres coincides with the regional trend of major fractures within the Gambier Limestone (Sprigg 1952). The fracture sets are normal to the approximate locus of the Mount Gambier Upwarp developed in the gently folded Oligo-Miocene Gambier Limestone. The upwarp is situated approximately half-way between the Mount Burr Volcanic Group and the younger eruption centres Mount Gambier and Mount Schank.

The Mount Burr Volcanic Group is significantly older than Mount Gambier and Mount Schank. The western-most band of volcanic centres and associated higher regional landscape relief of the Mount Burr Volcanic Group shows evidence for erosional modification at times of high sea level, particularly on their western seaward side. The western margin of the volcanic centre is a broadly linear, wave-realigned feature, coincident with the regional trend of the coastal barrier Mount Gambier Range. Based on geomorphological reasoning and a count from the top approach for assigning ages to the interglacial barriers, Mount Gambier Range is at least 440 ka (MIS 11). It was assigned a numeric age of 581 ± 90 ka based on the extent of racemization of amino acids in the foraminifer *Elphidium crispum* (Blakemore et al. 2015).

Further evidence for the antiquity of the Mount Burr Volcanic Group is that outcrops of aeolianite of the Pleistocene Bridgewater Formation occur on several of the volcanic edifices (Mounts Graham, Muir, MacIntyre and Burr;

Fig. 4.1 Map of the Newer Volcanics in southern South Australia showing the location of the Pleistocene Mount Burr Volcanic Province and the Holocene volcanoes Mount Gambier and Mount Schank

Firman 1973). At Mount Burr the aeolianite occurs as a broad, sheet-like deposit extending from the footslope of the volcanic edifice at 66 m APSL up to 200 m APSL (Hossfeld 1950; Firman 1973; Fig. 4.2). In places the aeolianite has been eroded creating a fenster of weathered

Fig. 4.2 View looking NE to Mount Burr, a Pleistocene volcanic crater of the Mount Burr Volcanic Group (*Photograph* Murray-Wallace 2017)

volcanic rock. Mount Gambier and Mount Schank, in contrast, have formed stratigraphically above the Bridgewater Formation.

A Shuttle Radar Topography Mission (SRTM) image reveals that the Mount Burr Volcanic Group initially represented an archipelago some 35–44 km south-west from the Kanawinka Fault scarp during the early-Middle Pleistocene history of the Coorong Coastal Plain (Fig. 4.1). The regional trend of the coastal barrier landforms to the north and south of the volcanic group is in the form of a series of arcuate-shaped barriers that created a tombolo in the form of a cuspate foreland linked to the higher relief of the Mount Burr Volcanic Group. This pattern of sedimentation has occurred since at least the earliest Middle Pleistocene, as the West Naracoorte Range can be traced as one of the oldest barriers in this cuspate foreland complex. The West Naracoorte Range is of normal magnetic polarity and has been correlated with MIS 19 ($\leq$ 781 ka) sea level highstand (Belperio and Cann 1990), indicating that the Mount Burr Volcanic Group significantly predates this barrier. Mount Muirhead on the north-western margin of the Mount Burr Volcanic Group erupted between the West Avenue Range (MIS 9) and Reedy Creek (MIS 7) and is considered to post-date these barriers (Firman 1973). Volcanic ash partially covers Reedy Creek Range in this locality attesting to the relative age of volcanism at Mount Muirhead.

4.3 Holocene Volcanism

Mount Gambier formerly was regarded as the only region in Australia in which Holocene volcanism has occurred and where a current volcanic hazard may be considered to exist (Sheard 1995; Joyce 2005; cf., Cohen et al. 2017). The Holocene volcanoes, Mount Gambier and Mount Schank are constructional features produced by basaltic phreatomagmatic eruptions

(Fig. 4.1). In terms of volcanic landform classification, Mount Gambier and Mount Schank are examples of maars, named after the distinctive volcanic landforms of the Eifel region in Germany (Ollier 1969). Characteristically these volcanic landforms are significantly wider than their depth and have resulted from volcanic explosions producing craters with surrounding rims of volcanic ejecta, rather than subsidence producing caldera-like features as suggested by Woods (1862), Howchin (1901) and Fenner (1921). A comprehensive overview of the early literature on Mount Gambier and its associated lakes was presented by Fenner (1921). Mount Gambier and Mount Schank are the youngest volcanoes in a province of several hundred volcanic centres in south-eastern Australia extending across much of western Victoria (Joyce 1975; Sheard 1983, 1995; Price et al. 2003; Boyce 2013). Magmas were derived by partial melting of basanite parent materials in either deep crustal or upper mantle environments (Irving and Green 1976).

The Mount Gambier volcanic complex comprises six well-defined conduits, four of which are now occupied by lakes, the most notable being the Blue Lake, the eastern-most conduit (Fig. 4.3). The other lakes include Leg of Mutton Lake, Valley Lake, and Browne's Lake (Fig. 4.4). The other conduits, Devil's Punchbowl and the site of Tenison College Oval are on topographic highs above the regional water table. The volcanic conduits are situated within a topographic depression between two aeolianite coastal barriers, the Mount Gambier and Glenburnie Ranges of Middle Pleistocene age (Blakemore et al. 2015). More recent investigations have identified over 14 vents (van Otterloo and Cas 2013).

Situated 9 km south of Mount Gambier, Mount Schank is a hybrid-maar structure that resulted from explosive phreatomagmatic

Fig. 4.3 Blue Lake, a mid-Holocene volcanic maar at Mount Gambier with Mount Schank visible in the horizon. The lower portion of the crater wall is Oligo-Miocene Gambier Limestone which is overlain by basalt lava and tuff agglomerate (*Photograph* Murray-Wallace 1996)

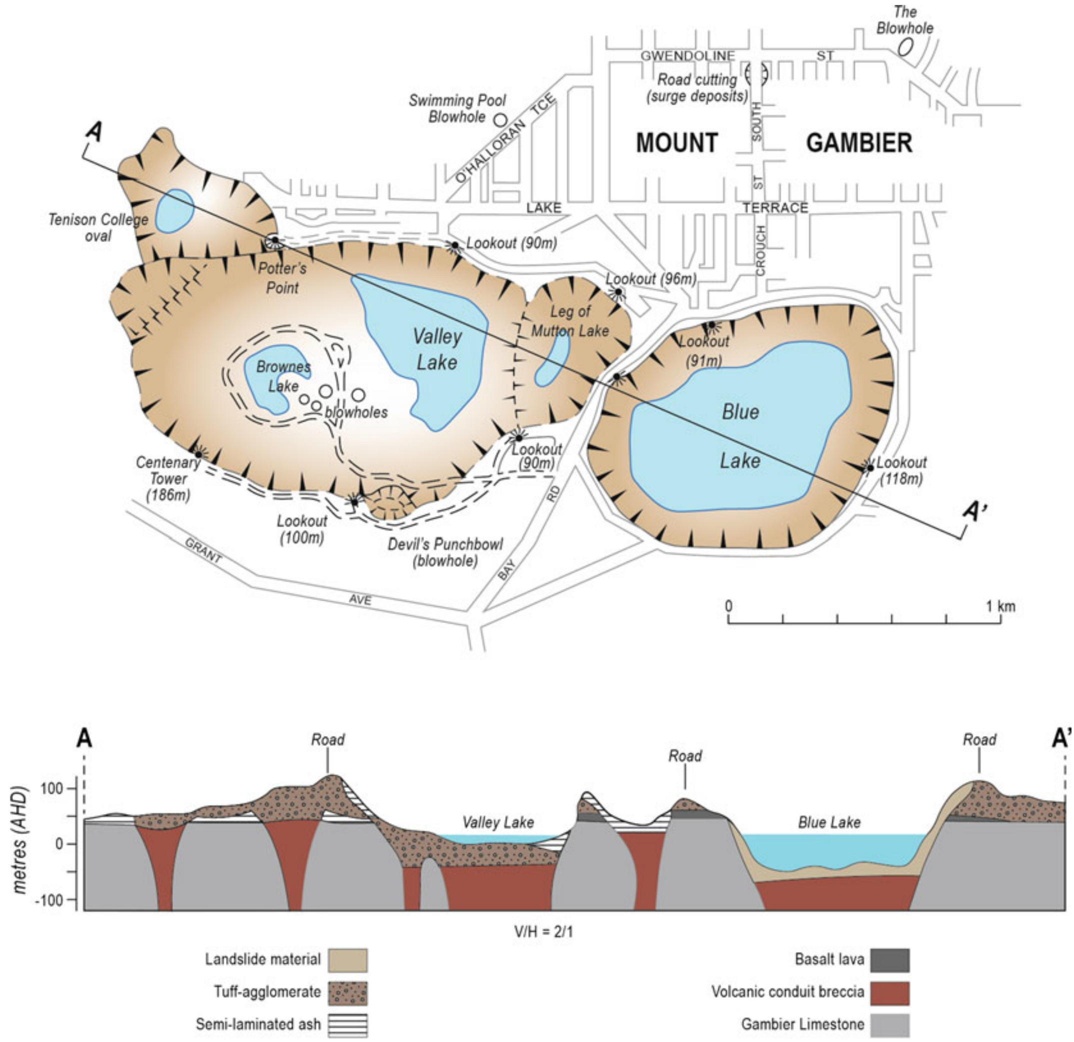

Fig. 4.4 Map of the Mount Gambier Volcanic complex after Sheard (1983, 1995)

volcanism (Fig. 4.5a, b). The volcanic complex comprises a main crater up to approximately 500 m in diameter measured at the crest of the structure, a slightly smaller maar on its southern flank and a small crater and lava flow on its western margin (Fig. 4.6). A series of scoria cinder cones occurs on the north-western flank of the volcano having erupted along a fissure within the Gambier Limestone during the early stages of the eruption (Fig. 4.7). Exposures within a quarry, now rehabilitated, formerly revealed a sequence of volcanic rocks on a pre-existing surface of Gambier Limestone. Cones of red scoria are overlain by black vesicular basalt, which in turn is capped with a white, carbonate rich tuff. The scoria cones appeared to have developed along a fissure; jointing within the overlying basalt is an expression of lava flow over the cones. At the site overlooking the small, youngest crater there is a clear exposure of Gambier Limestone, overlain by a thin basalt flow and subsequent deposits of pyroclastics.

Pyroclastics of the main cone are exposed in a disused quarry and road cutting east of Mount

Fig. 4.5 **a** External and **b** internal views of Mount Schank. The external view is taken 2 km to the east of the volcano. The internal view is taken from the southern rim of the crater. Mount Schank, a hybrid-maar volcano formed by phreatomagmatic volcanism (*Photographs* Murray-Wallace 2016)

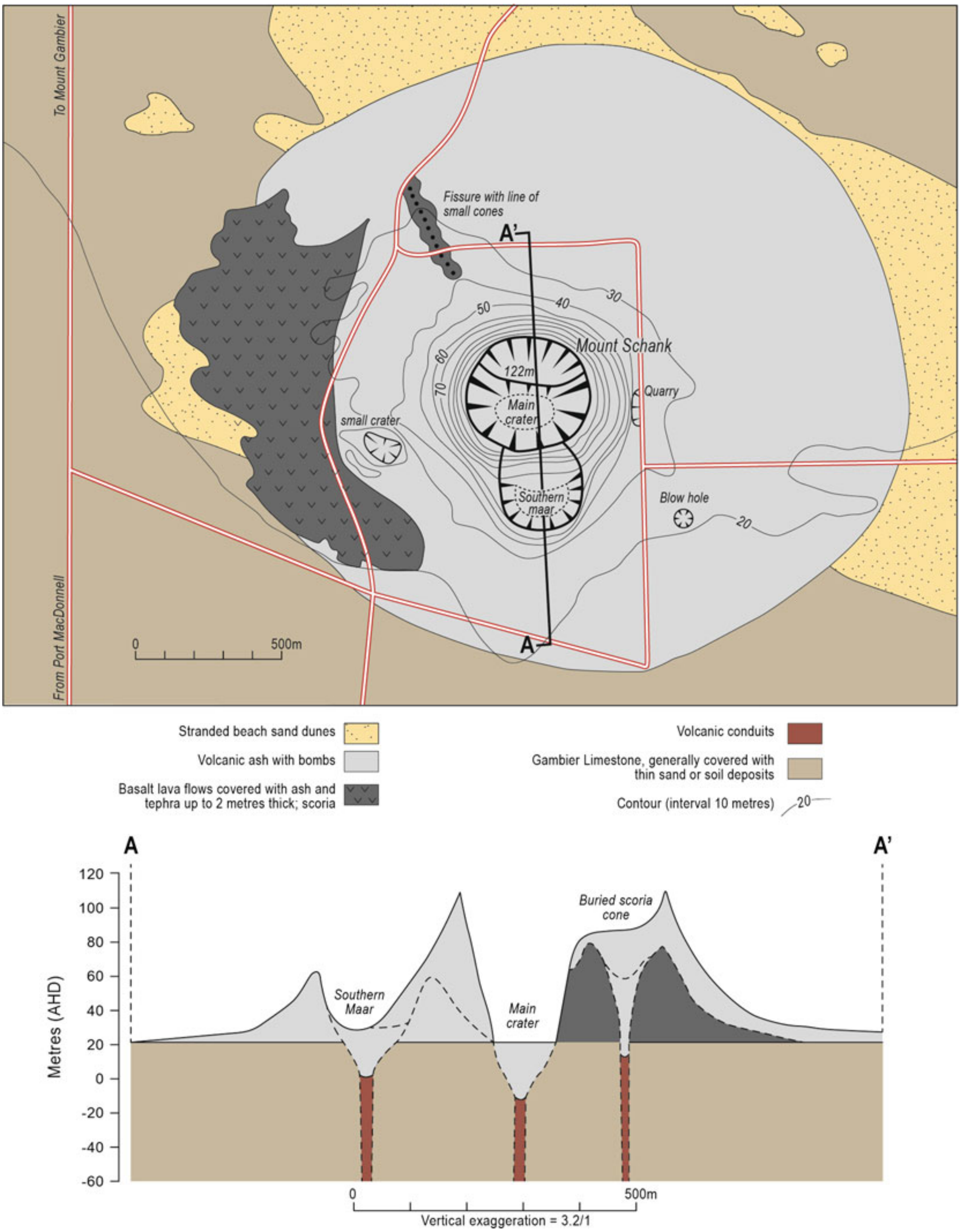

Fig. 4.6 Map of Mount Schank complex after Sheard (1983, 1995)

Schank. They represent air-fall scoria from an essentially continuous episode of phreatomagmatic eruption. Mount Schank erupted on the immediate seaward side of Burleigh Range, a coastal barrier of penultimate interglacial age (Murray-Wallace et al. 1996; Blakemore et al. 2015).

Fig. 4.7 A cinder cone on the northern margin of Mount Schank (*Photograph* Murray-Wallace 1995)

Several distinct volcanic episodes have been identified in the eruption histories of Mount Gambier and Mount Schank (Sheard 1978, 1995; van Otterloo and Cas 2013; van Otterloo et al. 2013). The phases of volcanism at Mount Gambier commenced from about 4.8 to 4.4 ka ago (Sheard 1978; Robertson et al. 1996). The initial phase involved the formation of maars due to the release of steam resulting from the interaction of magma with ground waters in the Gambier Limestone. The volcanic vents were initially 25–100 m in diameter with surrounding ramparts up to 10 m high (Sheard 1978). A thin but well-defined stratum of ejectamenta is associated with this first phase of volcanism. The basal portion contains abundant country rock dominated by Gambier Limestone set within volcanic ash, which is in turn overlain by finely laminated volcanic ash with lapilli. A second phase of activity involved the extrusion of lavas in a passive Icelandic style of volcanism. The lava flows were constrained by the coastal barrier landforms of the Mount Gambier and Glenburnie Ranges (Fig. 2.20). The third phase of activity in the first major volcanic episode was more violent and of Strombolian character producing a scoria cone in the western side of the volcanic complex.

A second period of volcanism at Mount Gambier was inferred by Sheard (1978) to have commenced from about 1.5 ka ago based on a radiocarbon age which most likely represents an underestimate of the true age of the volcanic succession. In the absence of evidence for a prolonged break in volcanism, van Otterloo et al. (2013) concluded that the volcanic episodes occurred relatively continuously. The latter events were more violent than the earlier period of activity and also involved three phases of eruption. The first phase commenced in the area of the Blue Lake and between Valley and Leg of Mutton Lakes. Tuff agglomerates were deposited during this phase of activity with some volcanic clasts reaching up to 2 m in diameter. The second phase was characterised by the most intense volcanism, with numerous conduits merging to form larger eruption centres. Volcaniclasts within the tuff agglomerates include fragments of Gambier Limestone, flint of diagenetic origin from the Gambier Limestone, and marcasite, a dimorph of pyrite. Volcanic materials include volcanic bombs consisting of course grained olivine crystals with chilled margins of basalt, lapilli, cinders and ash. The third and final phase of activity followed the continued influx of water to the volcanic conduits, leading to the eruption of Leg of Mutton crater and the destruction of much of the crater rim of Valley Lake. A minimum volume of erupted material of 3.25×10^8 m^3 has been estimated that included 0.60×10^8 m^3 of country rock consisting of Gambier Limestone and granodiorite from the crystalline basement (van Otterloo and Cas 2013; van Otterloo et al. 2013).

The magnitude of the eruption at Mount Gambier is considered to have had a Volcanic Explosivity Index (VEI) of 4, but with a lower height in the plume of volcanic ejecta of approximately 5–10 km (van Otterloo and Cas 2013). The magnitude of the eruption is also considered to have been similar to the Hawaiian to phreatomagmatic style of Eyjafjallajökull in Iceland in 2010.

4.4 Petrography and Geochemistry of the Newer Volcanics

Low maars, lava flows and scoria cones developed before a series of dramatic phreatomagmatic explosions in the Newer Volcanics in both the Mount Burr Volcanic Group and Mounts Gambier and Schank. Ash, lapilli and bomb ejecta formed layered deposits up to 8 km from the source vents, with an estimated tephra volume of c. 1.3 km^3 ejected. Based on their ages, basaltic cryptotephra horizons dated at 4589–3826 yr cal BP and 7149–5897 yr cal BP within the lacustrine sediments of Lake Keilambete, are most likely derived from either Mounts Gambier or Schank, some 200 km to the west, reflecting the dominant winds at the time of deposition (Smith et al. 2017). The dimensions and volcano-sedimentary structure of the Blue Lake Crater indicate that this was the largest phreatomagmatic explosion (Sheard 1995). Mantle-derived Cr-diopside lherzolite (composed chiefly of olivine, orthopyroxene and clinopyroxene) xenoliths and non-igneous country rock (e.g. Oligo-Miocene Gambier Limestone) fragments are common in the tephra (Fig. 4.8). Clinopyroxene phenocrysts formed within the groundmass of basalts at 1105–1224 °C (Demidjuk et al. 2007). The presence of spinel-lherzolite xenoliths in some of the basalts from Mount Gambier reveal that the magmas quickly rose through the crust with minimal interaction with the country rock.

The volcanic materials of the Mount Burr Volcanic Group have alkaline basalt affinities and range from K-rich nepheline hawaiite at Mount Burr to olivine analcimite at Mounts Watch, McIntyre and The Bluff (Irving and Green 1976). Mantle-derived lherzolite xenoliths, typically green and granular in texture, are present in lava flows and as volcanic bombs and lapilli (20–500 mm in diameter) within the tephra. Non-igneous lithologies are common within the tephra, particularly fragments of the Gambier Limestone.

The volcanic eruptions at Mount Schank were initiated along a major fracture in the Gambier Limestone, initially in the form of extrusive ash deposition (Sheard 1995). This was followed by extrusion of lava which covered an area of approximately 300,000 m^2 with an average thickness of 3.5 m. The final phase of eruption was manifested by violent phreatomagmatic explosions producing the main cone. During the volcanic activity, a linear array of scoria cinder cones formed along a fracture in the Gambier Limestone on the north-western flank of the main cone (Fig. 4.7).

Basalts from Mount Gambier are classified as Nepheline Hawaiites while Mount Schank and Mount Burr are classified as K-rich Nepheline Hawaiites (Irving and Green 1976) indicating minimal geochemical differentiation throughout the Quaternary.

X-ray fluorescence analyses on modern soil samples collected within a 12 km radius of Mount Gambier have highlighted the contribution of volcanic ash to soil development.

Fig. 4.8 Volcanic ejecta in an ash fall accumulation on the southern rim of the Blue Lake at Mount Gambier. The large light-coloured clast on the right-hand side of the image is derived from the Oligo-Miocene Gambier Limestone and the large black clast on the left in the same stratum is a volcanic bomb (*Photograph* Murray-Wallace 2017)

Approximately half of the volcanic ash has weathered to clay minerals since eruption some 5000 years ago (Hutton 1974). Volcanic ash has been found encircling Mount Gambier up to 6 km and a maximum distance of 16 km has been documented for some localities (Hutton et al. 1959).

Liquid CO_2 of magmatic origin is currently produced from a 2.5 km deep petroleum exploration well, Caroline #1, some 18 km southeast of Mount Gambier (Chivas et al. 1987; McKirdy and Chivas 1992). In 1987, annual production of CO_2 from the well was 28,000 tonnes. The commercial well produces c. 98% CO_2, c. 1% CH_4 and c. 0.5% N_2). The CO_2 has accumulated within a dome representing an extension of a linear chain of volcanoes that range from Pleistocene to Holocene age. A magmatic origin for the fluid has been proposed in view of its association with centres of known volcanism, $\delta^{13}C_{PDB}$ of −4‰ for the CO_2 and a relatively high ^3He component of the contained helium and high $^3He/C$ ratio (6.4×10^{-10}) (Chivas et al. 1987). It is likely that the liquid CO_2 of volcanic origin may expand rapidly at shallow levels within the Earth's crust and have contributed to the explosive volcanism that characterised the region.

4.5 Age of the Holocene Volcanic Episodes

Determining the age of the volcanic episodes has been difficult as the weathered nature of the volcanic successions has presented a significant challenge to the satisfactory application of geochronological methods. In addition, radiocarbon analyses on charcoal from beneath volcanic ash deposits have yielded some ambiguous results, as some of the materials appear to relate to modern plant root systems that have been burnt in more recent fires (Blackburn 1966; Blackburn et al. 1982). Analyses of older charcoal within palaeosols considered likely to pre-date the volcanic episodes have yielded an age of 18,100 ± 350 yr BP (ANU-646) on 'soft charcoal in discrete fragments' from a buried soil draping the Burleigh Range, a penultimate interglacial barrier (Joyce 1978, p. 365). It is also of note that some of the early reported radiocarbon analyses (Blackburn 1966) had not used a sodium hydroxide wash to remove humic acids, thereby representing a potential source of modern contamination.

Radiocarbon ages on charcoal buried beneath volcanic ash (Blackburn et al. 1982) and palaeomagnetic data reported by Barbetti and Sheard (1981), suggest that the Mount Gambier eruptions commenced between 5 and 4.3 ka ago. The radiocarbon ages for the charcoal samples subjected to a more rigorous sample pre-treatment strategy, involving both acid and alkali washes, ranged from 6500 ± 240 yr BP to 3310 ± 200 yr BP. Three of the samples were also modern and most likely relate to modern tree roots, burnt since European settlement, but indistinguishable from older charcoal during sampling. Based on two samples collected closer to the Mount Gambier volcanic centres, Blackburn et al. (1982) concluded that the two principal eruptions identified by Sheard (1978) occurred between 4000 and 4300 years BP. The palaeomagnetic directions determined on basalts from Mounts Gambier and Schank suggest that they differ in age by three centuries or slightly greater (Barbetti and Sheard 1981).

In a study of ostracod ecology and the chemistry of ostracod valves from sediment infill of the Blue Lake at Mount Gambier, Gouramanis et al. (2010) reported a radiocarbon age on ostracod calcite of 6890 ± 190 yr BP (ANUA36030) at a depth of 2.08 m from a core. The dated sample horizon comprised moderately laminated clay and provides a minimum age for volcanism. Paired radiocarbon measurements on charcoal and ostracod calcite in the same core revealed that the ostracod calcite had reservoir ages that ranged between 800 and 2800 years older than contemporaneous organic material such as plant fibres. The sediment beneath core interval 242.5 cm consisted of homogeneous dark brown mud devoid of ostracods and containing reworked pollen derived from the Oligo-Miocene Gambier Limestone. A modern water sample collected from the Blue Lake yielded a radiocarbon age of 2395 ^{14}C yr BP (Gouramanis et al. 2010). Collectively, these results corroborate a mid-Holocene age for the eruption of Mount Gambier.

The timing of the onset of volcanism at Mount Gambier was questioned by Leaney et al., (1995), based on radiocarbon dating of inorganic and organic carbon fractions of sediments from the Blue Lake. Leaney et al. (1995) concluded that Mount Gambier is considerably older than previously indicated on the basis of dating ejectamenta from the volcano (Blackburn 1966; Blackburn et al. 1982) and suggested a minimum age of 28 ka. Despite the careful study by Leaney et al. (1995) there remains the possibility that they underestimated the amount of detrital and authigenic contamination of calcium carbonate, depleted in ^{14}C that may have been incorporated into the Blue Lake sediments from external sources such as the Gambier Limestone, thus yielding an apparently older radiocarbon age.

Robertson et al. (1996) derived a thermoluminescence (TL) age of 4.2 ± 0.5 ka based on the analysis of baked tuff underlying a lava flow at Valley Lake, a prominent crater immediately to the west of Blue Lake at Mount Gambier. They also noted the possibility of an earlier event at about 7 ka. The TL ages are consistent with magnetic remanence and susceptibility analyses on organic mud from Valley Lake which indicate the absence of volcanic eruptions over the past 5 to 6 ka (Barton and McElhinny 1980).

The Mount Schank volcanic centre, a hybrid maar-cone structure, is an order of magnitude smaller in volume than Mount Gambier. While palaeomagnetic measurements by Barbetti and Sheard (1981) indicated a range of possible ages from >7 to 1 ka, they demonstrated that Mount Schank was not contemporaneous with Mount Gambier. TL dating of penultimate interglacial

(MIS 7) marine sands of the Burleigh Range, directly beneath a lava flow associated with Mount Schank was undertaken by Smith and Prescott (1987). The sample site within a former basalt quarry on the western flank of Mount Schank has since been destroyed and subsequently infilled and the landscape rehabilitated without trace of the quarry. The TL age of 4930 ± 540 years for the heating event and basalt extrusion indicates that major vent-clearing phreatomagmatic explosions during this eruption created a broad cone with both maar and cone crater characteristics.

No modern eruptions have been observed although an Aboriginal legend about Craitbul's ovens suggests people witnessed these events in the province during Holocene time (Smith 1880; Roberts and Mountford 1975). According to the legend, a giant named Craitbul, his wife and sons created the edifices as cooking ovens using a large wooden digging stick. Their first camp was at Mount Muirhead. One night they were attacked by a bird called 'bullin' and thus ventured south creating another oven at Mount Schank. One night they heard the sound of bullin and abandoned Mount Schank and travelled inland to Mount Gambier. After a while, water rose within the edifice and extinguished the fire and Craitbul created yet another oven. In total he had created four ovens. The widespread occurrence of shell middens of early-middle Holocene age along the coastal landscapes of the Coorong Coastal Plain (Luebbers 1978; Cann et al. 1991; Cann and Murray-Wallace 1999 and see Chap. 3) attest to a human presence within the broader region coinciding with the volcanic episodes.

Sprigg (1959) linked two strong earthquakes centred on Kingston in 1887 and Robe in 1948 with presumed 'submarine lava flows' offshore from Beachport. Such a link has yet to be confirmed by sampling and palaeomagnetic measurements. The volcanic province is seismically active and is believed to be the driving force behind Quaternary upwarp of this region (Murray-Wallace and Belperio 1991; Murray-Wallace et al. 1996). Thus the province can be considered to be dormant rather than extinct. Using available geochronological data and eruption probability equations, the volcanic hazard is calculated to be <2% for an eruption in the next 100 years (Sheard 1995).

4.6 Neotectonism

Neotectonism refers to geologically recent tectonic movements within the Earth's crust. Bates and Jackson (1987) define neotectonism as the post-Miocene geological history and structures of the Earth's crust. The style of neotectonic behaviour may involve gradual ductile deformation producing regional fold structures, more rapid brittle fracture characterised by vertical or horizontal displacements, or a combination of these modes of displacement with some associated folding in the form of fault drag.

Regional in situ stresses within the Indo-Australian Plate in southern Australia (Sandiford 2003), and local Quaternary volcanism with associated crustal doming in the vicinity of the Mount Burr Volcanic Group and Mount Gambier and Mount Schank (Fig. 4.9) has resulted in epeirogenic uplift of the Coorong Coastal Plain. The general pattern of subsidence in the north-western portion of the coastal plain, in the region of the River Murray Mouth, adjacent to the uplifted Mount Lofty Ranges, and the progressive uplift in the south-eastern portion of the coastal plain, towards the Quaternary volcanic complexes accords with the present day trend in maximum horizontal tectonic stress within this region of the Australian continent (Rajabi et al. 2017). The volcanism resulted from Australia drifting over a mantle hotspot (more strictly, a hot region). Genetically related volcanism can be traced into Victoria and New South Wales (Sutherland 1983; Sutherland et al. 2014).

The region from Robe, south-east to Mount Gambier has experienced two of South Australia's largest earthquakes (Greenhalgh et al. 1986). The Beachport-Kingston SE earthquake of 10th May 1897 is considered to have registered a magnitude of 6.5 and the Robe earthquake of 8th April 1948 registered 5.6. Their epicentres are considered to have been located between 16 and 32 km north-west of Beachport

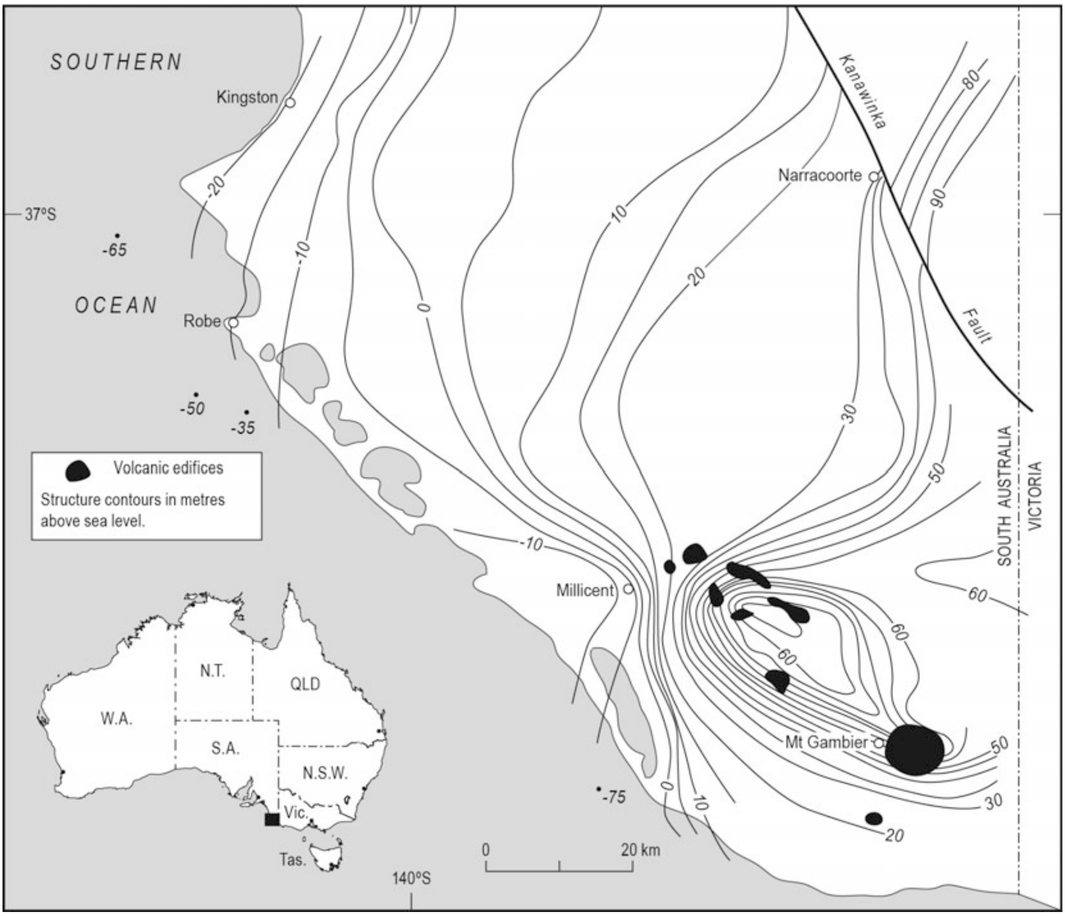

Fig. 4.9 Sub-crop map of the upper surface of the Oligo-Miocene Gambier Limestone (Cook et al. 1977) and its relation to the distribution of Pleistocene and Holocene volcanic centres (Sheard 1995). A regional dome structure, the 'Gambier Upwarp' *sensu* Sprigg (1952) is evident, relating to the intrusion of magma within the upper crust

(Sprigg 1959). Numerous earthquakes with magnitudes between 3 and 4 have been recorded offshore from Robe and Mount Gambier, in the continental slope environment (Greenhalgh et al. 1986). The 1897 earthquake was recorded as far west as Streaky Bay on Eyre Peninsula and in Melbourne, some 600 km to the east in Victoria (Sutton et al. 1977). The 1948 earthquake was felt up to 400 km from the epicentre. Numerous buildings were cracked, clocks stopped and crockery dislodged from shelves (Sprigg, 1959). Sprigg (1959) speculated that these earthquakes were related to the position of three south-west-trending linear features on the Bonney Shelf, 16–32 km long, which he presumed to be submarine lava flows related to the Mount Gambier and Mount Schank phase of volcanism.

In an investigation of the seismicity of the region, four earthquake epicentres were found to be aligned with the general trend of the volcanic edifices between the Mount Burr Volcanic Group and Mounts Gambier and Schank (Sutton et al. 1977). Sutton et al. (1977) also noted that the earthquake foci occurred predominantly at the boundary of the Lower Cretaceous strata defining the margin of the Otway Basin.

The crustal dome structure associated with the Newer Volcanics (Mount Burr Volcanic Group and Mounts Gambier and Schank) is highlighted by the form of the upper surface of the Oligo-Miocene Gambier Limestone (Fig. 4.9). The sub-crop map of the upper-bounding surface of the Gambier Limestone reveals an elongate dome structure trending NW-SE concentrated between these two volcanic groups. The crest of the structure, which occurs midway between these two volcanic groups occurs at just over 80 m APSL. Approximately 40 km to the SW of the crest of the dome structure, the upper surface of the Gambier Limestone occurs at 75 m BPSL (Fig. 4.9). When traced in a north-north-westerly direction from Millicent, the gradient of the upper surface of the Gambier Limestone in sub-crop is similar to that noted for back-barrier and palaeoshoreline facies of the last interglacial (MIS 5e) Woakwine Range (Murray-Wallace et al. 1996, 1998; Fig. 4.10). Collectively, these observations reveal that Quaternary volcanism and the emplacement of magma chambers within the Earth's upper crust were major contributing factors in epeirogenic uplift. The location of the fold culmination between these volcanic groups also points to the occurrence of additional crustal intrusions that do not have a direct extrusive, volcanic expression.

Palaeo-shorelines associated with specific interglacial highstands provide valuable datums for mapping spatial variations in epeirogenic uplift (Fig. 4.10). The last interglacial shoreline (MIS 5e) is particularly useful, as deposits of this age occur extensively along the Australian coastline and sufficient time has elapsed since the interglacial for even modest uplift to be quantified.

Murray-Wallace and Belperio (1991) documented an Australian datum of 2 m APSL for a eustatic (ice-equivalent) sea level during the Last Interglaciation and quantified differential neotectonic movements that had occurred around Australia since the Last Interglacial Maximum (MIS 5e; 125 ka). Subsequent work on Eyre and Yorke Peninsulas in southern Australia revealed that sea level during the last interglacial is likely to have been higher than previously considered and somewhere between 2.1 ± 0.5 to 4.8 ± 1 m APSL and possibly over different time intervals during the interglacial (Murray-Wallace et al. 2016; Pan et al. 2018).

The Coorong Coastal Plain records some of the most significant variations in last interglacial shoreline elevations in Australia, a continent that otherwise shows a high degree of tectonic stability (Murray-Wallace 2002; Fig. 4.11). At Salt Creek, the height of last interglacial shoreline facies of the Woakwine Range is 3 m APSL, indicating minimal post-depositional uplift at this site, as the shoreline elevation is similar to last interglacial successions from western Eyre Peninsula, which occur within the tectonically highly stable setting of the Archean to Mesoproterozoic Gawler Craton (Murray-Wallace et al. 2016). The elevation of the last interglacial beach and back-barrier estuarine-lagoon facies rises progressively along the length of the

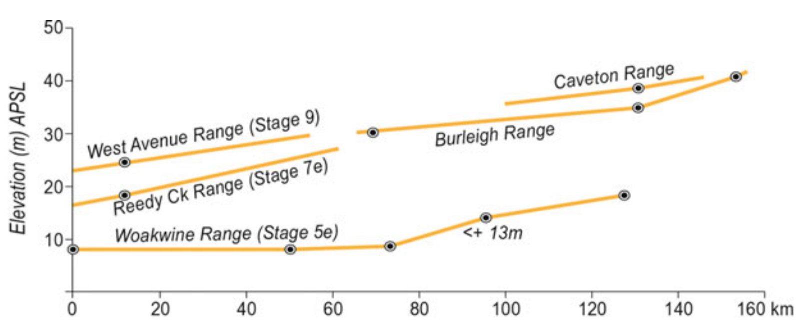

Fig. 4.10 Spatial variation in shoreline elevation in metres above present sea level (APSL) for the West Avenue, Reedy Creek and Woakwine Ranges (Robe area) and Caveton, Burleigh and Woakwine (MacDonnell) Ranges, Mount Gambier area based on data reported in Murray-Wallace et al. (1996)

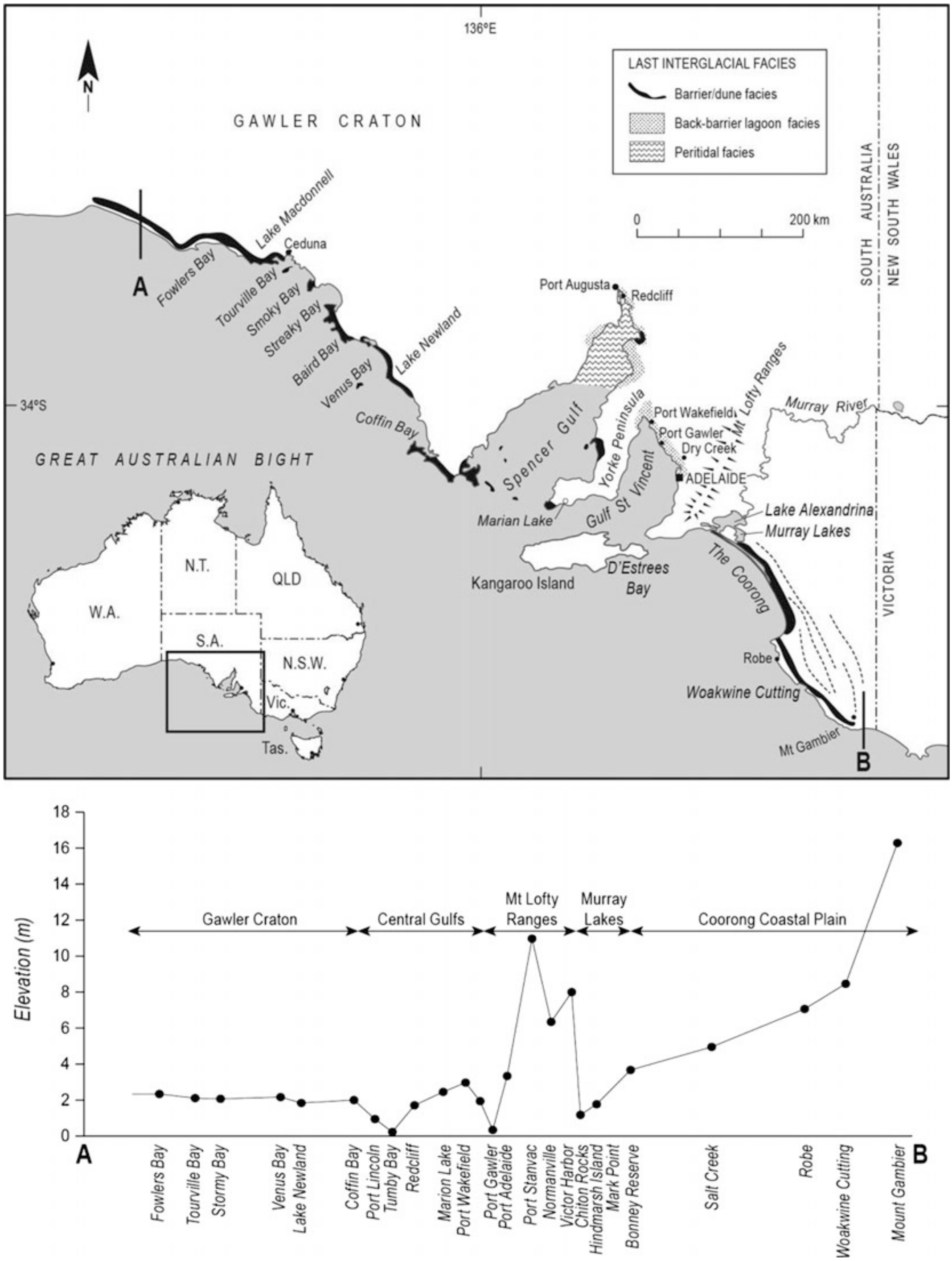

Fig. 4.11 Elevation of last interglacial (MIS 5e) shoreline successions in southern Australia illustrating the effects of neotectonism at various sites along this passive margin (Murray-Wallace 2002)

Woakwine Range south from Salt Creek to near Mount Gambier. Near Beachport in the McCourt Cutting within the Woakwine Range, littoral and back-barrier facies rise from 6.4 to 11.6 m APSL, uncorrected for tectonic uplift (Murray-Wallace et al. 1999). Approximately 24 km south-west of Mount Gambier equivalent shoreline facies occur at 18 m APSL (Murray-Wallace et al. 1996).

North of Salt Creek the barriers coalesce in a transition zone from minimal uplift to an area of basin subsidence closer to the Mount Lofty Ranges and River Murray Mouth area. In the northern-most region of the coastal plain, foreshore facies of the Woakwine Range crop out on the immediate landward side of the Coorong Lagoon with abundant fossil molluscs of the Goolwa cockle *Donax deltoides* and *Spisula* (*Notospisula*) *trigonella*. The successions occur at 2 m APSL (Bourman et al. 2000). At Goolwa equivalent facies occur at 0.8 m below present sea level (BPSL) and on western Hindmarsh Island at 0.9 m APSL (Bourman et al. 2016).

Similar systematic variations in palaeo-shoreline elevations occur along the older Pleistocene shorelines (Hossfeld 1950; Sprigg 1952). Local datums for MIS 7 and MIS 9 palaeosea-levels are documented by Belperio (1995). Near Robe, the lagoon facies of the Woakwine Range occurs at 8 m APSL indicating an average uplift rate of 50 mm/ka for this portion of the coastal plain. Inland, the Reedy Creek Range (MIS 7) at 18 ± 1 m APSL and the West Avenue Range (MIS 9) at 24 ± 1 m APSL indicate slightly higher, longer-term rates of uplift of 80 mm/ka. However, the uncertainties inherent in interpreting and measuring palaeo-shoreline elevations of the older barriers suggest that an uplift rate for the Robe region of 70 mm/ka based on all data, as previously determined by Schwebel (1978, 1984) and Belperio and Cann (1990) is more representative than measurements from individual shorelines. At the southern-most extremity of the Woakwine Range near Mount Gambier, shoreline facies occur up to 18 m APSL, indicating close to 16 m of uplift since the Last Interglacial Maximum with an uplift rate of 130 mm/ka, based on a TL age of 132 ± 9 ka for the last interglacial Woakwine Range (Huntley et al. 1994). Longer-term uplift rates for the Burleigh and Caveton Ranges are similar, being 140 and 120 mm/ka respectively; thus the uplift rates since the late Middle Pleistocene at least, have always been faster near Mount Gambier and nearly double that of the area around Robe (Murray-Wallace et al. 1996). These data thus indicate significant spatial variations in the rates of neotectonic uplift along the coastal plain. As more specific palaeo-shoreline data become available for the older barriers, it may be possible to document temporal variations in uplift more rigorously.

4.7 Summary and Conclusions

The southern-most portion of the Coorong Coastal Plain is the only area of the coastal plain that experienced Quaternary volcanism. The volcanism is related to two spatially and temporally distinct episodes which are genetically related to the intra-plate volcanism of the eastern Australian margin (Newer Volcanics of western Victoria). The older Mount Burr Volcanic Group influenced the spatial configuration of the coastline at least since earliest Middle Pleistocene time. The volcanic edifices would have represented an island archipelago extending up to 44 km offshore from the Kanawinka Fault scarp on the inner continental shelf during deposition of the West Naracoorte Range. The volcanic islands would have acted as focal points influencing the geometry of coastal barrier deposition for four interglacials, producing a major tombolo structure (cuspate foreland), from the time of formation of the West Naracoorte Range (MIS 19; ≤ 781 ka) to the Glenburnie Range (MIS 13; c. 500 ka). In contrast, the middle Holocene age volcanoes Mount Gambier and Mount Schank post-date the Bridgewater Formation and did not influence coastal sedimentation as they erupted through pre-existing coastal barrier successions of Middle Pleistocene age. Despite their contrasting age little geochemical differentiation is evident in the volcanic ejecta from the Mount Burr and Mount Gambier and Schank volcanic complexes. In a subtle manner, the younger volcanic complexes may have also contributed to the differential shoreline elevations of the younger coastal barriers such as the last interglacial MacDonnell Range (equivalent of the Woakwine Range) and Robe Range as magma intruded the Earth's upper crust as attested by the domed upper bounding surface of the Gambier Limestone.

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5 Soils, Palaeosols, Calcrete and Karst

Abstract

Landforms associated with karst weathering are extensively developed on the Oligo-Miocene Gambier Limestone in the Mount Gambier region and within the Pleistocene Bridgewater Formation across wide areas of the Coorong Coastal Plain in southern Australia. More complex and mature karst weathering features have developed on the Gambier Limestone due to its more highly cemented and jointed nature. Karst landforms associated with the Gambier Limestone include cenotes, limestone pavements, karren, solution depressions and underground drainage and cave systems. The karst forms have developed on a marine abrasion surface that has resulted from multiple marine transgression flooding events associated with Quaternary interglacial sea level highstands and forced regressions. At Naracoorte, several well-developed caves contain sediments which preserve the fossil remains of Pleistocene vertebrate fauna. The fossils record a richly diverse assemblage of both extinct and extant animals, ranging from giant browsing marsupials to various small amphibians and reptiles. Excluding the ubiquitous occurrence of calcrete, six principal soil groups occur across the coastal plain that includes Podzols, Humus Podzols, Rendzinas, Solodized Solonetz, Terra Rossa and Calcareous Sands. The degree and nature of soil development and spatial distribution is directly related to coastal barrier morphology, composition and age of different sedimentary facies and the prevailing regional Mediterranean climate. Calcretes, strongly indurated accumulations of calcium carbonate, are particularly well-developed within the Bridgewater Formation across much of the coastal plain and record a complex record of subaerial exposure and prolonged periods of pedogenesis in dryland conditions.

Keywords

Calcrete · Karst topography · Pedogenesis
Palaeosols

5.1 Introduction

The Coorong Coastal Plain in southern Australia is host to a variety of karst landscape features and preserves a complex succession of calcretes and palaeosols and a distinctive assemblage of soils.

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The long history of coastal landscape evolution throughout the Quaternary means that these features can be seen at different levels of development across the coastal plain. Soils have progressively developed over the calcarenite ranges and interdunal flats throughout the Quaternary. Exact distinction between modern (ongoing) soil development and palaeosols is not always easy to establish particularly where thick calcareous soils including calcretes occur at the land surface. Buried relict soils (palaeosols) can be more confidently identified. Palaeosols are soils of the geological past indicative of periods of landscape stability or cessation of sedimentation. Protosols, less well-developed soil horizons, are also present within the Pleistocene Bridgewater Formation. They indicate shorter periods of landscape stability, limited sedimentation and relatively prolonged subaerial exposure of aeolianite successions but with less intense soil development. Collectively palaeosols and protosols may indicate climatic conditions different from the present. Calcretes represent one of the most common pedogenic features across the coastal plain.

5.2 Calcretes

Calcrete accumulations (palaeosols) are particularly well-developed within the relict barrier successions of the Coorong Coastal Plain and highlight major erosional truncations within the calcarenite successions (Fig. 5.1). Calcretes are indurated accumulations of calcareous sediment that have formed through the concentration of calcium carbonate by pedogenic processes. Calcretes occur as a protective cap rock over extensive areas of the coastal plain (Fig. 5.2) as well as buried within portions of the Bridgewater Formation on surfaces

Fig. 5.1 A representative example of a calcrete pavement developed on moderately cemented aeolian dune sediments of a portion of the Robe Range barrier at Cape Dombey (Robe III in the stratigraphical terminology of Schwebel 1978, 1983, 1984). The sedimentary succession relates to the Late Pleistocene warm interstadial MIS 5c which occurred 105 ka ago. The blocky and laminar calcrete acts as a protective capping to the aeolianite succession and has helped to preserve the original dune morphology (*Photograph* Murray-Wallace 2017)

Fig. 5.2 Caprock of calcrete on the seaward side of the last interglacial (MIS 5e) Woakwine Range, northern Hindmarsh Island, southern Australia. The calcrete has been subject to minor karst weathering and resulted in the formation of low relief solution depressions (*Photograph* Murray-Wallace 2010)

of unconformity. The subaerially exposed forms have a long history of development and given their continued surface exposure means that they are not necessarily relict features and may be subject to continued pedogenesis.

Calcrete formation involves leaching and re-precipitation of calcium carbonate in the vadose zone, with increasing alteration of the primary physical characteristics of the sedimentary successions on which calcretes have developed (Milnes and Hutton 1983). In addition, there is an aeolian contribution to calcrete development as originally speculated by Crocker (1946). Microids, pisoids and a micritic carbonate matrix result from grain micritization and illuviation of calcium carbonate.

The processes involved in the formation of calcretes are complex and site dependent. They may involve the capillary rise of calcium carbonate in solution through a soil profile and evaporative loss of water leaving a residue of calcium carbonate, the concentration of carbonate through downward movement of water (illuviation), and in settings of variable relief, the erosion and re-deposition of carbonate nodules within landscape depressions (Milnes and Hutton 1983; Chen et al. 2002). The Mediterranean climate of the region, characterised by hot, dry summers and cool, wet winters means that these contrasting processes of concentration of calcium carbonate will vary with the seasons (evaporative concentration dominating in summer and illuviation in winter).

Carbonate pedogenic profiles formed on and within the Bridgewater Formation vary greatly in morphological characteristics, thickness and induration. They include chalky, peloidal, nodular and laminar calcrete forms that reflect variable degrees of soil development, truncation and alteration (Hutton and Dixon 1981; Warren 1983; Farrand and Belperio 1987; Belperio 1988; Phillips and Milnes 1988). Lithification of the differentiated horizons to form carbonate hard pans with a high preservation potential is a common polygenetic end process (Fig. 5.3). Also common are reworked

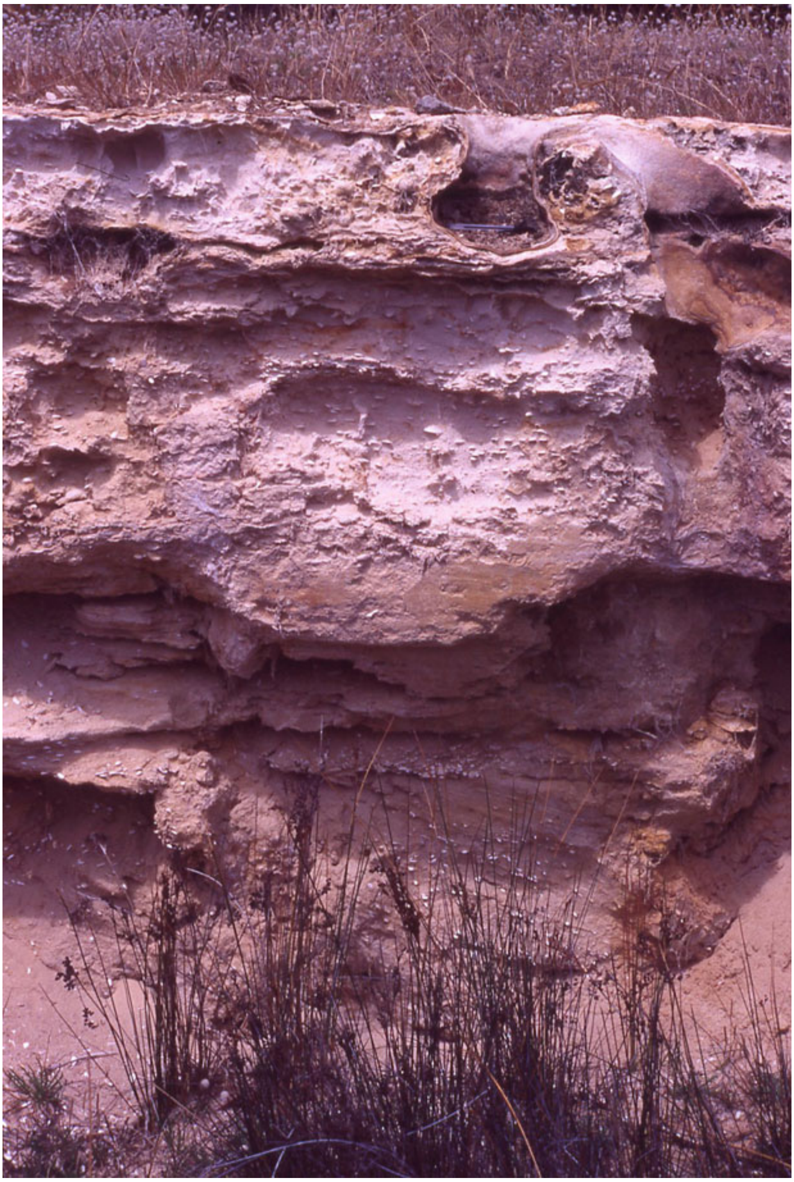

Fig. 5.3 Strongly-indurated laminar calcrete profile developed on richly-fossiliferous, back-barrier, estuarine-lagoon facies of the Late Pleistocene Glanville Formation, north-western Hindmarsh Island. The field site is situated adjacent to the River Murray on the northern Coorong Coastal Plain, southern Australia. The pen for scale within the solution depression is 15 cm long (*Photograph* Murray-Wallace 2002)

lithoclast horizons, rhizomorphs (rhizocretions – plant root replacement features) and truncated profiles. In general, grain alteration, cementation and matrix occlusion within the Bridgewater Formation aeolianites (calcarenites) decrease over a few metres down the pedogenic profile to reveal original textures and bedforms associated with littoral or aeolian sedimentation.

The calcrete successions of the Coorong Coastal Plain effectively blanket the regional landscape and act as a protective capping to the coastal barrier landforms, characteristically preserving the original morphology of the large-scale dune forms (20–30 m high and up to 100 s m long within barriers that extend up to 3 km across; Fig. 5.1). The calcrete profiles are commonly between 1 to 3 m thick. Rhizomorphs and joint infills of calcium carbonate are a common element of the calcretes. As within wider parts of southern Australia, the calcrete profiles have a range of morphologies that include multi-layered laminar forms, pisolitic units capping blocky calcrete, breccia-like carbonate lithoclast deposits, strongly indurated pisolitic and concretionary calcrete, and rhizomorph-rich calcareous units in which the rhizomorphs are accentuated by cavernous weathering (Milnes and Hutton 1983; see Fig. 2.4).

Schwebel (1978), Belperio (1988) and Phillips and Milnes (1988) have demonstrated a cyclic repetition of calcrete formation in the coastal sedimentary sequences of southern Australia. The calcrete profiles developed on the barrier shoreline complexes of the Coorong Coastal Plain are not time equivalent as originally considered by Firman (1973) but time transgressive, having initially formed during glacial cycles immediately following the interglacial in which each barrier formed, with further pedogenesis superimposed during subsequent glacial-interglacial cycles. Although an increase in the intensity of calcrete development with barrier age is noticeable landwards across the coastal plain, there are insufficient distinctive criteria to distinguish age relationships on pedogenic features alone. The early stages of soil development on the Holocene dunes of Younghusband Peninsula, is evident in the form of networks of rhizomorphs. The rhizomorphs highlight former periods of dune stabilization by vegetation and that calcrete development is a rapid and ongoing process (see Fig. 3.4).

Calcretes of the Coorong Coastal Plain are associated with two Great Soil Groups; Podzols with well-developed siliceous sand profiles and *terra rossa* with a distinctive uniform red earth profile (Blackburn et al. 1965; Blackburn 1983 Fig. 5.4). In both Groups, there are sharp transitions to underlying, case-hardened limestone (calcrete) and a more diffuse transition to the parent weakly consolidated calcarenite.

5.3 Soils of the Coorong Coastal Plain

At the regional landscape scale, excluding the ubiquitous occurrence of calcrete, six distinct soil-landform associations have been identified across the Coorong Coastal Plain, as well as several soil types with a more restricted occurrence (Blackburn 1959; Blackburn et al. 1965; Blackburn 1983; Lowe and Palmer 2005; Fig. 5.4). The principal soil groups that cover much of the coastal plain include Podzols, Humus Podzols, Rendzinas, Solodized Solonetz and Solodic soils, Terra rossa soils and Calcareous Sands. The soils have a distinct spatial distribution related to physical landscape setting and underlying parent rock (sedimentary facies). In the most general sense, the soil associations are predominantly related to formation on Quaternary aeolian dune sands of coastal barriers, or back-barrier, estuarine-lagoon facies. The degree of soil development across the coastal plain also relates to their age.

In view of the limited diversity of country rock, it may at first appear surprising, the variety of soil types within the region. Despite the seemingly uniform nature of the country rock, numerous soil forming processes have contributed to the soil diversity. The translocation of calcium carbonate by groundwater movements and the transportation of fine grained sediment, particularly silt and clay, have been significant in this regard.

5.3.1 Terra Rossa

Terra rossa is essentially a residual soil, derived from the acid-insoluble residue of the underlying parent calcarenite although with a possible contribution of silt and clay by aeolian accession from adjacent lacustrine plains (Blackburn et al. 1965). Local deflation of sections of the back-barrier flats to form lunettes has also contributed silt and clay, enhancing the development of *terra rossa* soils on the barrier surfaces. Small scale *terra rossa* soil development associated

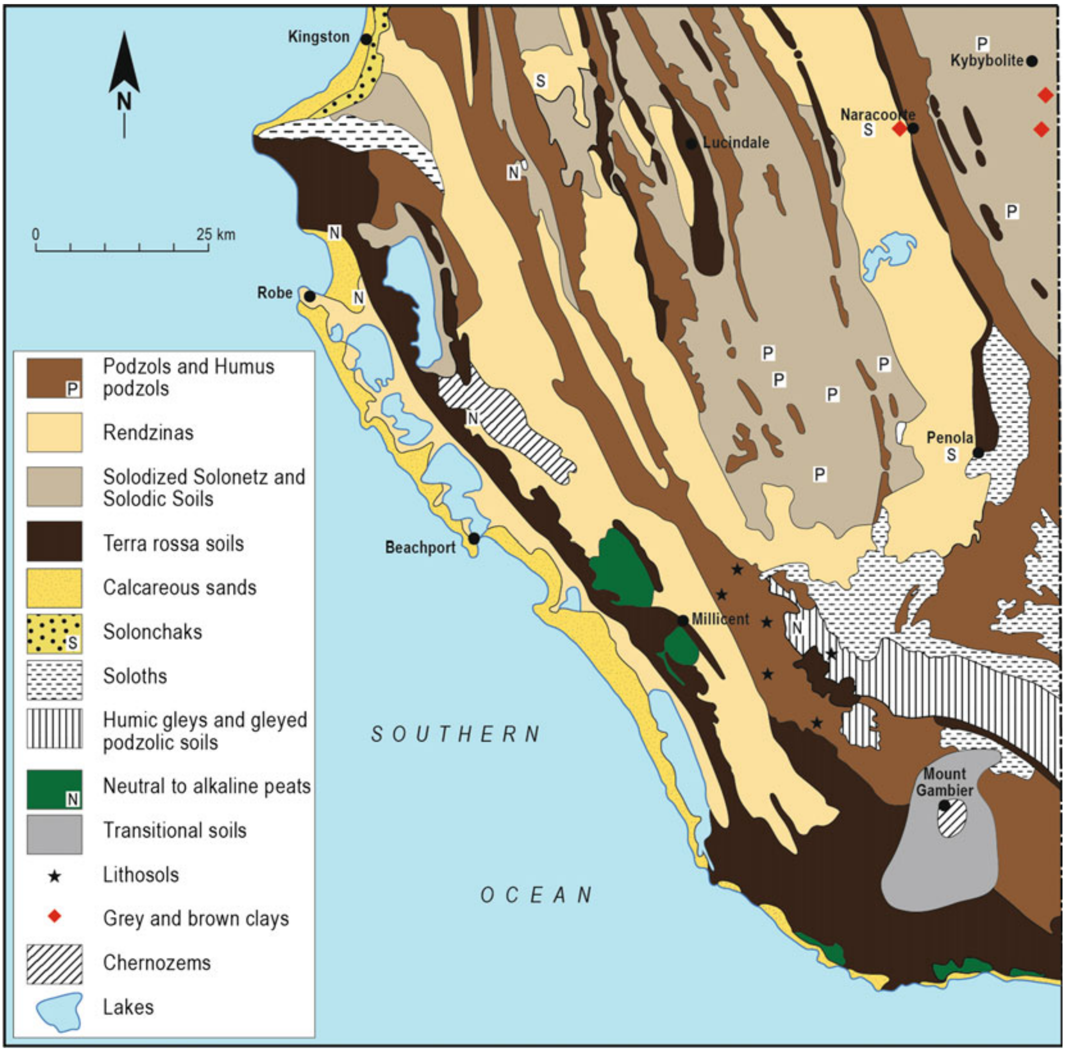

Fig. 5.4 Distribution of the principal soil groups in the southern part of the Coorong Coastal Plain, southern Australia after Blackburn (1983)

with internally draining topographic depressions can be seen in a number of drain cuttings east of Robe. *Terra rossa* soils occur extensively between Coonawarra and Penola where these soils are a critical component of one of Australia's premier wine provinces (Fig. 5.5). *Terra rossa* appears best developed on the seaward toes of the calcarenite barrier landforms (Bridgewater Formation) close to, or associated with younger lacustrine facies (Padthaway Formation). With increasing age of barriers, the *terra rossa* soils show progressively greater depths of development, thicker calcareous illuvial horizons, incipient ferruginous and manganiferous pisolite development and the formation of deeper solution pipes (Blackburn et al. 1965). Solution pipes and other karst features also increase in genetic diversity and complexity with age.

Terra rossa soils occur extensively within the Coonawarra wine province north of Penola.

Fig. 5.5 *Terra rossa* soil profile exposed in Wrattonbully Quarry within the West Naracoorte Range, Coorong Coastal Plain, southern Australia. The *terra rossa* soil has formed on the earliest Middle Pleistocene portion of the Bridgewater Formation. The depth of the limestone—soil contact is highly irregular reflecting differential rates of limestone solution. The in situ *terra rossa* soil is covered by soil relocated during quarry excavation. The total depth of the exposure is approximately 8 m. The quarry is now occupied by a winery (*Photograph* Murray-Wallace 2008)

A well-developed *terra rossa* soil, typical of the region, is exposed within an excavation between Rouge Homme and Wynns Wineries (Fig. 5.6). The soil profile is developed on a Middle Pleistocene occurrence of the Padthaway Formation, a back-barrier lacustrine facies, close to the western toe of the West Naracoorte Range. The section shows the characteristic three-part profile of the *terra rossa* Group; viz uniform red earth/case hardened limestone/parent limestone. A marked unevenness of the lower boundary of the red earth is evident with solution pipes extending down into the parent material. The red soil horizon is typically only 50 cm thick, resting with a sharp contact on the underlying limestone. The soil also fills solution depressions within the limestone, and generally has a neutral to slightly alkaline pH with a low water storage capacity.

5.3.2 Calcareous Sands

Calcareous sands are mainly confined to the areas of Holocene sand such as Sir Richard and Younghusband Peninsulas and the equivalent sand bodies that cover the Pleistocene interstadial barrier Robe Range to the south of Robe. Apart from the presence of calcareous rhizomorphs in places, the sands show minimal evidence for pedogenesis and have formed on the surfaces of coastal barrier landforms younger than 7000 years, coinciding with the cessation of post-glacial sea-level rise. The sands comprise mixed quartz-skeletal carbonate and the profiles are seldom thicker than 30 cm (Blackburn 1983). The calcareous sands have a very low nutrient status given their primary composition. They are also subject to high inputs of salt given the proximity to the modern coastline.

Fig. 5.6 *Terra rossa* soil profile at Wynns Winery, Coonawarra. The soil is developed on the Padthaway Formation, a succession of back-barrier lacustrine facies of Middle Pleistocene age (*Photograph* Murray-Wallace 1996)

5.3.3 Podzols

Podzols tend to occur on the higher relief of many barriers landward of the last interglacial Woakwine Range. These soils are characterised by an upper horizon of ash-grey to white, unconsolidated sand separated by a sharp contact to an underlying horizon of organic matter and iron oxides. The accumulation of iron oxides has resulted from illuviation from the overlying horizon. These soils are common in *Eucalypt* woodlands.

5.3.4 Humus Podzols

Humus Podzols have formed within some of the depressions in the lee of barrier landforms subject to seasonal flooding. They are typically associated with brown to black hardpans at shallow depth (<1 m) popularly referred to as 'coffee rock'. A characteristic Humus Podzol profile in descending order includes a grey sand horizon, overlying bleached white sand, which in turn overlies moderately indurated coffee rock.

5.3.5 Rendzinas

Rendzinas occur within the back-barrier depressions that formerly represented lagoonal-estuarine environments. The sedimentary facies of these environments have higher clay and silt content favouring Rendzina development. Rendzinas are characteristically dark grey to black and show minimal horizon development. The high water contents of these back-barrier depressions have also favoured the development of these soils.

5.3.6 Solodized Solonetz and Solodic Soils

Solodized Solonetz and Solodic Soils are common on the low relief back-barrier, former estuarine lagoonal areas to the south-east of Lucindale. These are examples of texture-contrast soils in which sand or loam sharply overlie clay. The clay horizon may be well-jointed as in the case of Solodized Solonetz or massive without the presence of peds (soil aggregates) beneath Solodic Soils.

5.4 Karst in Paleogene–Neogene and Quaternary Sedimentary Carbonates

The southern-most portion of the Coorong Coastal Plain near Mount Gambier experiences a seasonally wet, humid to sub-humid climate and hosts a variety of temperate climate karst landforms. Karst in the Oligo-Miocene Gambier Limestone is more spectacular and extensive than in the Pleistocene Bridgewater Formation. Karst weathering forms include limestone pavements with solution cups and karren, uvalas (complex enclosed depressions), large cenotes (dolines), and joint-controlled cave systems (Twidale et al. 1983). Karst landforms are less well-developed within the Bridgewater Formation, particularly in the northern portion of the coastal plain which experiences a marginally lower rainfall (<650 mm/year) than in the Mount Gambier area (>750 mm/year). The general lack of surface drainage is a characteristic feature of these karst landscapes, particularly in the Mount Gambier region. The regional landscape of the coastal plain is of consistently low relief amplitude and substantial karst forms such as tower karst are absent.

Syngenetic karst features developed within the calcarenites of the Bridgewater Formation include clay-pots, limestone pavements with karren, horizontal solution features and some cave development along the coast (Sheard 1995) and within the Naracoorte Range.

5.4.1 Cenotes

Cenotes are a distinctive landform of the southern-most portion of the Coorong Coastal Plain in the area surrounding Mount Gambier having formed in the Oligo-Miocene Gambier Limestone (Marker 1976). Cenotes, a form of doline, are broadly circular depressions bounded by vertical, water-smoothed rock walls (Fig. 5.7). Some examples may have overhanging rock and be wider near their bases. The more strongly indurated nature of the Gambier Limestone, a micritic limestone, and presence of well-defined joints within the formation, combined with the higher rainfall of the region have favoured the formation of cenotes. The landforms have developed by the combined processes of sub-surface solution weathering, cavern formation and collapse of the superincumbent rock.

Cenotes are most commonly developed along regional joint sets, particularly at fold culminations in the Gambier Limestone, on the marine abrasion surface between the MacDonnell Range (Woakwine Range equivalent; MIS 5e) and the Burleigh Range (MIS 7) implying that these landforms have primarily developed following the marine regression after the last interglacial maximum (126 to 118 ka; Fig. 2.20). The average surface elevation of the marine abrasion surface on the Gambier Limestone in this region is approximately 20 m APSL. The current piezometric surface in this area is approximately 13 m below the limestone abrasion surface and thus the conditions are optimum for cenote development in this portion of the coastal plain (Marker 1976). Closer to the modern coastline the landscape is only a few metres APSL and the cenotes are drowned and act as springs. Landward of the Burleigh Range and in the vicinity of Mount Gambier, the marine abrasion surface on the Gambier Limestone ranges between 30–40 m APSL. In this area the cenotes are dry. Lower sea levels of the last glacial cycle may have also influenced cenote development by locally controlling the position of the regional water table. Accordingly, a longer history of sea-level oscillations may have been instrumental in the development of cenotes in this region.

Accessible caves in the Mount Gambier area include Tantanoola Cave, with well-developed speleothems, Umpherston Cave, Engelbrecht

Fig. 5.7 Little Blue Lake, an example of a cenote approximately 5 km west of Mount Schank. The circular depression is approximately 50 m in diameter and 6 m deep to water level (*Photograph* Murray-Wallace 1993)

Cave and Mitchell Cave (Cave Gardens, Mount Gambier). Caves intersecting the present day watertable (cenotes) include Little Blue Lake (Fig. 5.7) and Hells Hole, while The Shaft forms a spectacular water-filled collapse chamber with a narrow entrance. The depth to which karst features have developed increase towards the coast due to an increasing thickness of the Gambier Limestone and lower sea levels and water tables during Pleistocene glacial periods.

Within the Naracoorte area numerous caves have formed within Paleogene-Neogene limestones, although some are partly within Pleistocene aeolianites. These include doline to horizontal passage solution and collapse complexes. The best known are at Victoria and Blanche Caves where significant bone-bed fossil deposits are also located (see Sect. 5.4.5).

5.4.2 Limestone Pavements

Extensive limestone pavements of bare, stony ground extending over several tens of square kilometres have developed on the Oligo-Miocene Gambier Limestone to the south of Mount Gambier (Fig. 5.8). The karst pavements are particularly well-developed immediately to the south of the Burleigh Range, extending some 10 km to the present coastline. The pavements initially developed by marine abrasion processes associated with multiple transgressive and regressive episodes during the Middle and Late Pleistocene during successive coastal barrier development. Subsequent prolonged phases of subaerial exposure have resulted in a variety of solution forms on the limestone pavement surfaces including solution cups, karren and joint exploited depressions. Soil is only thinly

Fig. 5.8 Limestone pavement on Gambier Limestone, 11 km south of Mount Gambier. The pavement surface represents a former marine abrasion surface and is now characterised by the highest concentration of cenote development such as the Little Blue Lake (Fig. 5.7). The area depicted occurs between the Penultimate Interglacial (MIS 7) Burleigh Range and the Last Interglacial (MIS 5e) MacDonnell Range (Woakwine Range equivalent) (*Photograph* Murray-Wallace 1996)

developed within the solution depressions on the limestone pavements, commonly less than 10 cm thick. The more limited supply of sediment from the Bonney Shelf has resulted in the concentration of skeletal-carbonate sediment within the coastal barrier landforms, with the absence of calcarenite sediment on the adjacent plains, apart from the development of some beach ridges (relict foredunes) on the seaward sides of some of the barriers such as the MacDonnell Range.

5.4.3 Solution Pipes

Solution pipes are well-developed within the Gambier Limestone. Quarry exposures reveal that some pipes are up to 1 m wide and penetrate down several metres from the ground surface (Fig. 5.9). Many pipes are infilled with *terra rossa* soils (Fig. 5.10). The forms are wider near the ground surface and become narrower with depth. The pipes have clearly formed by solution weathering and cannot be confused with casts of tree trunks as they have formed in shallow water marine limestones, and their general form tapers to a progressively thinner and sharpened base. The initiation of these weathering forms may be structurally controlled and reflect exploitation of regional vertical jointing within the Gambier Limestone.

Solution pipes are also common within the Bridgewater Formation and their size increases with distance landwards across the coastal plain directly related to the progressively older ages of the aeolianite successions and longer periods for karstification (Blackburn et al. 1965; Fig. 5.11).

Fig. 5.9 Linear solution pipes within the Oligo-Miocene Gambier Limestone at Attiwill Quarry, 6 km SE of Mount Gambier. The solution pipes penetrate some 7 m down through the profile and are commonly 1 m wide (*Photograph* Murray-Wallace 1993)

5.4.4 Caves and Sinkholes

Caves and sinkholes are widely scattered throughout the coastal plain, particularly in the region near Mount Gambier. Over 570 caves have been recorded from the southern portion of the coastal plain (Reed and Bourne 2000). Umpherstone Cave on the eastern outskirts of Mount Gambier and the Cave Gardens within the city provide scenic overviews of the drier sinkholes. Sinkholes that intersect the water table include Little Blue Lake, Hells Hole, Piccaninnie Ponds and Ewen Ponds. Although providing an immense groundwater resource, the karst topography presents significant engineering, geohazard and pollution problems for the region. An anecdotal illustration, somewhat embellished over the years, concerns a karst subsidence (sinkhole formation) in the Glencoe West oval which opened during a football match (Nelson 1971). More serious problems of locally sourced and diffuse pollution arising from farming, industrial and domestic activities and stormwater disposal have been well documented, and monitoring of underground water quality is an ongoing necessity.

5.4.5 Naracoorte Caves and Fossil Remains

The caves within the Conservation Park at Naracoorte are solution features developed within the Oligo-Miocene Gambier Limestone and in places initiated within the overlying Pleistocene Bridgewater Formation. Many of the cave systems preserve sandy cave infills that have accumulated at the bases of karst swallow holes (sinkholes) within the Bridgewater Formation. The sandy accumulations include fragments of limestone derived from aeolianites of the Bridgewater Formation, as well as spalled cave wall material from the Gambier Limestone. The sandy sediment comprises moderately sorted

Fig. 5.10 Oblique view of the openings of linear solution pipes within the Gambier Limestone at the modern ground surface, infilled with *terra rossa* soil at Attiwill Quarry, 6 km SE of Mount Gambier (*Photograph* Murray-Wallace 1993)

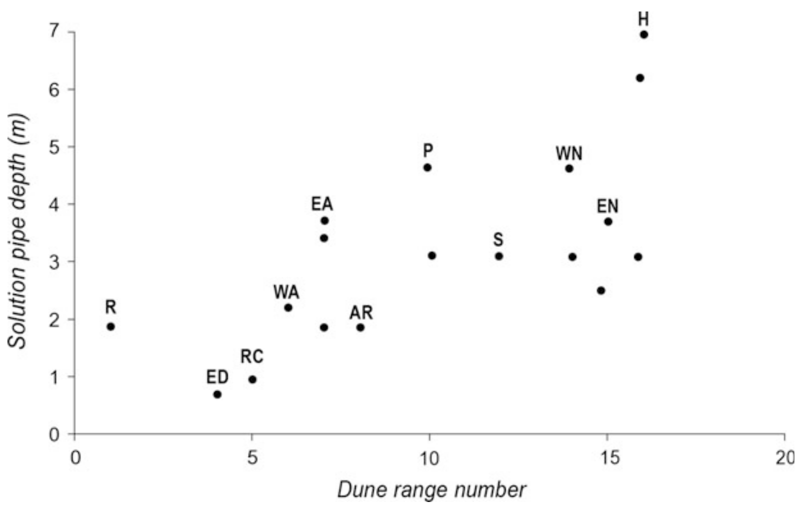

Fig. 5.11 Increase in the size of solution pipes within the Pleistocene Bridgewater Formation with distance landwards across the Coorong Coast Plain. Dune Ranges; *R* Robe Range; *ED* East Dairy; *RC* Reedy Creek; *WA* West Avenue; *EA* East Avenue; *AR* Ardune; *P* Peacock; *S* Stewarts; *WN* West Naracoorte; *EN* East Naracoorte; *H* Hynam. Based on field observations in Blackburn et al. 1965)

quartz sand, many of the grains being highly spherical in form with frosted surfaces indicating prolonged wind transportation and mechanical abrasion in more arid conditions. Clay aggregates of silt to sand size also occur within cave-fill accumulations and appear to be of pedogenic origin (Moriarty et al. 2000). Guano derived from bats frequenting the caves is also present within the sand accumulations (Forbes and Bestland 2006). While the caves and their decorative speleothems are spectacular in their own right, the caves gained World Heritage listing in 1994 for their preserved Pleistocene fossil vertebrate fauna.

Vertebrate remains accumulate within cave deposits in a variety of ways. Sinkholes have been particularly effective as pit-fall traps for surface dwelling animals. Some 2686 identifiable specimens of vertebrate fossils were retrieved from Grant Hall within Victoria Fossil Cave at Naracoorte, of which approximately 62% of all fossils were complete (Fraser and Wells 2006). Caves also provide a home for many different kinds of animals such as bats, birds, possums and other small marsupials, frogs and snakes. Some cave dwellers such as owls are carnivorous and the hard parts of their prey contribute to the remains. The fossil deposits at Naracoorte Caves include the bones, teeth and claws of animals derived from all these sources. Pleistocene vertebrate faunal assemblages include numerous extinct forms such as *Zygomaturus* (marsupial rhinoceros), *Diprotodon* sp., *Thylacoleo carnifex* (marsupial lion), *Procoptodon* (giant short-faced kangaroo), *Wonambi naracoortensis* (giant boid snake), *Progura naracoortensis* (giant mallee fowl) and *Zaglossus ramsayi* (large echidna) (Wells 1975; Wells and Pledge 1983). More than 90 species have been identified and thousands of partial or complete skeletons exhumed. Approximately 25% of the Pleistocene faunal assemblages in the Naracoorte Caves are represented by extinct taxa, particularly leaf-eating kangaroos such as *Macropus titans*. Ages for these bones range from >150 to 18 ka (Wells 1975; Williams 1980; Wells and Pledge 1983). A list of Pleistocene fossil vertebrate sites is presented by Reed and Bourne (2000).

The Pleistocene fauna of Australia underwent major changes in the time leading up to the Last Glacial Maximum (MIS 2 at 21 ka). The more central areas of the continent became increasingly arid and many large species of marsupials became extinct. The fossil pollen record shows that in southeastern Australia, forests gave way to more open grassed woodlands (Dodson 1977). This transition appears to have coincided with extinction of the larger browsing animals.

In a comprehensive investigation involving uranium-series dating of bones and speleothems from Victoria Cave at Naracoorte, Ayliffe and Veeh (1988) found that speleothem growth tended to occur during warmer and marginally wetter interglacials, such as the penultimate (MIS 7) and last interglacial (MIS 5e). Their uranium-series ages suggest that the bone deposit in Victoria Cave accumulated during the drier climate phase of the MIS 6. The rate of speleothem formation is remarkably slow and was found to be approximately 0.2 mm/ka (Ayliffe and Veeh 1988). In a subsequent investigation using higher-resolution, thermal ionisation mass spectrometry, Ayliffe et al. (1998) reported a series of $^{230}Th/^{234}U$ ages on speleothems from several caves at Naracoorte. The ages revealed four principal phases of speleothem growth; 420–340 ka, 300–270 ka, 220–155 ka and 115–20 ka separated by periods of non-deposition and dissolution. They concluded that speleothem growth during the past 400 ka tended to occur after full interglacial or warm interstadials. During the last glacial cycle, speleothem growth occurred during 115–105, 100–90, 85–70, 50–40 and 35–20 ka.

At Starburst Chamber (also termed Spring Chamber) in Victoria Cave at Naracoorte, two principal growth phases of speleothem (179–162 ka and 114–96 ka) separated by a period of non-deposition and dissolution have been documented (Ayliffe et al. 1998). Oxygen and carbon isotope analyses of the same speleothem revealed a pattern of systematic variation consistent with the uranium-series chronology and suggest that drier periods coincided with cooler periods, at times of lower sea level characterised by enriched isotopic signals, while the converse applied during warmer, wetter intervals at times of higher sea level (Bestland and Rennie 2006).

At Cathedral Cave within the Naracoorte Cave complex, 103 large mammal and 107 small vertebrate fossils were found, dominated by the Eastern Grey Kangaroo, *Macropus giganteus* (Brown and Wells 2006). The age of the fossil assemblage was constrained by uranium-series dating of flowstones which bracketed approximately half of the sedimentary infill between 279.2 ± 7.2 ka to 159.2 ± 2.2 ka. The basal portion of the succession is younger than 399 ± 19 ka.

Forbes et al. (2007) present a Late Pleistocene to Holocene palaeoenvironmental reconstruction based on excavations of cave sediment infills at Robertson Cave, Naracoorte. Radiocarbon dating of discrete charcoal fragments has revealed that the sedimentary record extends back to about 32 ka and three distinct sedimentary units were identified covering the latter part of the Last Glacial Cycle. A significant component of the cave sediment infill post-dating 30 ka comprises aeolian sourced quartz sand associated with the enhanced aridity with the progressive onset of the Last Glacial Maximum. From about 13 ka ago, organic-rich sediment was introduced into the cave system, possibly associated with enhanced surface moisture following full glacial conditions. The presence of increased charcoal concentrations in the upper-most sedimentary unit within the cave system may possibly coincide with the arrival of Aboriginal people within the region and provide a condensed record of fire burning practices.

Radiocarbon dating of charcoal has also been used to help constrain the ages of vertebrate fossil remains from cave infills in the Naracoorte Caves (Pate et al. 2006). This is a particularly challenging application of the method in view of the small sample mass, degraded nature of some charcoal fragments and the fact that the ages for some of the materials are close to the practical limits of the radiocarbon method. Radiocarbon ages reported for the charcoal from Wet Cave at Naracoorte are younger than 46 ka. While the radiocarbon ages are consistent with the notion of a continent-wide megafaunal extinction event at about 46 ka ago (Roberts et al. 2001), given the age-range of the radiocarbon method, it cannot strictly be used to validate the timing of extinction as it is not possible to derive older finite ages based on this method alone.

5.5 Significance of Karst Forms in Understanding Coastal Landscape Evolution

The coastal barrier successions of the Bridgewater Formation within the Mount Gambier region can provide insights about the rates of karst development within the Gambier Limestone. The Little Blue Lake, a cenote 5 km to the west of Mount Schank most likely developed following the marine regression at the end of the Last Interglacial (MIS 5e) as there is no evidence for calcarenite sediment infill within this cenote associated with the formation of MacDonnell Range. This would imply that the cenote, Little Blue Lake, formed on the seaward side of Burleigh Range during the past 125 ka.

Karst weathering processes in the portion of the coastal plain closer to the town of Mount Gambier have led to unusual landscape relationships such as inversion of relief, where former low points of the landscape are now represented by higher ground. This is seen in a section of the Compton Range in the town of Mount Gambier (Grey Street; S 37°49′31.7″; E 140°43′14.3″; Blakemore 2014). Here, interglacial shell beds of the Bridgwater Formation are now situated within high points of the landscape that are now surrounded by lower relief associated with solution depression development that has post-dated deposition of the shell beds.

5.6 Human Impacts on the Landscape

In the southern portion of the Coorong Coastal Plain, shallow unconfined aquifers are at particular risk of contamination because of the extensive development of karst. Before the development of modern sewerage, septic and household wastes were disposed directly to the ground throughout Mount Gambier and other towns within the region. Point sources of pollution such as stock yards, food processing facilities, fuel oil storage facilities, timber mills, stormwater disposal points and abattoirs have been documented (Waterhouse 1977; Smith 1983; Smith and Schrale 1982; Schrale et al. 1984; Emmett and Tefler, 1994). Diffuse pollution also occurs from animal husbandry activities and fertiliser, herbicide and pesticide application. Karst regions also have a positive effect on groundwater in that meso-scale solution features aid rapid infiltration and recharge.

Dryland salinity is a major land degradation problem in southern Australia, including the Coorong Coastal Plain, with over 250,000 ha of agricultural land currently affected by saline seepage. Dryland salinity is caused by the historical widespread clearing of native vegetation which has upset a delicate hydrologic balance. Replacement of deep-rooted perennial vegetation with shallow-rooted annual pastures has allowed the groundwater table to rise, with salts concentrated at the surface by evaporation. In places the groundwater levels are rising at a rate of 0.5–1.0 m every 10 years. The increasing salt levels near the ground surface, manifested as saline seepages and scalds in low-lying depressions, have a devastating effect on crops and vegetation. Because dryland salinity is essentially a groundwater problem, measuring the long-term trends in groundwater levels is the only way to predict where and when salinization will occur and at what rate it will spread. Remedial measures include revegetating recharge areas with high water use plants, improved land-use practices and in some areas, enhancing discharge and drainage.

5.7 Summary and Conclusions

The extensive production of cool-water sedimentary carbonate successions along the southern margin of Australia was initiated with the final separation of Australia and Antarctica some 43 Ma ago. This phase of deposition resulted in the formation of the Oligo-Miocene Gambier Limestone within the Gambier Embayment of the Otway Basin. The progressive northward movement of the Australian continent, with the southern portion of the Coorong Coastal Plain located within a mid-latitude, seasonally wet, temperate climate region, presented the necessary conditions for karst development during the Late Quaternary. A range of karst landforms have developed on the low relief coastal plain, with more pronounced karstification evident in the southern-most section near Mount Gambier, characterised by dolines (cenotes), complex enclosed depressions, limestone pavements and absence of confined surface drainage. The network of caves within the Gambier Limestone, particularly in the Naracoorte area, have been instrumental in preserving rich fossil faunal records, that in part chronicle significant environmental and climatic changes, as well as the extinction of some megafauna. Enhanced aridity during the Last Glacial Maximum enhanced regional calcrete development, particularly in the dryer, northern portion of the coastal plain, which has assisted in the preservation of the original physical form of the coastal barriers.

Given the general uniformity of the underlying country rock, a surprisingly diverse array of soil-landform associations occur across the coastal plain, confined within broad linear belts associated with the barrier landforms (Pleistocene Bridgewater Formation) and their back-barrier lagoon facies (Pleistocene Padthaway Formation). The intensity of soil development and the size of solution pipes increase landward across the coastal plain, associated with the progressive increase in the age of coastal landforms on which they have developed. Arguably the most renowned soil group in the popular imagination are the *terra rossa* soils, which give rise to one of Australia's premier wine regions, the Coonawarra.

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Geochronological Framework for the Age of the Coastal Barrier Successions of the Coorong Coastal Plain

6

Abstract

The coastal barrier landforms and sedimentary successions of the Pleistocene Bridgewater Formation represent a natural laboratory to evaluate critically and refine methodological aspects of a range of Quaternary geochronological methods. The age of many of the barriers of the Coorong Coastal Plain is now securely established within a framework of radiocarbon, luminescence (thermoluminescence—TL and optically stimulated luminescence—OSL), amino acid racemization (AAR), electron spin resonance (ESR), uranium-series disequilibrium and magnetostratigraphy, principally in terms of the position of the Brunhes—Matuyama geomagnetic polarity reversal between the East and West Naracoorte Ranges (781 ka). This geochronological framework is broadly in accord with oxygen isotope records of global ice-volume fluctuations and the inferred timing of sea-level highstands from Middle Pleistocene time to the present. The long sedimentary record of interglacial sea-level highstand events provides a unique opportunity to further develop a range of geochronological methods, which has been the focus of many investigations within the region.

Keywords

Amino acid racemization · Optically-stimulated luminescence dating Thermoluminescence dating · Electron spin resonance · Quaternary geochronology

6.1 Introduction

Before the systematic evaluation and application of luminescence (thermoluminescence—TL and optically-stimulated luminescence—OSL), amino acid racemization dating (AAR) and electron spin resonance (ESR), there was limited geochronological control for the age of the coastal barrier successions of the Bridgewater Formation across the Coorong Coastal Plain. Recognition of the Brunhes–Matuyama geomagnetic polarity reversal between the East and West Naracoorte Ranges (Cook et al. 1977; Idnurm and Cook 1980) provided the first significant datum for establishing a broad time framework for the Pleistocene barrier successions. As outlined in Chap. 7, early attempts at establishing the age of the coastal

Photos by the author, if not indicated differently in the figure/photo legend.

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barrier landforms was based on altitudinal correlations of shoreline complexes from other parts of the world (Tindale 1933) based on the four-fold model of Quaternary Alpine Glaciation, as well as correlations invoking the Croll-Milankovitch Hypothesis (Hossfeld 1950; Sprigg 1952).

Identification of the Brunhes–Matuyama boundary revealed that at least 16 physically distinct barriers had formed since 781 ka as well as additional components within some composite barriers (e.g. Robe, Woakwine and Naracoorte Ranges; see Chap. 2).

Subsequent limited uranium-series dating of fossil molluscs and aragonitic lagoonal facies (Schwebel 1978, 1984) and aminostratigraphy (von der Borch et al. 1980; Murray-Wallace and Belperio 1991; Murray-Wallace et al. 1996) established the Late Pleistocene age (last interglacial 125 ka) for the Woakwine Range, correlative with Marine Isotope Substage 5e (MIS 5e) of deep sea and ice core records. The extent of racemization for several amino acids in the fossil marine bivalve molluscs *Anadara trapezia* and *Katelysia rhytiphora* from the back-barrier estuarine-lagoon facies of Woakwine Range indicated a correlation with other successions of confirmed last interglacial age in southern Australia (MIS 5e; Murray-Wallace et al. 1996; Fig. 6.1). The fossil molluscs were collected from widely separated sites along a portion of the dune range over a distance of 60 km. The amino acid data support previous assumptions about the uniformity of age along the strike of individual barriers.

Since the pioneering work of Hossfeld (1950) and Sprigg (1948, 1952) it has been recognised that there is good agreement between the uplifted coastal plain successions and long-term records of global climate and glacio-eustatic sea-level changes influenced by variations in insolation as explained by the Croll-Milankovitch hypothesis (Cook et al. 1977; Sprigg 1979; Idnurm and Cook 1980; Schwebel 1983; Huntley et al. 1993a, b; Murray-Wallace et al. 2001; Murray-Wallace and Woodroffe 2014). In the absence of more complete geochronological data, ages were assigned to the barriers by correlation with the marine oxygen isotope record, initially by Schwebel (1978, 1983, 1984) based on the record of Shackleton and Opdyke (1973), and subsequently by Belperio and Cann (1990) using the marine-based oxygen isotope record of Williams et al. (1988). The stratigraphical approaches also used the palaeomagnetic

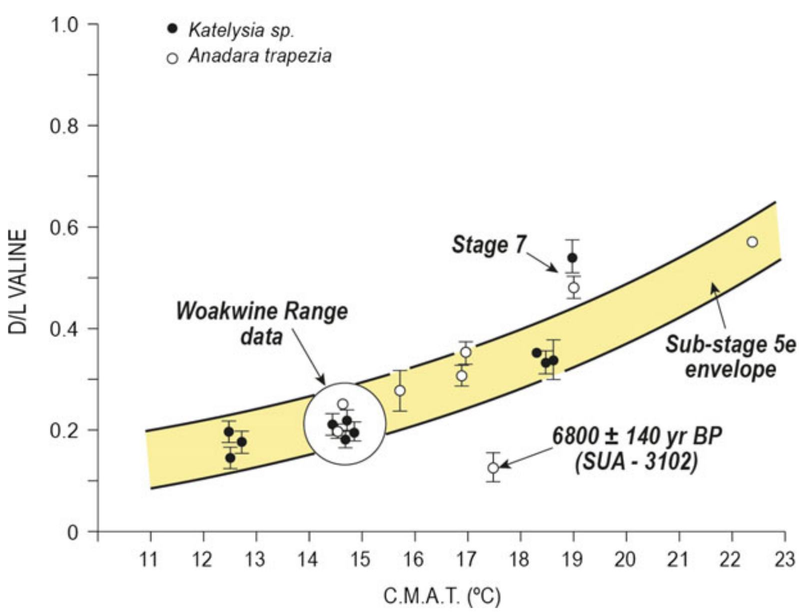

Fig. 6.1 AAR data for the fossil marine molluscs *Anadara trapezia* and *Katelysia rhytiphora* from the back-barrier lagoon facies of the Woakwine Range, based on analyses reported in Murray-Wallace et al. (1999)

evidence (Brunhes-Matuyama geomagnetic polarity reversal between the East and West Naracoorte Ranges) as a critical tie point. A relatively complete sequence of stranded high sea-level deposits from MIS 1 to MIS 19 was suggested, indicating coastal sedimentation in phase with periods of globally synchronous climatic events, principally interglacials and interstadials (Belperio and Cann 1990; Huntley et al. 1993a, b; Huntley et al. 1994). Former sea-level highstands were estimated by correcting shoreline and back-barrier estuarine-lagoon facies elevations for tectonic uplift since barrier shoreline formation. A rate of uplift of 0.07 mm/year for the past 800 ka is indicated by the highly coherent plot of shoreline elevation versus inferred age for the Robe-Naracoorte line of section (Belperio and Cann 1990; Fig. 6.2) and approximately 130 mm/ka near Mount Gambier (Murray-Wallace et al. 1996). Uplift-corrected palaeoshoreline data indicate a repetition of interglacial sea-level highstands close to or just below present sea level over the past 800 ka. Uplift along with calcrete development on the surfaces of the dune ranges have been fundamental factors in the preservation of these strandlines above present sea level.

6.2 Luminescence Dating

Luminescence dating (thermoluminescence—TL and optically stimulated luminescence—OSL) has greatly enhanced the understanding of the ages of the barrier shoreline successions of the Coorong Coastal Plain, as luminescence methods directly quantify the time of sedimentation based on the last time that quartz sand grains were exposed to sunlight. The pioneering research by Dave Huntley, John Hutton and John Prescott has contributed enormously to understanding many fundamental aspects of luminescence dating including aspects of dosimetry and the significance of variable sediment burial depths affecting the contribution of cosmic rays on dose rate (Huntley et al. 1993a, b; Huntley and Prescott 2001; Prescott and Hutton 1994). Their work established the first coherent

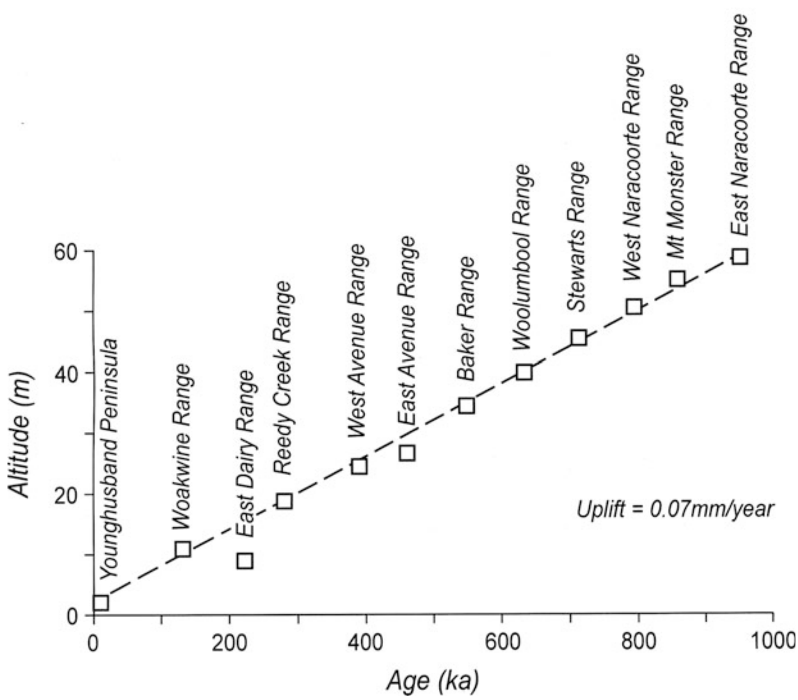

Fig. 6.2 Graph of relict shoreline elevation against inferred age for the past 800 ka modified after Belperio and Cann (1990)

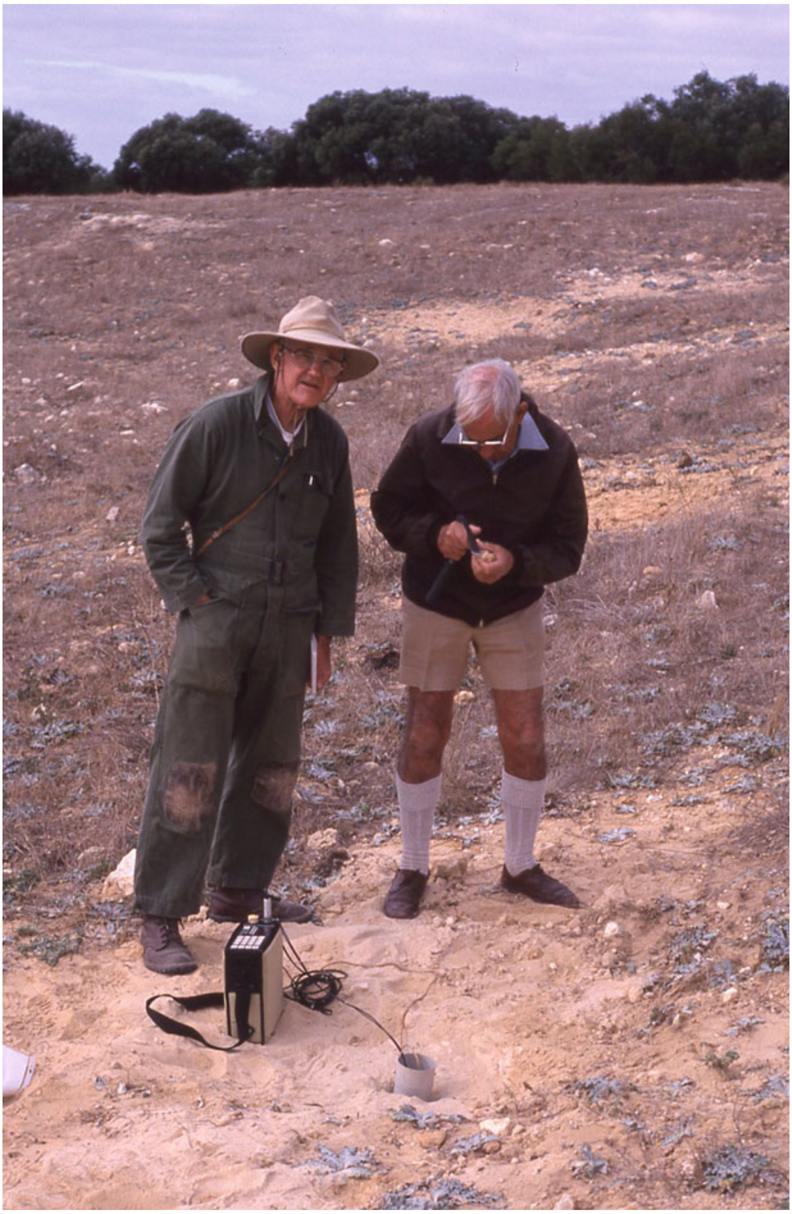

Fig. 6.3 Two pioneers in luminescence dating—the late John Prescott (left) and the late John Hutton taken during fieldwork in 1993, in this case, at a field site near Millicent in southern South Australia (*Photograph* Murray-Wallace 1993)

geochronological framework for the coastal barrier successions of the Bridgewater Formation (Fig. 6.3).

Preliminary studies by Huntley et al. (1985) on quartz grains from five barriers across the coastal plain (Robe II, Woakwine I, Reedy Creek, West Avenue and West Naracoorte) showed increasing thermoluminescence (TL) with age and the distance of each barrier inland from the modern coastline. Subsequent studies (Huntley et al. 1993a, b; 1994; Huntley and Prescott 2001; Murray-Wallace et al. 1999; Banerjee et al. 2003) have derived numeric ages by TL and OSL that range from about 100 to

800 ka with excellent age coherence, characterised by the systematic increase in luminescence age landwards across the coastal plain. Additional TL ages for the Burleigh and Caveton Ranges near Mt Gambier reveal the age equivalence of these barriers with the Reedy Creek Range (MIS 7) and East Dairy Range (MIS 9) respectively (Murray-Wallace et al. 1996). OSL ages for Robe Range equivalent and MacDonnell Range (Woakwine Range equivalent) at Port MacDonnell are reported by Blakemore et al. (2014). TL ages for the aeolianite successions from the northern-most portion of the coastal plain in the River Murray Mouth and terminal lakes region are reported by Bourman et al. (2000) and Murray-Wallace et al. (2010).

Luminescence methods are particularly suited to the dating of sediments of the Bridgewater Formation for several reasons. There is sufficient quartz within the skeletal carbonate sand for analysis, typically at least 40–50% of the total sediment. The sediments across the entire coastal plain have experienced particularly low environmental dose rates (characteristically 0.5 mGy/year, both for the Pleistocene and Holocene successions; Huntley et al. 1993a, b; Murray-Wallace et al. 2002). This has permitted sediments significantly older than the normal practical limit of luminescence dating (200 to 400 ka depending on sediment properties and environmental dose rates) to yield numeric ages by conventional luminescence methods (Huntley et al. 1993a, b; 1994, Huntley and Prescott 2001; Murray-Wallace et al. 1999; Banerjee et al. 2003). Generally, disequilibrium is not experienced in the uranium-series within these sedimentary successions and the mode of aeolian sedimentation together with abundant sunlight ensures that the quartz grains are well bleached with only a low residual TL (Huntley et al. 1985).

Several analytical approaches have been used in the luminescence dating of quartz sand from the aeolianites of the Bridgewater Formation on the Coorong Coastal Plain. TL measurements of approximately 6.5–12 mg of 100 μm quartz sand on single aliquots (Huntley et al. 1993a; Huntley and Prescott 2001); the optical dating of inclusions within quartz grains including potassium feldspars based on their infrared stimulation within single aliquots of 6.5 mg quartz sand (Huntley et al. 1993b); and the single-aliquot regenerative-dose (SAR) procedure (Banerjee et al. 2003).

The luminescence-based chronology of Huntley and co-workers (Table 6.1), and associated oxygen isotope curve matching, is based on dating quartz sand from the aeolian dune facies of the barriers. As these facies successions are confidently identified based on their large-scale planar and trough cross-bedding, there is greater likelihood that their component quartz grains have been adequately bleached in contrast to subaqueously deposited sediment such as beach or sublittoral facies. Although aeolian dune facies do not define palaeosea-level (i.e. not dating 'fixed' but 'relational' sea level indicators such as coastal dunes where palaeosea-level will always have been below the aeolian dune facies; Chappell 1987; Murray-Wallace and Woodroffe 2014), it is unlikely that the age of the associated shoreline facies exceeds the analytical precision of the individual TL measurements. This is because the dated sediments are genetically related to the beach and back-barrier lagoonal facies and not separated by major unconformities.

The TL results for the Woakwine Range are of particular interest as they yielded ages of 132 ± 6 ka, 132 ± 9 ka and 118 ± 4 ka (Huntley et al. 1993a; Huntley et al. 1994), consistent with the presently accepted duration of the Last Interglacial Maximum (MIS 5e; c. 128 to 116 ka) (Lambeck and Nakada 1992; Chen et al. 1991; Zhu et al. 1993). Huntley et al. (1994) attributed the variation in TL ages to analytical precision, but as the youngest of the three ages falls just outside the range of the other two ages, there is the possibility that the younger result relates to a later phase of the Last Interglacial Maximum and is therefore a statistically resolvable age. Both Woakwine Range Drain L samples yielded ages of 132 ka, but the younger age was obtained on a sample from a geomorphologically younger component of the Woakwine Range from a road cutting on the seaward branch of the

Table 6.1 Luminescence ages (TL and OSL) for the Pleistocene coastal barrier successions of the Coorong Coastal Plain, southern Australia

Dune Range	Luminescence method (OSL/TL)	Luminescence age (ka)	MIS	References
Robe I	TL	0	Modern	Huntley et al. (1994)
Robe II	OSL	61 ± 3.6	5a?	Banerjee et al. (2003)
Robe II?	OSL	53 ± 4	3?	Blakemore et al. (2014)
Robe III?	TL	95 ± 6	5c	Huntley and Prescott (2001)
Robe III	OSL	100 ± 6.7	5c	Banerjee et al. (2003)
Robe III	TL	116 ± 6	5c	Huntley et al. (1994)
Robe III	TL	105 ± 5	5c	Murray-Wallace et al. (2010)
Woakwine I	OSL	120 ± 8.7	5e	Banerjee et al. (2003)
Woakwine I	TL	132 ± 6	5e	Huntley et al. (1993a)
Woakwine I	TL	118 ± 4	5e	Huntley et al. (1994)
Woakwine I	TL	132 ± 9	5e	Huntley et al. (1994)
Woakwine I	TL	117 ± 8	5e	Murray-Wallace et al. (1999)
Woakwine I/Narrung I	TL	120 ± 15	5e	Murray-Wallace et al. (2010)
MacDonnell	OSL	124 ± 10	5e	Blakemore et al. (2014)
Woakwine II	OSL	175 ± 11	7	Banerjee et al. (2003)
Woakwine II/III	TL	230 ± 11	7a or 7c	Huntley et al. (1993a)
West Dairy	TL	196 ± 12	7a	Huntley et al. (1994)
East Dairy	TL	292 ± 25	9	Huntley and Prescott (2001)
Point Sturt	TL	230 ± 50	7e	Murray-Wallace et al. (2010)
Millicent (East Dairy?)	TL	255 ± 24	7e	Huntley and Prescott (2001)
Burleigh	TL	237 ± 16	7e	Murray-Wallace et al. (1996)
Reedy Creek	OSL	220 ± 20	7e	Banerjee et al. (2003)
Reedy Creek	TL	258 ± 25	7e	Huntley et al. (1993a)
Caveton	TL	320 ± 22	9	Murray-Wallace et al. (1996)
West Avenue	TL	315 ± 25	9a	Huntley and Prescott (2001)
West Avenue	TL	342 ± 32	9a	Huntley et al. (1993a)
East Avenue	TL	404 ± 23	9c	Huntley and Prescott (2001)
East Avenue	TL	414 ± 29	9c	Huntley et al. (1993a)
Baker	TL	456 ± 37	11c	Huntley et al. (1993a)
Harper	TL	585 ± 40	13	Huntley et al. (1993a)
Stewarts/Cave	TL	725 ± 100	21	Huntley and Prescott (2001)
West Naracoorte	OSL	570 ± 38	<780 ka	Banerjee et al. (2003)
West Naracoorte	OSL	710 ± 62	<780 ka	Banerjee et al. (2003)
West Naracoorte	TL	800 ± 100	<780 ka	Huntley et al. (1994)
East Naracoorte	TL	720 ± 70	21 or 25	Huntley et al. (1993a)

MIS Marine Isotope Stage

dune range where it bifurcates at its northern end (Huntley et al. 1994).

The TL studies by Huntley and co-workers have provided conclusive data confirming that the barrier shorelines from Robe to Naracoorte formed during successive interglacial highstands. This conclusion accords in broad view with Sprigg's 1952 interpretations, but contrasts with his revised reasoning (Sprigg 1979) that the seaward-most dune complexes (Bridgewater Catena) represented lowstand glacial age barrier dune complexes while the innermost, landward dunes (Wimmera Catena) represented highstand deposits.

6.3 Amino Acid Racemization Dating

Amino acid racemization (AAR) analyses have been undertaken on fossil marine molluscs and "whole-rock" sediment samples from the Coorong Coastal Plain (Murray-Wallace et al. 1996, 1999, 2001, 2010). In the protein of living organisms, amino acids are bound in peptides exclusively as left-handed molecules. During life, enzymic reactions prevent the right-handed non-protein amino acids from developing in most tissues (excluding teeth, eye lenses and long-lived shells such as *Tridacna* sp.). With the cessation of protein formation and enzymic activity, amino acids undergo a slow and reversible racemization reaction in which left-handed amino acids change their configuration to right-handed counterparts until an equilibrium is established (Clarke and Murray-Wallace 2006). The relative age of fossils is expressed by an amino acid D/L value. In modern biological materials such as marine shells, D/L values are close to zero (typically 0.01–0.03 depending on the racemization rate of different amino acids; the non-zero D/L values are due to the slight amount of racemization induced in the hydrolysis step in sample preparation: for example heating for 22 h in 8 mol/L HCl). The D/L value becomes larger with increasing fossil age until an equilibrium ratio is obtained (i.e. 50:50 mixture of left- and right-handed enantiomeric amino acids). As the racemization reaction is strongly temperature dependent, the age range of the technique will vary significantly spatially, particularly with significant latitudinal differences in diagenetic temperature during the burial history of fossils. In the Coorong Coastal Plain, the age range of the amino acid racemization technique is likely to be in the order of 1.6–2 Ma depending on the rate of racemization for the specific amino acid of interest (Murray-Wallace et al. 2001).

The first application of AAR to the Quaternary successions of the Coorong Coastal Plain was by von der Borch et al. (1980). They reported the extent of AAR on *Katelysia scalarina* shells from back-barrier lagoon facies of the Woakwine Range from two sites (Drain L and Lake Hawdon). Based on a correlation with the extent of racemization in fossil *Chione* shells from a marine terrace in San Diego, California, they assigned a last interglacial age of 120 ± 10 ka to the shells from the back-barrier lagoon facies of the Woakwine Range. *Katelysia scalarina* shells from a borehole at Lake Hawdon in the lee of the Woakwine Range yielded a lower extent of racemization than the Drain L sample. Von der Borch et al. (1980) speculated that the lower extent of racemization may imply an age younger than the Last Interglacial Maximum (MIS 5e) and possibly relate to the warm interstadial MIS 5c of 105 ka. As the results for only one shell specimen was reported, this interpretation should be viewed with caution. Given the morphostratigraphical context of the shell sample from the back-barrier setting of the Last Interglacial Woakwine Range, the lower extent of racemization is more likely to reflect the effects of leaching in the groundwater environment during diagenesis (i.e. loss of more extensively racemized free amino acids resulting in a lower D/L value for the total hydrolysable amino acids).

The extent of valine racemization in the fossil cockles *Katelysia* sp. and *Anadara trapezia* from the back-barrier lagoon facies of the last interglacial Woakwine Range (McCourt Cutting and Old Penola Road site at Lake Hawdon South; see Sect. 2.8.1) is indicated in Fig. 6.1. The amino acid racemization data fall within the MIS 5e

(c. 125 ka) envelope for the Last Interglaciation in southern Australia. The envelope accounts for the variability in the extent of racemization in fossils from different field sites which will have experienced different diagenetic temperatures. The end members in the data set are from Tasmania (Current Mean Annual Temperature; CMAT = 12.5 °C) and Shark Bay (CMAT = 22.5 °C). The observed trend in the last interglacial data set reflects the exponential effect of increasing temperature on racemization rates for equivalent age (i.e. the same Marine Isotope Stage), but selected from contrasting latitudinal settings with different diagenetic temperatures. The empirical evidence is in accord with that theoretically predicted by the Arrhenius equation (i.e. that for every 1 °C increase in temperature there is a corresponding 18% increase in the racemization rate).

The "whole-rock" AAR method has also been applied to skeletal carbonate sand from the calcarenite, aeolian dune facies of the coastal barriers across the coastal plain (Murray-Wallace et al. 2001). The rationale of the 'whole-rock' AAR method is that relative ages of different stratigraphical units should be able to be resolved provided that the sedimentary constituents are relatively well-preserved. The whole-rock method has been used where entire fossils are not present that would have otherwise been the preferred medium for analysis. In a pilot study examining the potential of whole-rock dating, Murray-Wallace et al. (2001) measured the extent of leucine racemization in the 63–500 µm particle size fraction of skeletal carbonate sand from the aeolian dune facies of nine Pleistocene coastal barriers across the coastal plain (Figs. 6.4 and 6.5). Analyses were undertaken on free amino acids (FAA) and the total hydrolysable amino acids (THAA). The extent of leucine racemization for the THAA generally increased monotonically with age (Fig. 6.4). The extent of leucine racemization is consistently higher in the whole-rock samples than in entire fossil molluscs from the same stratigraphical units. The offset in these two curves reflects the lengthy residence time for bioclasts in this high wave energy coastal environment, and a component of sediment recycling from older barriers (i.e. partial erosion of older barriers during a younger interglacial sea level highstand provides a source of older bioclastic skeletal carbonate sand). The extent of racemization of free amino acids in the whole-rock samples is significantly higher than observed for the THAA for the same sediment samples, as noted elsewhere for fossil molluscs (Murray-Wallace and Kimber 1987, 1989; Murray-Wallace 2000). Analysis of the free amino acid fraction provides the opportunity to evaluate the integrity of the results for the THAA. For example, anomalously low D/L values for the THAA may have resulted from the diffusive loss of lower molecular weight peptides and free amino acids, both characterised by higher extents of racemization, so that the D/L value in the THAA is dominated by the extent of racemization of the remaining amino acids, bound in higher molecular weight peptides characterised by lower extents of racemization.

Non-linear racemization kinetics is evident in the whole-rock data set as with the entire fossil molluscs (Fig. 6.4). The data are in accord with early observations of the non-linear nature of racemization kinetics in foraminifers and marine molluscs (Wehmiller and Hare 1971). Accordingly, the data show an early, rapid initial phase of racemization immediately following the death of an organism and lasting for several thousand years, followed by a much slower rate of racemization up to ten times slower than the initial rate (Wehmiller 1984; Clarke and Murray-Wallace 2006).

The extent of racemization in the whole-rock samples from the Coorong Coastal Plain, when plotted against the luminescence ages reported by Huntley et al. (1993a, b, 1994), reveals that the data are consistent with a model of apparent parabolic racemization kinetics (Mitterer and Kriausakul 1989: Fig. 6.5). In Fig. 6.5 the extent of leucine racemization is plotted against the square root of the luminescence ages reported by Huntley et al. (1993a, b, 1994) to assess the degree to which the amino acid whole-rock data set conforms to a model of apparent parabolic kinetics. Linear regression reveals a highly concordant relationship for the data ($r^2 = 0.9845$).

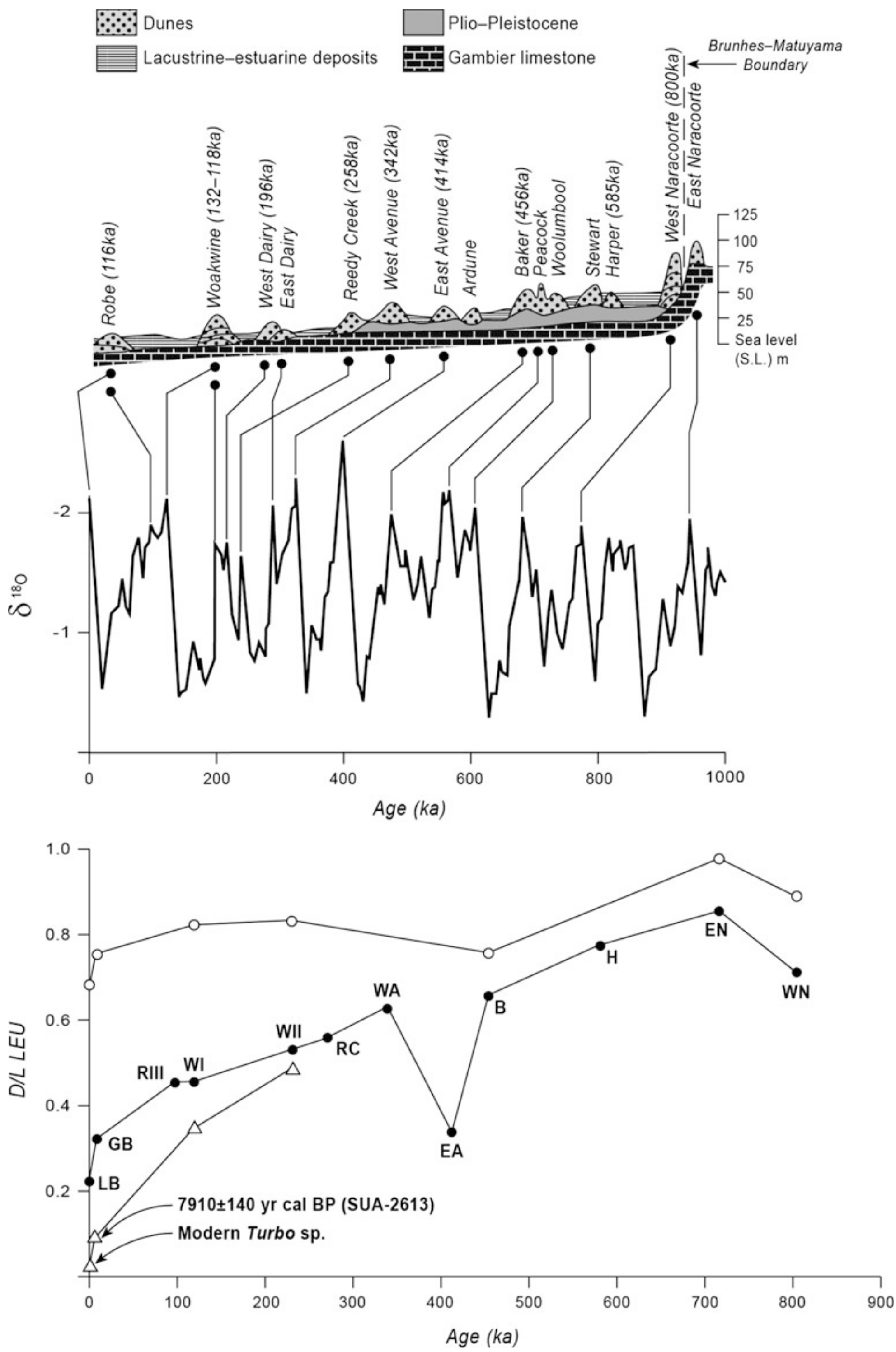

Fig. 6.4 Extent of leucine racemization for the total hydrolysable amino acids (THAA—solid circles) and free amino acids (open circles) in whole-rock sediment samples of aeolianite (aeolian dune facies) from each of the relict coastal barriers across the Coorong Coastal Plain in southern South Australia, based on data reported by Murray-Wallace et al. (2001)

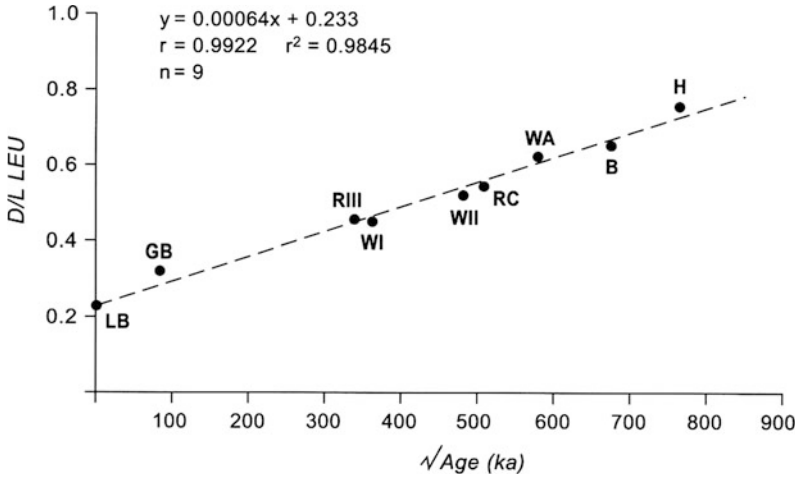

Fig. 6.5 Linear regression of the extent of leucine racemization, total hydrolysable amino acids (THAA) in whole-rock samples against the square root of luminescence age (Murray-Wallace et al. 2001)

Data excluded from this correlation include the results for the East Avenue Range, as well as the East and West Naracoorte Ranges. Results for the East Avenue Range most likely reflect in situ leaching resulting in an artificially low leucine D/L value for the THAA (symbol EA in Fig. 6.4). The extent of leucine racemization in the whole-rock sample from the East Avenue Range is clearly at variance with the general trend of increasing extent of racemization with age as defined by the results from the other barriers. Both field evidence and microscope inspection of the sediment from East Avenue Range reveal that the sediment is highly leached. The remaining carbonate bioclasts are exclusively calcite echinoid spines, rare foraminifers, molluscs and bryozoan fragments. This together with the analysis of thin sections which reveal that the carbonate grains exhibit extensive recrystallization and some dissolution is compelling evidence for extensive leaching of carbonate, the loss of lower molecular weight and more highly racemized amino acids from the sediment, therefore yielding a lower D/L for the total hydrolysable amino acids (THAA; Murray-Wallace et al. 2001).

The TL ages reported by Huntley et al. (1993a, 1994) reveal an apparent age inversion for the East and West Naracoorte Ranges when considered only in the context of the derived TL ages. The TL ages, however, when considered in terms of their age uncertainty terms are not significantly different. In view of other considerations, such as the age of these two barriers in the context of the position of the Brunhes-Matuyama geomagnetic polarity reversal within the dune sequence, which is known to occur between the East and West Naracoorte Ranges (Cook et al. 1977; Idnurm and Cook 1980), and their possible ages in the context of the Croll-Milankovitch Hypothesis (Imbrie et al. 1984), the AAR whole-rock results for these barriers were also excluded in the regression analysis (Fig. 6.5).

Numeric ages for the coastal barriers based on the AAR whole-rock data are given in Table 6.2. The ages are determined based on the extent of leucine racemization in the THAA. Ages were calculated based on a model of apparent parabolic racemization kinetics (Mitterer and Kriausakul 1989) using the equation:

$$t = \left[(\mathrm{D/L})_s/\mathrm{Mc}\right]^2$$

where t is the determined age, $(\mathrm{D/L})_s$ is the extent of racemization in a fossil or sediment of unknown age and Mc is the slope of the line defined as [= $(\mathrm{D/L})/t^{1/2}$]. Calibration was determined based on the extent of racemization in sediments from the last interglacial component of Woakwine Range; Woakwine I in the stratigraphical terminology of Hossfeld (1950), Sprigg (1952) and Schwebel (1978, 1983, 1984). A leucine D/L value of 0.451 corresponding with

Table 6.2 AAR numeric ages (whole-rock) for the relict coastal barriers of the Coorong Coastal Plain, southern Australia (Murray-Wallace et al. 2001)

Dune range	Sample code	Leucine D/L value[a]	AAR age (ka)
Guichen Bay modern beach sand	AAB#4	0.317 ± 0.003	9.4 ± 1.8
Robe III	AAB#5	0.453 ± 0.005	127 ± 24
Woakwine I	AAB#6	0.451 ± 0.099	125[b]
Woakwine II	AAB#7	0.521 ± 0.020	214 ± 41
Reedy Creek	AAB#10	0.545 ± 0.013	251 ± 48
West Avenue	AAB#11	0.620 ± 0.010	382 ± 73
East Avenue	AAB#12	0.332 ± 0.021	–
Baker	AAB#13	0.648	438 ± 83
Harper	AAB#14	0.757 ± 0.021	693 ± 132
West Naracoorte I	AAB#15	0.696 ± 0.005	543 ± 103
East Naracoorte	AAB#16	0.843	935 ± 178

[a]Total hydrolysable amino acids
[b]Calibration sample based on uranium-series age (Schwebel 1978)

an age of 125±20 ka as determined independently by uranium-series dating (Schwebel 1983, 1984) was used for age calibration. The *y*-intercept (modern age; t_o value) is based on the extent of racemization in a 'modern' shoreface sample from Longbeach, Guichen Bay (t_o D/L leucine of 0.225). For the age calculations, the t_o value was subtracted from the measured extent of racemization in each of the whole-rock samples of unknown age. This accounted for the extent of racemization since the death of the individual marine invertebrates, their comminution and subsequent incorporation within the sediment before final deposition, as well as sediment recycling from older barriers.

It is noteworthy that the extent of racemization in the 'modern' shoreface sand from Longbeach, Guichen Bay (sampled 2 cm beneath the beach face surface), greatly exceeds values typically obtained for modern molluscs (i.e. alive at the time of collection; D/L leucine ≤ 0.03). The leucine D/L value of 0.225 for the modern shoreface sand most likely reflects the physical intermixing of Pleistocene bioclasts with modern and Holocene bioclasts. For example, between 0.5 and 2 km of erosion (landward coastal recession of Robe Range) has occurred since the attainment of the Holocene sea level highstand some 7000 years ago, providing a vast supply of relict skeletal carbonate grains on the inner shelf to nourish modern beach development.

The whole-rock AAR numeric ages based on apparent parabolic kinetics are generally in accord with the TL ages reported by Huntley et al. (1993a, 1994: Table 6.2). Particularly close agreement in the numeric ages derived by these two methods is evident for Robe III, Woakwine II, Reedy Creek, West Avenue and Baker Range.

With improved developments in chromatography such as reverse phase, high performance liquid chromatography (RP-HPLC), it is now possible to analyse fossils of significantly lower mass than was previously possible by gas chromatography. Accordingly it has become possible to analyse multiple and single tests of the benthic foraminifer *Elphidium crispum* (sample mass of several milligrams; Blakemore et al. 2015) from the Pleistocene aeolianites. The extent of racemization in the slow racemizing amino acid, valine, in single and multiple tests of *E. crispum* increased progressively with the successively older and more landward barriers in the Mount Gambier region. Notably, Dismal Range, the most landward barrier examined yielded an age of 933 ± 145 ka indicating an MIS 23 age for this coastal landform. The data also revealed that the analysis of foraminifers was more reliable than the whole-rock method for materials older than MIS 11 (Blakemore et al. 2015).

6.4 Other Dating Methods

6.4.1 Palaeomagnetism

As briefly introduced in Chap. 1, the application of palaeomagnetic analyses has provided a critical time marker for understanding the sequential evolution of coastal barriers across the coastal plain. The Brunhes—Matuyama magnetic reversal (781 ka) was found to have occurred between the time of deposition of the East and West Naracoorte Ranges. In the application of magnetostratigraphy to the dating of aeolianite successions it is significant to note that the magnetization is acquired potentially several thousand years after sedimentation. Accordingly, the magnetic reversal defines the timing of a diagenetic (weathering) event and therefore represents a chemical remanent magnetisation rather than the time of sedimentation. The reverse magnetic polarity of the East Naracoorte Range implies that this landform is significantly older than 781 ka. Idnurm and Cook (1980) inferred a time lag of 30 ka between the deposition of the East Naracoorte Range and the acquisition of chemical remanent magnetisation. Following this line of reasoning, Belperio and Cann (1990) correlated the East Naracoorte Range with MIS 25 sea-level highstand, while a whole-rock AAR age of 935 ± 178 ka suggested a correlation with MIS 31 (Murray-Wallace et al. 2001).

6.4.2 Electron Spin Resonance

In an investigation of the potential of electron spin resonance (ESR) to the dating of aeolianite based on the analysis of multiple grains of quartz sand using the Al and Ti centres (Ti–Li, Ti–H), Rittner (2013) dated numerous barriers of the Coorong Coastal Plain. The research revealed that the most reliable ESR results were obtained on the Al centres within quartz. This was most evident in exponential curve fits using the regenerative or additive methods in determinations of relative ESR intensity. In addition, Al centres revealed a higher level of thermal and optical stability, particularly in terms of partial bleaching experiments. A limitation in the use of the Al centre, however, is its application to younger materials in view of potential over estimation of ESR age due to the possibility of incomplete bleaching before sediment deposition.

Rittner (2013) analysed samples from eleven barriers (and their individual components) across the coastal plain (Table 6.3). Despite variability in the derived ages for some of the barriers, the ESR results highlight the potential of the method in dating these barrier complexes. The Woakwine Range (Woakwine I) was dated at 129 ± 24 ka consistent with the previously determined last interglacial (MIS 5e) age of this landform.

Reedy Creek Range, previously assigned to the Penultimate Interglacial (MIS 7e) (Huntley et al. 1993a; Banerjee et al. 2003) yielded older ages by ESR; 292 ± 57 ka, 291 ± 33 ka and 371 ± 55 ka (Rittner 2013). Given the uncertainty terms, the two younger ages in broad view are consistent with an MIS 7e age, while the older age based on a sample from the same stratigraphical succession represents an over-estimate of age.

The West Avenue Range previously assigned to MIS 9 based on TL ages of 342 ± 32 ka (Huntley et al. 1993a), 315 ± 25 ka (Huntley and Prescott 2001) and an AAR age of 382 ± 73 ka (Murray-Wallace et al. 2001), yielded ESR ages of 342 ± 52 ka and 742 ± 92 ka (Rittner 2013) with the latter age clearly representing an outlier. ESR ages for the East Avenue Range of 471 ± 61 ka and 378 ± 46 ka are consistent with the MIS 11, 405 ka age previously assigned to this barrier (Huntley et al. 1993a; Huntley and Prescott 2001; Murray-Wallace et al. 2001).

ESR ages of 612 ± 75 ka and 416 ± 43 ka were derived for Baker Range (Rittner 2013). Based on previous geochronological analyses Baker Range yielded TL ages of 456 ± 37 ka and 390 ± 40 ka (Huntley et al. 1993a, b) and an

Table 6.3 ESR ages (Al centre) on quartz sand from aeolianites of the Pleistocene Bridgewater Formation, Coorong Coastal Plain, southern Australia based on the research of Rittner (2013)

Dune range	Sample code	ESR age (ka)
Robe II	CG21	124 ± 16
Robe III	CG22	168 ± 52
Woakwine I	CG30	129 ± 24
Reedy Creek	CG17	292 ± 57
Reedy Creek	CG18	291 ± 33
Reedy Creek	CG29	371 ± 55
West Avenue	CG13	342 ± 52
West Avenue	CG14	742 ± 92
East Avenue	CG11	474 ± 61
East Avenue	CG12	378 ± 46
Baker	CG7	612 ± 75
Baker	CG8	416 ± 43
Woolumbool	CG6	541 ± 64
Stewarts/Cave	CG24	608 ± 84
Harper	CG9	449 ± 96
Harper	CG10	494 ± 63
West Naracoorte I	CG5	752 ± 57
West Naracoorte I	CG15	702 ± 81
West Naracoorte II	CG27	828 ± 75
East Naracoorte	CG2	1894 ± 197
East Naracoorte	CG4	1631±152

AAR age of 438 ± 83 ka (Murray-Wallace et al. 2001) indicating a correlation with MIS 11. On this basis the younger ESR age is more likely correct. The ESR age of 612 ± 75 ka is based on a sample collected 1 m below the younger ESR age sample (Rittner 2013). The absence of a major diastem within the stratigraphical section implies that the older ESR age is unreliable.

The Woolumbool Range had not previously been dated although an inferred age of MIS 15 had been assigned to this barrier (Belperio and Cann 1990). An ESR age of 541 ± 64 ka is broadly consistent with the duration of this isotope stage (628 to 560 ka; Masson-Delmotte et al. 2010).

The Stewarts/Cave Range was dated at 608 ± 84 ka by ESR (Rittner 2013). Huntley and Prescott (2001) derived an age of 725 ± 100 ka for the same barrier. Additional geochronological analyses are required to more accurately constrain the age of this barrier complex.

The age of the Harper Range is also problematic. Based on a count from the top approach, this barrier was originally correlated with MIS 17 in the absence of geochronological evidence (Belperio and Cann 1990). In the EPICA Dome C ice core MIS 17 is defined as ranging between 720 and 680 ka (Masson-Delmotte et al. 2010). ESR ages of 449 ± 96 ka and 494 ± 63 ka were derived for this barrier (Rittner 2013) which based on the ages of the more seaward, younger barriers would imply that these ESR ages represent an under-estimate of the true age of the Harper Range. Huntley et al. (1993a) reported a TL age of 585 ± 44 ka for Harper Range which may also represent an underestimate of age. Notwithstanding the large uncertainty term, a whole-rock AAR age of 693 ± 132 ka may represent a closer approximation of the antiquity of this barrier landform (Murray-Wallace et al. 2001).

Rittner (2013) reported two ESR ages from West Naracoorte Range I of 752 ± 57 ka and 702 ± 81 ka based on the analysis of aeolianite from Wrattonbully Quarry, adjacent Sydney Road, to the north of Coonawarra (see Fig. 2.11 for field site location). The younger age was on an aeolianite sample 0.8 m above the older ESR age. The two samples were collected 1.6 and 2.4 m above the unconformity surface separating West Naracoorte I and II. Given the nature of the trough-cross bedding within this single dune structure, reflecting deposition over a relatively short time interval of months, the difference in these ESR ages is more likely a function of differential bleaching of quartz grains at the time of sedimentation, rather than a true difference in age. No significant diastems are evident between the two samples. West Naracoorte I is of normal magnetic polarity and therefore younger than 781 ka. Huntley et al. (1994) derived an age of 800 ± 100 ka for the West Naracoorte Range I, and it was correlated with MIS 19 by Belperio and Cann (1990), which has more recently been defined as occurring between 791.6–769.6 ka (Masson-Delmotte et al. 2010). In broad view the ESR ages are consistent with the most probable age of West Naracoorte I.

West Naracoorte II ESR sample was collected from the same quarry site at approximately 1 m below the unconformity surface separating West Naracoorte II and I. An ESR age of 828 ± 75 ka is in general terms consistent with the likely age of this barrier component. The more landward East Naracoorte Range yielded ages of 1894 ± 197 ka and 1631 ± 152 ka (Rittner 2013). Given that these ages are considerably older than West Naracoorte II and that Rittner (2013) noted the presence of numerous bryozoan fragments within the sediments, it is possible that these ESR samples were collected from the underlying Camelback Member of the Oligo-Miocene Gambier Limestone.

In summary, the application of ESR analyses to the dating of the coastal barrier landforms of the Pleistocene Bridgewater Formation is an important contribution to understanding the sequential evolution of the coastal plain. A particularly noteworthy point is that none of the natural ESR signals for the Al centres were close to saturation indicating the potential to derive numeric ages for older materials.

6.4.3 Radiocarbon Dating

In the Coorong Coastal Plain radiocarbon dating has been applied primarily to the dating of Holocene marine shells from estuarine-lagoonal and beach facies and equivalent materials, as well as charcoal from archaeological contexts (Luebbers 1978; Cann et al. 1991, 1999; Bourman et al. 2000), volcanic ash (Blackburn 1966; Blackburn et al. 1982), and lake sediments within volcanic craters (Leaney et al. 1995; Gouramanis et al. 2010). As the culmination of the post-Last Glacial marine transgression occurred some 7000 years ago in southern Australia, the radiocarbon ages on the coastal landforms and associated deposits are commonly younger than this marker event. For fossil marine molluscs and other carbonates, a marine reservoir correction of approximately −450±35 years is required (Gillespie and Polach 1979).

6.4.4 Uranium-Series Dating

In view of the general absence of fossil corals within the temperate sedimentary carbonate realm of the Coorong Coastal Plain, few investigations have attempted to apply uranium-series dating to fossil marine invertebrates from the region. An exception is the analyses undertaken by Schwebel (1978). Schwebel (1978, 1983, 1984) reported ages on fossil molluscs and aragonitic muds from the back-barrier estuarine-lagoon facies of the Woakwine Range obtaining results consistent with a last interglacial age (MIS 5e) for this barrier complex. Uranium-series dating has, however, been applied to the speleothems and karst features of the Naracoorte Caves with considerable success and has constrained the extinction of some vertebrate taxa (Ayliffe and Veeh 1988; Ayliffe et al. 1998).

6.5 Summary and Conclusions

Geochronological methods are critically important for quantifying the rates of long-term landscape change of the Coorong Coastal Plain. Potentially, a range of geochronological methods can be applied to the dating of the coastal barriers of the Pleistocene Bridgewater Formation. Luminescence methods supplemented by amino acid racemization and electron spin resonance currently offer the greatest potential in establishing the ages of the coastal landforms, given their applicability to mixed quartz-skeletal carbonate sediments. Palaeomagnetism has also been important in delineating the position of the Brunhes-Matuyama boundary between the East and West Naracoorte Ranges and hence constraining the ages of a suite of barriers. While a broad-scale geochronological framework has been established, considerably more work is required to date the entire barrier succession. In view of the limited number of geochronological analyses undertaken on each barrier landform, as well as the lower age-resolving power of these methods, considerably more analyses will be required to reduce the statistical uncertainty of barrier ages. This will enable the more confident correlation of individual barriers with marine oxygen isotope stages. Another useful avenue for further research will be constraining the age range of some of the more significant breaks in deposition, manifested by the development of palaeosols and protosols within some of the barriers. The geographically wider application of palaeomagnetic analyses to include the Marmon Jabuk and Coonalpyn Ranges will also enhance the broader picture of regional coastal evolution, and provide insights about the relative ages of these barriers in relation to the East and West Naracoorte Ranges.

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7 Quaternary Sea-Level Changes and Coastal Evolution of the Coorong Coastal Plain, Southern Australia

Abstract

The sea level record of the Coorong Coastal Plain in southern Australia provides a chronicle of interglacial and interstadial sea-level highstands extending back in time for over the past 1 million years. East Naracoorte Range, one of the oldest and most landward coastal barriers considered in this book is at least of MIS 25 age but could be older (MIS 31). In a global context, the record is unique for its degree of preservation of relict coastal barrier landforms, as well as the number of interglacial events preserved in the stratigraphical record. The relative sea-level record from the coastal plain reveals that successive interglacial sea levels returned to a broadly common datum ranging between 9 m BPSL (Baker Range) to 3 m APSL (Harper Range). The inferred palaeosea-level record reveals no evidence for interglacial sea levels higher than the last interglacial maximum during the Middle Pleistocene. The record also reveals that MIS 11 is characterised by a more prolonged period of barrier development consistent with oxygen isotope records which indicate a longer duration for this interglaciation. Based on currently available geochronological evidence, Baker, Lucindale, Ardune and East Avenue Ranges all formed during the 'super-interglacial' MIS 11 with inferred palaeosea-levels ranging between 9 m BPSL for Baker Range and 2 m BPSL for the Ardune Range and East Avenue Range. Inferred relative sea levels for MIS 11 from the Coorong Coastal Plain are in accord with the EPICA Dome C ice core record which indicates larger ice volumes (lower sea levels) in MIS 11 than in MIS 5e. Over the past 1 Ma the coastal plain has prograded by over 90 km in its widest section in response to gradual epeirogenic uplift and sequential glacio-eustatic sea-level changes. Up to 20 coastal barriers formed during this period at times of high sea level. Quaternary volcanism (Early Pleistocene) created an archipelago of volcanic islands which influenced the geometry of the barriers in plan-view.

Keywords

Pleistocene sea-level changes · Interglacials and interstadials · Far-field · Holocene sea levels

Photos by the author, if not indicated differently in the figure/photo legend.

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7.1 Introduction

The Coorong Coastal Plain in southern Australia preserves a long record of Quaternary interglacial and interstadial sea-level highstands. The principal palaeosea-level indicators are open ocean beach facies and back-barrier, estuarine-lagoon facies as part of relict coastal barrier landform complexes. The coastal plain in association with the more landward succession of barriers of the Murray Basin of Early Pliocene to Early Pleistocene age, record the draw-down of global sea level accompanying glaciation and the progressive build-up of the Antarctic Ice Sheet (i.e. the continued transition from an ice free world to one characterised by fluctuating ice sheets; Kotsonis 1999; Bowler et al. 2006). The older, more landward succession of coastal barriers, termed the Loxton-Parilla Sands (Brown and Stephenson 1991) extends over 400 km inland from the Naracoorte Range towards the margin of the Murray Basin. The barriers occur up to 500 km inland from the modern coastline and up to 60 m APSL at their landward limit near the margin of the Murray Basin (Fig. 7.1). In parts of the Murray Basin the barriers occur at higher elevations resulting from localised uplift (e.g. 150 m APSL on the Padthaway High (McLaren et al. 2011). At least 600 relict shoreline features with a crest to crest spacing of 2–3 km and surface relief of 20 m have been identified within the strandplain of the Loxton-Parilla Sands (Bowler et al. 2006; McLaren et al. 2011). Stratigraphically, the upper portion of the Loxton-Parilla Sands comprises cross-bedded calcareous sands with shelly debris deposited as arcuate-shaped coastal barriers in plan form. The succession of barrier ridges represents a regressive sequence signifying the later stage of infill of the Murray and Otway Basins. Although their ages have yet to be precisely determined, preliminary $^{87}Sr/^{86}Sr$ analyses reveal that the ridges of the Loxton-Parilla Sands extend back in time to at least 6.86 ± 0.36 Ma (McLaren et al. 2011).

7.2 Relevance of Modern and Holocene Sedimentary Environments and Their Inferred Relative Sea-Level Records for Understanding Pleistocene Sea-Level Changes

Holocene sedimentary environments and their record of relative sea-level changes in southern Australia provide important insights for understanding the Pleistocene interglacial records of sea-level highstands on the Coorong Coastal Plain. Although the Holocene sedimentary record does not encompass a complete interglacial, it does cover a period of 7000 years since the culmination of post-glacial sea-level rise (Sloss et al. 2007; Lewis et al. 2013), and accordingly provides a template of facies models and the nature of depositional processes to compare with the ancient sedimentary successions.

Located in the extreme far-field of Pleistocene ice sheets, the Holocene sea-level highstand was attained earlier in southern Australia than in near- and intermediate-field sites around the world. In contrast, in south-eastern England in a near-field setting, present sea level was only attained within the past 2000 years (Shennan and Horton 2002). By implication, Pleistocene interglacial sea-level highstands, as recorded in the coastal barrier successions of the Coorong Coastal Plain, are likely to be of longer duration due to the earlier onset of highest sea level conditions than for equivalent interglacial successions in near- and intermediate-fields.

The limited ice cover in southern Australia, restricted to the Central Plateau and highlands of Tasmania (approximately 7000 km^2 during the Early Pleistocene at its maximum ice extent and thickness of 500–800 m; Colhoun et al. 2010) and the Snowy Mountains of the Great Dividing Range (with a probable area of 50 km^2; Galloway 1963; but more recently shown to be approximately 15 km^2 based on the mapping of outer moraines; Barrows et al. 2001), preclude localised glacio-isostatic adjustments as directly

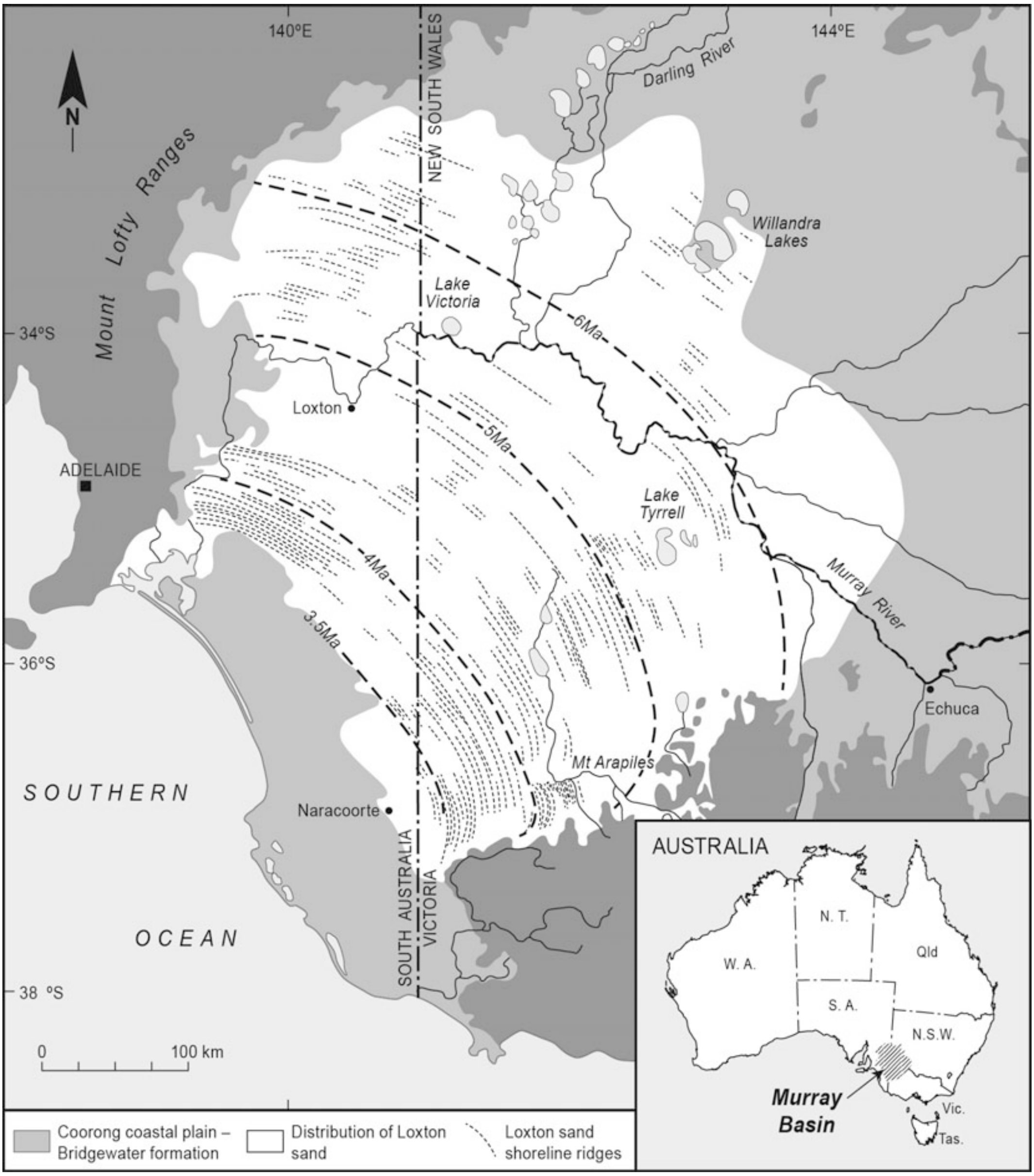


Fig. 7.1 Spatial distribution of siliciclastic Loxton-Parilla Sands within the Murray Basin, southern Australia, illustrating the general geometry of the relict shoreline successions and their inferred ages (linear accumulation model of Kotsonis 1999). The Pleistocene Bridgewater Formation comprising calcarenite (aeolianite successions) formed as coastal barriers on the Coorong Coastal Plain, seaward of the town of Naracoorte, and are younger than 1 Ma

contributing to the relative sea level records of the Coorong Coastal Plain or the southern Australian continental margin. Thus, the relative sea-level record is dominated by glacio-eustatic (ice-equivalent) sea-level changes with a minor and spatially variable hydro-isostatic contribution. The Holocene relative sea level record of southern Eyre Peninsula suggests up to 0.5 m of relative sea level fall following the Holocene highstand (Belperio et al. 2002), and a similar value may apply to the Coorong Coastal Plain given its geographical proximity to Eyre Peninsula, its open ocean setting, and location adjacent to a wide continental shelf.

Although located in the extreme far-field of Pleistocene ice sheets, the southern Australian continental margin is not immune to the effects of glacio-isostatic adjustments that occur within near-field regions. The estimated rate of present day relative sea-level change within the region due to elastic deformation of the solid Earth at a global scale, resulting from current deglaciation of glaciers and ice sheets is approximately 0–0.3 mm/year (Conrad 2013). In a similar manner, the postglacial viscous deformation of the wider southern Australian continental margin in response to past deglaciation is modelled at between −0.1 to 0.1 mm/year (Conrad 2013).

The Holocene depositional record within the Robe-Woakwine Corridor (see Chap. 3) shows that the coquinas formed by aggradation of shelly assemblages to present sea level, infilling the Late Pleistocene inter-barrier depression, and a similar mode of sedimentation is likely to have applied in earlier interglacials following the attainment of high sea level conditions. The Holocene record reveals that up to 3 m of shelly back-barrier estuarine-lagoon facies infilled the former landscape depression between the Robe and Woakwine Ranges over the period from 7000 to 2000 years ago (Cann et al. 1999). In many areas the Holocene shelly faunas are dominated by the cockle *Katelysia* sp., which frequents shallow water, protected estuarine environments, commonly representing the dominant mollusc genus in these settings. *Katelysia scalarina* commonly occurs within intertidal to shallow subtidal settings while *K. rhytiphora* tends to favour shallow subtidal waters immediately below the lower limit of the intertidal zone (Roberts 1984). Equivalent coquina facies dominated by *Katelysia rhytiphora* occurs in the back-barrier setting of the last interglacial (MIS 5e) Woakwine Range at Lake Hawdon South (Fig. 2.3a, b), but unlike the Holocene example, the shelly assemblages are coeval with the last interglacial barrier landform (Woakwine Range) and interfinger with back-barrier aeolian dune facies.

The modern Coorong Lagoon provides some insights about the likely position of sea level relative to the Pleistocene barriers at the time of their formation. The modern Coorong Lagoon comprises nine interconnected basins with a maximum water depth of up to 4 m commonly in the centre of each basin. Average water depth in the North Lagoon in summer is 1.2 ± 0.1 m (Noye and Walsh 1976) with the lagoon water surface ≤ 0 m AHD (Australian Height Datum—a geodetic datum for altitude measurements in Australia adopted in 1971 based on mean sea level for 1966–1968; Roelse et al. 1975). In winter, lagoon water level is approximately 0.4–0.8 m AHD (Webster 2007). A pronounced seasonal oscillation of water level of approximately 1–1.5 m results in part from higher winter sea levels, as well as alternating dominance of winter rainfall and summer evaporation. In addition to these variations, tidal oscillations account for 1 m of variability in the elevation of the lagoon water depth. It is likely that the back-barrier environments to the Pleistocene barriers were equally as dynamic in terms of seasonal water-level changes. Accordingly, the elevation of the upper bounding surface of the back-barrier estuarine-lagoon facies immediately landward, in the toe of the barrier structure, is likely to provide more reliable palaeosea-level information than the open ocean beach facies which Sprigg (1952) suggested had an uncertainty of approximately ± 3 m for inferred palaeosea-level. A realistic time-averaged water cover of 1.5 m above the sediment-water interface of the lagoon facies in this setting has been adopted in this investigation for estimates of palaeosea-level.

As several of the Pleistocene back-barrier lagoon environments were considerably wider than the modern Coorong Lagoon, attaining widths of up to 10 km, they might not have been completely flooded during sea-level highstands. The more easterly (landward) portions of the inter-barrier depressions may have been subaerially exposed depending on the elevation of the highstand. The back-barrier lagoonal flats in the lee of the West Avenue Range for example, in a line of section directly east of Robe, rise from 24 m APSL in the immediate lee of the dune range to 28 m APSL on the seaward side of the East Avenue Range some 8 km from the West Avenue Range.

7.3 Why the Coorong Coastal Plain Is Important for Understanding Interglacial Sea Levels

In a global context the preserved landforms and morphostratigraphy of the Coorong Coastal Plain and Murray Basin in southern Australia, represent one of the world's longest on-land interglacial and interstadial sea-level highstand records extending from Pliocene time through to the present (Sprigg 1948, 1952; Hossfeld 1950; Murray-Wallace et al. 2001; Bowler et al. 2006; McLaren et al. 2011). The record is important because it provides direct empirical evidence for the magnitude of relative sea-level changes from geomorphological and palaeosea-level indicators, rather than indirectly inferred from other sources such as oxygen isotope records from deep sea and ice cores.

As outlined in Chap. 1, the geographical location of the coastal plain is also significant for palaeosea-level investigations. The coastal plain is in the extreme far-field of the former, Pleistocene ice sheets so that the relative sea-level record is dominated by the processes of glacio-eustasy. The general absence of ice sheets in this far-field setting means that glacial isostasy is not locally expressed in the relative sea-level record of the region. The effect of glacio-isostatically induced sea-level changes occurring within near-field areas represents a very minor contribution to the overall magnitude of relative sea-level change affecting the coastal plain. In a similar manner, hydro-isostasy represents a minor component affecting the observed magnitude of sea-level variation during interglacial maxima within the region. In terms of a plate-tectonic setting, the coastal plain is located in a trailing-edge, passive continental margin, within an intra-plate region remote from plate boundaries and accordingly has not been subject to rapid tectonic uplift. Epeirogenic processes have been responsible for the emergence of the coastal plain, but the slow and monotonic nature of uplift, combined with the Mediterranean climate and regional calcrete development on the surfaces of the barrier landforms have assisted in preserving the morphostratigraphical record of relative sea-level changes. Located in one of the world's highest wave energy settings, there is a natural tendency for sand to accumulate within barrier structures on this passive margin.

The coastal plain has a low gradient in shore-normal cross-section (approximately 0.5%) and depending on the magnitude of relative sea-level rise during interglacials, the resultant barriers can be up to 10 km apart. Thus the coastal plain is geomorphologically very sensitive to subtle variations in relative sea level. The low gradient of the coastal plain means that on the seaward side of older barriers they may be less prone to erosion during a subsequent interglacial highstand provided that the magnitude of sea-level rise does not greatly exceed the level of the basal foot slope of the older barrier. The presence of the original coastal dune morphology preserved by calcrete on the former seaward side of older barriers, as well as beach ridges associated with the foot slopes of some of the barriers (possibly a product of forced regressions at the termination of sea-level hightsands), and the general absence of scarping by wave action during younger sea-level highstands for many of the barriers implies that relative sea-level highstands occurred within a narrow band-width of elevation. These observations accord with the findings of Belperio and Cann (1990) that interglacial sea levels did not deviate by more than ±6 m of present sea level for Middle and Late Pleistocene time indicating that the sea surface returned to a similar regional elevation.

Given its passive margin, intra-plate setting, the uplift rate of the Coorong Coastal Plain is slow in global terms being only 0.07 m/ka in the Robe area (Schwebel 1983, 1984; Belperio and Cann 1990) and 0.13 m/ka in the Mount Gambier area (Murray-Wallace et al. 1996). These slow rates of uplift are illustrated by the elevation of last interglacial (MIS 5e, 125 ka) shelly successions which occur between 6.4 and 11.6 m APSL within the McCourt Cutting near Beachport (Murray-Wallace et al. 1999) and up to 18 m APSL near Mount Gambier (Murray-Wallace et al. 1996). In a global context, this contrasts remarkably with other regions that preserve long highstand records such as subduction-related settings where the Earth's lithosphere is being reincorporated within the mantle. On the Huon Peninsula in Papua New Guinea for example, where rapid rates of co-seismic uplift range between 0.5–0.7 m/ka in the north-western portion of the peninsula to 3.3–3.5 m/ka in the south-east closer to the subduction zone, last interglacial (MIS 5e) reef successions range between 60 and 400 m APSL respectively (Chappell 1974). Similarly, in north-eastern Sicily, last interglacial (Tyrrhenian) marine terraces extend up to 130 m APSL (Bordoni and Valensise 1998).

7.4 Early Palaeosea-Level Frameworks for the Coorong Coastal Plain

The first serious attempts at assigning ages to, and inferring relative sea levels of presumed global applicability from the Quaternary barriers of the Coorong Coastal Plain (Tindale 1933; Hossfeld 1950; Sprigg 1952), involved global correlations of shoreline elevations and the assignment of interglacial and interstadial ages based on the four-fold model of Quaternary Alpine glaciation (Penck and Brückner 1909; Fairbridge 1961; Fig. 7.2). Correlations of shoreline elevations involved the widely held notion at the time, that sea levels had fallen progressively during the Quaternary as inferred from the Mediterranean region, and that the Quaternary record showed evidence for only four glaciations (Gignoux 1913; Daly 1934; Baulig 1935).

In evaluating previous attempts at assigning ages to the barriers, it is important to appreciate that in 1950 little was known about the complex nature of glacio-eustatic sea-level changes during the Quaternary. In addition, a critical line of evidence for understanding the relative ages and history of the dune ranges in terms of the Quaternary evolution of the coastal plain was the degree to which subsequent interglacial sea level highstands flooded the regional landscape, particularly in the lee of prior barriers. Related questions concerned whether the subsequent erosion of some of the barriers involved marine or subaerial denudation, and the former size of some barriers before erosion.

Tindale (1933) correlated several 'coastal terraces' (coastal barriers) of the Coorong Coastal Plain with relict shoreline features identified by Cooke (1930) from the Atlantic Coastal Plain of North America. Tindale suggested that there was a close correspondence for six barriers from the Coorong Coastal Plain noting that the Woakwine Range correlated with the Pamlico Terrace through to the Naracoorte Range correlating with the Brandywine Terrace (Fig. 7.3). The correlations were based on the assumptions that only glacio-eustatic sea-level changes were responsible for the relict shoreline elevations (i.e. excluding the feed-back effects of glacio-hydro-isostatic adjustments within both regions), that the series of shoreline complexes represent a complete record of sea-level changes, that the highest shoreline represented the oldest feature, and that successively younger shorelines were encountered with lower elevation. The differential elevation of the barriers along the shore-parallel length of the Coorong Coastal Plain due to regional tilting, however, significantly reduces the validity of correlations based on relict shoreline elevation as it potentially permits a wide range of elevation values to be selectively and uncritically used in shoreline correlations. Present day understanding also reveals that the two regions Tindale correlated (1933) have fundamentally different glacio-isostatic adjustment histories affecting their relative sea level records, with the Atlantic Coastal Plain representing near- and intermediate-field regions, and the Coorong Coastal Plain being in the extreme far-field of Pleistocene ice sheets (Clark et al. 1978).

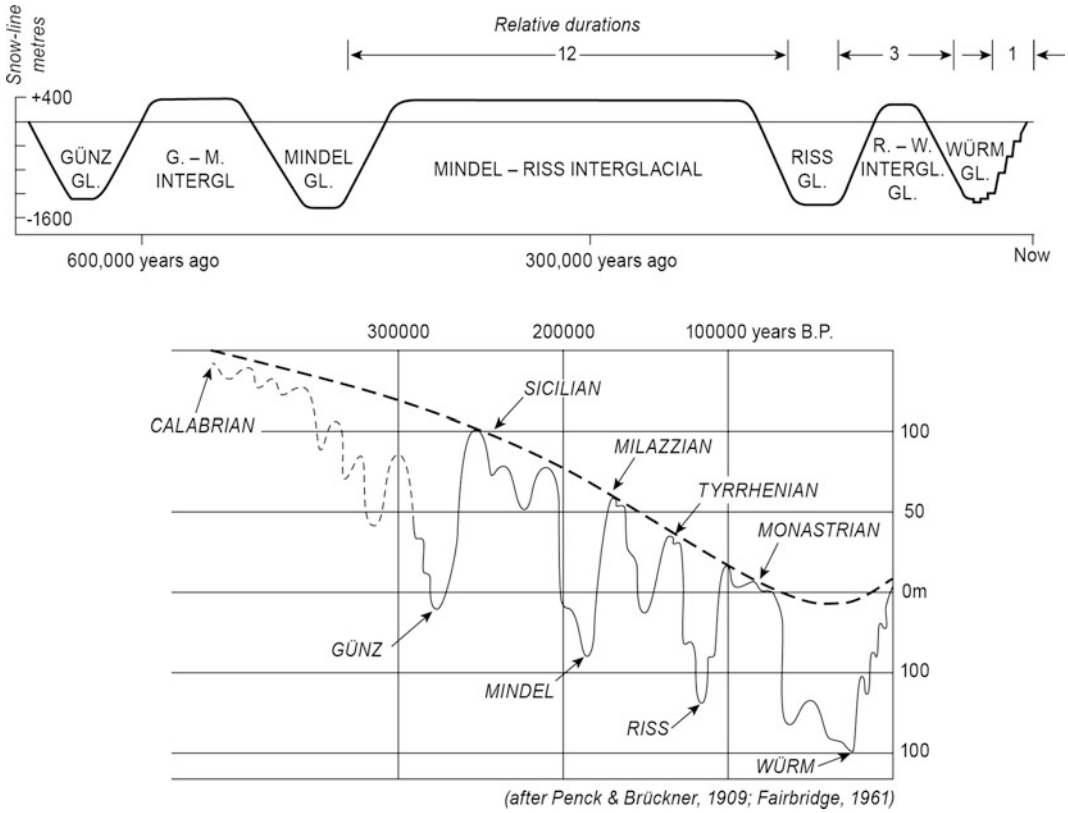


Fig. 7.2 The four-fold model of Alpine Glaciation as proposed by Penck and Brückner (1909) and glacio-eustatic sea-level oscillations as inferred from the Mediterranean region after Fairbridge (1961)—conceptual frameworks used in the early interpretations of the Quaternary relative sea-level records of the Coorong Coastal Plain. Note the compressed timescale of the Fairbridge curve compared with that assumed by Penck and Brückner

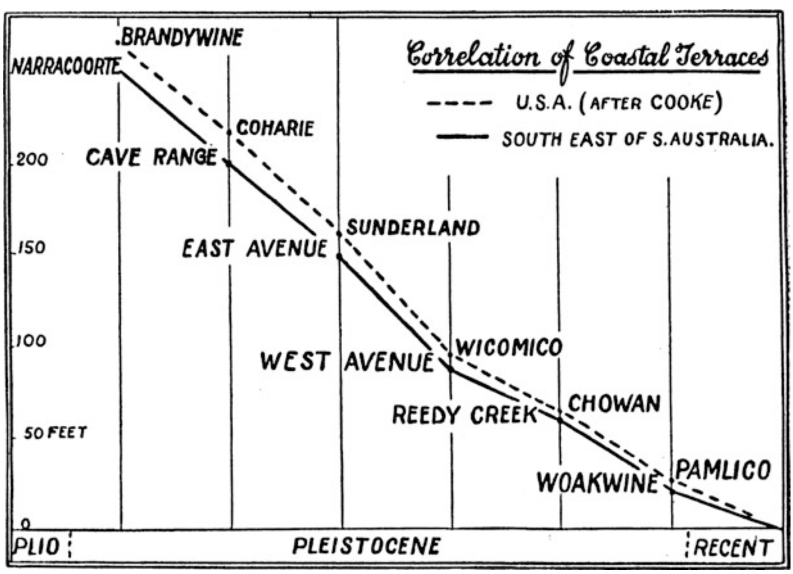


Fig. 7.3 Correlation of some of the coastal barriers of the Coorong Coastal Plain with marine terraces of the Atlantic Coastal Plain, North America (Tindale 1933; Reproduced with permission of the Royal Society of South Australia)

Hossfeld (1950) assigned ages to the coastal barriers based on the four-fold model of Quaternary Alpine Glaciation (Penck and Brückner 1909). In many respects the analytical approach illustrates the general difficulty, and in a sense his struggles, in using the highly constrained conceptual framework of the four-fold model of Alpine Glaciation for inferring the relative ages of the barrier successions. In assigning various barriers to parts of glaciations, the designations specifically referred to warmer interstadial sea level highstands during glacial cycles, rather than periods of low sea level during glacial maxima. Hossfeld reasoned that the East Naracoorte Range, presumed to be the oldest barrier shoreline, was therefore of 'Pre-Glacial' age. He also concluded that the West Naracoorte Range formed during the 'Second or Great Interglacial', that the Stewarts/Cave Ranges formed during the Third Interglacial as it was not submerged during the subsequent sea level rise after its formation, and that the Reedy Creek Range formed during the onset of the Penultimate (Third; Riss) Glaciation. Based on the above, Hossfeld considered that the West Avenue Range formed during either the First or Second Glaciation but favoured the maximum of the First Interglacial for this dune range. Following this reasoning, the second and third interglacial barriers were proposed to have formed landwards of the West Avenue Range, which represents a problem in terms of sufficient wave energy to build the younger coastal barrier landforms in the protected lee-side of an older barrier due to the limited fetch and wave energy required for barrier construction.

Having established these tie points, Hossfeld (1950) then assigned ages to the other barriers. He considered that Harper Range formed during the retreat of the sea heralding the Günz (First) Glaciation. The Woolumbool and Peacock Ranges were considered to represent stillstands during separate glaciations, with the more landward barrier, Woolumbool Range having formed first. In view of their highly eroded character he considered that both these ranges had been submerged and that they had accordingly formed during the Günz (Woolumbool) and Riss (Peacock) glacial cycles respectively. The Baker, Ardune and Reedy Creek Ranges were correlated with the Third (Penultimate or Riss) Glaciation and the Lucindale and East Avenue Ranges were correlated with the Fourth (Würm) Glaciation. Hossfeld noted the highly eroded character of the East and West Dairy Ranges and suggested that they correlated with the Second (Mindel) and Third (Riss) Glaciations respectively.

Based on a traverse of the Drain L drainage channel near Robe, Hossfeld (1950) noted the composite structure of the Woakwine Range and suggested the presence of four components (Fig. 2.17b). He concluded that the partly eroded portion of the Eastern Woakwine Range (component C) and component D of the Western Woakwine Range, which showed minimal erosion, probably related to two separate glaciations; Third (Riss) and Fourth (Würm) respectively. He also suggested that Woakwine A formed during an interstadial of the first glaciation (Günz) and that Woakwine B formed during an interstadial in the Second Glaciation (Mindel) respectively (Fig. 2.17b).

Hossfeld concluded that the low degree of cementation of the calcarenites of Robe Range compared with all the other dune ranges, attested to its geologically recent age, and that it formed in an '… interstadial oscillation of the Present or Fourth Interglacial or as some prefer, the Fourth Glaciation.' (Hossfeld 1950, p. 264).

Sprigg (1952) also assigned relative ages to the sequence of barrier landforms of the Coorong Coastal Plain based on their heights above present sea level and within the context of the four-fold model of Quaternary Alpine glaciation (Penck and Brückner 1909), and a compilation of elevations of Mediterranean relict shoreline features (Zeuner 1945, 1946; Fig. 7.4). He then invoked the Croll-Milankovitch Hypothesis using insolation curves of Milankovitch (1938) to assign numeric ages to the barriers across the coastal plain.

In the former approach, Sprigg (1952) adopted a less complicated framework of reasoning than Hossfeld (1950). He noted that Robe, Woakwine and the Dairy Ranges are composite barriers having formed in more than one sea level highstand, and that the older dune ranges had

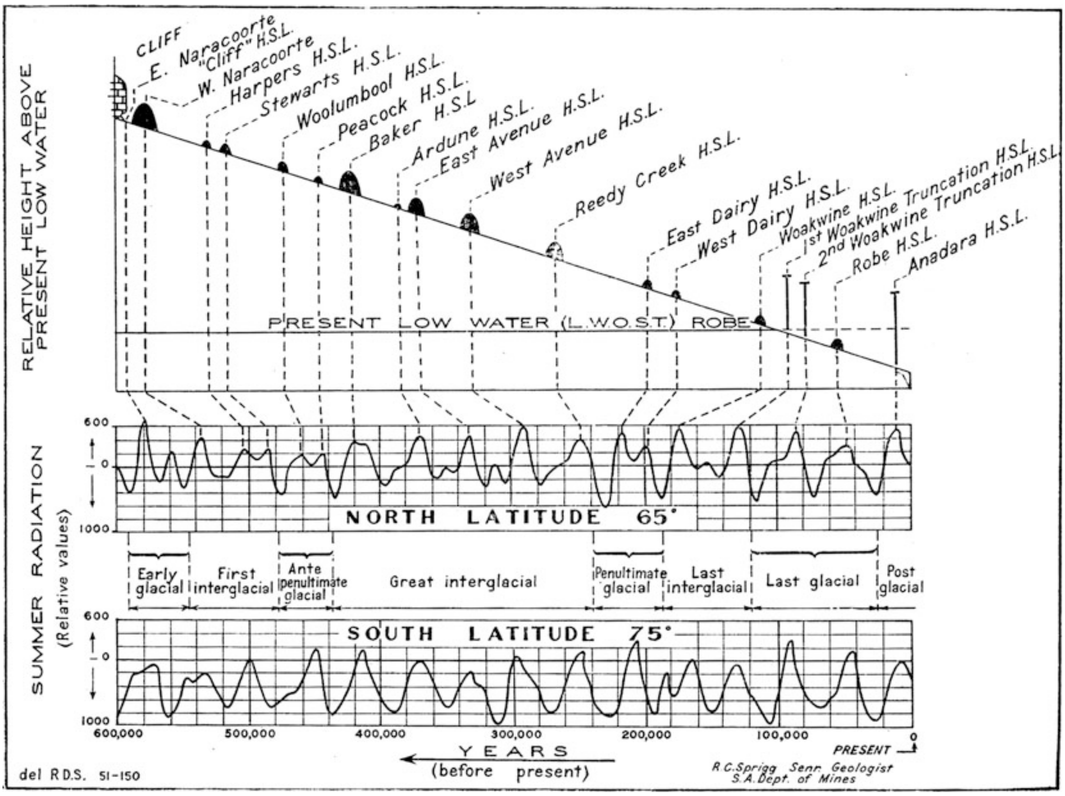


Fig. 7.4 Reg Sprigg's 1952 Milankovitch-based correlation of the coastal barriers of the Coorong Coastal Plain with the insolation curves as a framework for assigning numeric ages to the barriers (Reproduced with the permission of the Resources and Energy Group, Department of the Premier and Cabinet (DPC), South Australia)

each formed during single interglacial events. This framework implied that the barrier sequence formed in a unilinear fashion without overtopping of earlier barriers to form younger barriers in more landward situations. By comparing the elevation of the stranded beaches he assigned the Naracoorte Range to the Early Glaciation (Sicilian) representing the first barrier structure of the coastal plain. He then worked in a seaward direction assigning the Baker, Ardune, East Avenue and West Avenue Ranges to the Great Interglaciation (Milazzian), Reedy Creek Range to the Penultimate Glaciation (Tyrrhenian) and the Woakwine Range to the Last Interglaciation (Main Monastirian) and the Second truncation of Woakwine Range and the Robe Range to the Last Glaciation (Late Monastirian) respectively. The gradient of the coastal plain in Fig. 7.4 is schematic but illustrates the relative positions of the barriers.

Sprigg (1952) acknowledged that the heights of the shoreline successions did not agree with those presented by Zeuner (1945, 1946) and explained this in terms of differential neotectonic behaviour of the region, particularly warping of the Coorong Coastal Plain and the coalescence of many of the barriers in the northern sector of the coastal plain. Sprigg (1952) then used the Milankovitch (1938) north latitude 65° and south latitude 75° insolation curves to assign numeric ages to the barrier landforms. This involved two approaches. The first used a count from the top approach back in time from the youngest barrier (Robe Range) matching radiation maxima to earlier sea-level highstands. The second approach assumed that the Naracoorte Range formed following the early glaciation at 590 ka, and then correlated the successively younger barriers with the insolation maxima, representing Pleistocene warm (high sea level) events. Both these approaches revealed a high level of correspondence, which some workers at the time viewed with scepticism '…because the fit seemed too good…' (Sprigg 1989, p. 259). In the latter approach, it was critical that the Naracoorte Range represented the oldest barrier. In some respects this is problematic as the highly eroded Hynam Range, to the east of Naracoorte Range might have been a more appropriate choice as the oldest dune range of the barrier sequence. In a similar manner, the older more landward barriers that were then regarded as of Pliocene age (cf. the current presumption of their Early Pleistocene age) could potentially have been considered as tie points in the assignment of ages.

At the time of the publication by Sprigg (1952) it was generally considered that relative sea levels had progressively fallen in the Quaternary as seen in the stepped sequences of marine terraces in the Mediterranean region (Gignoux 1913; Daly 1934; Baulig 1935). Based on the evidence from the Coorong Coastal Plain, Sprigg (1952) implicitly accepted this phenomenon but also regarded that the coastal plain had been progressively uplifted (also acknowledging down-warp in the northern- and southern-most sectors of the coastal plain) and that sequential sea-level oscillations, superimposed on an emerging coastal plain explained the numerous barrier landforms. In this sense he reasoned that the barriers related to discrete sea-level highstands.

The approaches adopted by Tindale (1933), Hossfeld (1950) and Sprigg (1952) for assigning relative and numeric ages to the barrier successions of the Coorong Coastal Plain illustrates the strong intellectual constraint that remained during the mid-twentieth century imposed by the four-fold model of Quaternary Alpine Glaciation advanced by Penck and Brückner (1909).

7.5 Orbital Forcing Frameworks for Barrier Ages and Inferred Palaeosea-Levels

An understanding of the age of specific sea-level highstands inferred from the coastal barrier successions of the Coorong Coastal Plain was significantly enhanced by independent research on the application of oxygen isotopes for deriving long, and presumed continuous, records of Quaternary climate change (Emiliani 1955; Shackleton and Opdyke 1973; Hays et al. 1976). The ability to infer ice volume and as a corollary, glacio-eustatic sea-level changes for long-time series, revolutionized the understanding of the complex nature of Quaternary eustatic sea-level history. The recognition of systematic and sequential changes in the stable isotope composition of foraminifers with time in deep sea sediment cores, corroborated the Croll-Milankovitch Hypothesis that changes in the Earth's orbital configuration could explain coherently, insolation changes and the resultant periodic phases of glaciation and sea-level fluctuations at a global scale (Murray-Wallace and Woodroffe 2014; Summerhayes 2015). This resulted in the paradigm of Orbital Forcing based on oxygen isotope results for the foraminifer *Globigerina bulloides* from two deep sea sediment cores in the southern Indian Ocean (Hays et al. 1976). Hays et al. (1976) concluded that the observed spectral peaks occurred over time intervals of 23, 42 and 100 ka. Significantly, research on the application of oxygen isotopes to stratigraphy provided compelling evidence for more than the four glaciations in the Quaternary period suggested by Penck and Brückner (1909).

Stratigraphical investigations and uranium-series dating of emergent coral reef complexes such as the Huon Peninsula, Papua New Guinea (Bloom et al. 1974; Chappell 1974; Chappell and Shackleton 1986; Chappell et al. 1996) and Barbados (Mesolella et al. 1969; Matthews 1973) coincident with oxygen isotope studies of deep sea sediment cores, provided critical temporal calibration for oxygen isotope records. In particular, the correlation of dated reef terraces associated with the Last Interglacial Maximum (MIS 5e, c. 125 ka), and the two warm interstadials of the last interglacial sensu lato, MIS 5c at 105 ka and MIS 5a at 82 ka represented critical tie points for assigning ages to oxygen isotope records from deep sea cores. Collectively this body of research represented a major breakthrough for Quaternary science in a global context as it represented a record of globally synchronous events, and in particular, fluctuations in volume of the continental ice sheets and valley glaciers. As Shackleton and Opdyke (1973, p. 48) remarked;

> …it is highly unlikely that any superior stratigraphic subdivision of the Pleistocene will ever emerge. Even more important, this subdivision is a convenient one to use because the underlying variable which we are using to correlate is the volume of terrestrially stored ice.

The wide-spread acceptance of Orbital Forcing as a paradigm in Quaternary science in the latter 1970s highlights the prescient research achievements of Sprigg (1952) in evaluating the sedimentary record of the coastal plain based on Milankovitch insolation curves. Since then, oxygen isotope records have provided important temporal frameworks for indirectly evaluating the age and relative sea-level records from the Coorong Coastal Plain.

Schwebel (1978, 1983, 1984) derived a palaeosea-level curve for the past 400 ka for the western portion of the Coorong Coastal Plain, in a transect from Robe inland towards Naracoorte (Fig. 7.5). The palaeosea-level record was derived from the Robe, Woakwine, Reedy Creek, East and West Dairy Ranges and the West Avenue Range (Fig. 7.5). He found that depending on which dune ranges were studied the uplift rates ranged between 0.05 and 0.09 mm/year and based on an average rate of uplift of 0.07 mm/year, concluded that the broad pattern of inferred relative sea-level changes for the last glacial cycle agreed with the previously derived records from Barbados and Huon Peninsula, Papua New Guinea (Matthews 1973; Bloom et al. 1974; Chappell 1974). Schwebel also concluded that interglacial sea levels during the period 400 ka to 125 ka ago (MIS 11 to MIS 5e) were no higher than present. The morphostratigraphical evidence used for inferring palaeosea-level included the elevations of several features such as marine abrasion surfaces, the facies boundary between beach-dune units, lagoonal facies and palaeosols. The palaeosea-level record primarily documents the culminations of post-glacial sea-level rise (highstands) and the range in the inferred sea level associated with each highstand takes into account the relative thickness of the barrier successions. Uplift-corrected sea levels for the past three interglacials included 2–7 m APSL for the last interglacial maximum (MIS 5e) component of Woakwine Range, 8-3 m BPSL for MIS 7e (Reedy Creek Range), up to 27 m BPSL for MIS 9 (East Dairy Range) (Schwebel 1984).

In his study of the Coorong Coastal Plain, Schwebel (1978, 1983) also correlated the barriers across the entire coastal plain with the oxygen isotope record from the equatorial Pacific Ocean deep sea core V28-239 (Shackleton and Opdyke 1976). This represents the first attempt at an isotopically-based land-sea correlation of the coastal plain barrier successions. Based on a count from the top approach from the modern coastline, landwards across progressively older barriers of the coastal plain, Schwebel (1983) correlated the Late Pleistocene component of Robe Range with MIS 5c (Robe III; 93 ka), MIS 5a (Robe II; 83 ka) and the Holocene (Robe I; 4 ka). The Roman numeral scheme proposed by Schwebel for the Robe Range does not conform to a straight forward time-location sequence as the Robe III barrier is topographically higher in the landscape than Robe II due to their associated interstadial sea levels. Thus, stratigraphically, Robe III is unconformably overlain by Robe I, and Robe II abuts and partially overlies Robe III as it is located in a more seaward position.

Schwebel (1983, 1984) suggested that there were five stratigraphical components to the Woakwine Range and correlated these with the last interglacial maximum (MIS 5e –Woakwine I; 120 ka), penultimate interglacial (MIS 7—Woakwine II and III; 203 ka and 218 ka

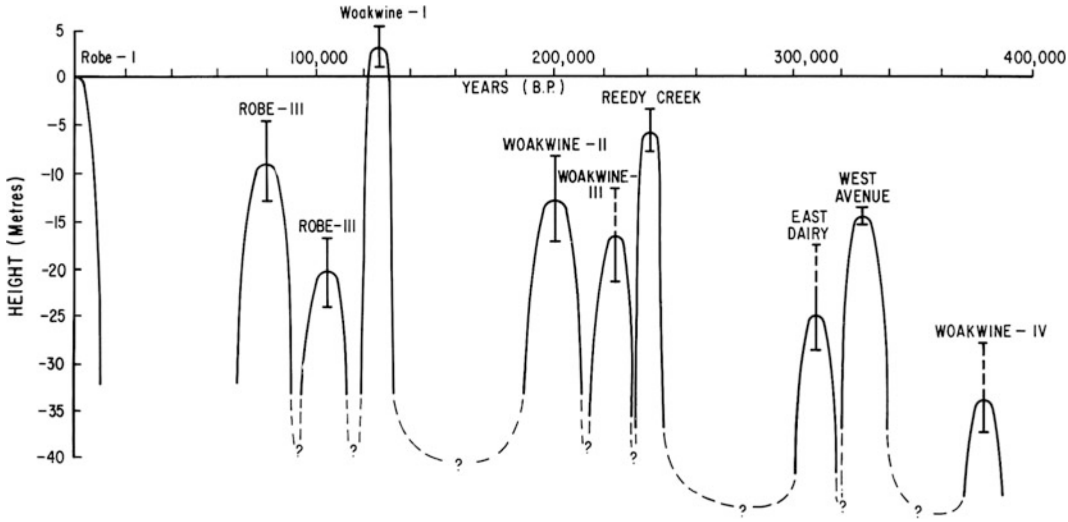


Fig. 7.5 Inferred relative sea-level curve for a portion of the Coorong Coastal Plain, southern Australia. The inferred palaeosea-levels relate to a line of section from Robe across towards Naracoorte (specifically Robe Range across to the West Avenue Range) and apply to the past 400 ka of coastal evolution modified after Schwebel (1978, 1983)

respectively), and MIS 11 (Woakwine IV; 384 ka and Woakwine V; numeric age not designated). In the absence of geochronological evidence, this stratigraphical subdivision of the Woakwine Range should be viewed with caution, as further discussed in Sect. 7.6.3. The remaining dune ranges Schwebel correlated in the following manner; East Dairy (MIS 9; 309 ka), Reedy Creek (MIS 7; 248 ka), West Avenue (MIS 9; 347 ka), East Avenue, Ardune and Baker Range (MIS 11), Woolumbool and Stewarts (MIS 13), Harper and West Naracoorte I and II (MIS 15), West Naracoorte III (MIS 17) and West Naracoorte IV (MIS 19; Table 7.1). The correlations involved limited geochronological control, principally a last interglacial (MIS 5e; 125 ka) age for the Woakwine Range based on uranium-series dating of fossil molluscs and aragonitic sediments from the back-barrier estuarine-lagoon facies (Schwebel 1978), and the Brunhes–Matuyama geomagnetic polarity reversal between the East and West Naracoorte Ranges, then dated at 690 ka (Idnurm and Cook 1980).

Belperio and Cann (1990) documented barrier shoreline elevations and uplift-corrected sea levels for each barrier of the Coorong Coastal Plain in a transect from Robe to Naracoorte. They assumed that apart from the Robe, Woakwine and West Naracoorte Ranges, which are composite structures, all the other barriers related to a single highstand event that could be matched with the oxygen isotope record. Belperio and Cann (1990) invoked a count from the top approach in a unilinear manner for assigning ages to the successive barriers, and determined an uplift rate of 0.07 m/ka which they assumed to be constant for the past 1 Ma. They also concluded that the relict estuarine-lagoon facies provided a more reliable indicator of palaeosea-level than the beach facies on the seaward side of the barriers. The notion that each barrier landform developed during a single interglacial sea level highstand, was supported by a series of continuously cored drill holes through the sequence of barriers (Cook et al. 1977; Schwebel 1978).

The uplift-corrected palaeosea-levels determined by Belperio and Cann (1990) assumed a 2 m APSL local reference for sea level during the Last Interglacial Maximum (MIS 5e) as determined from shelly facies of the Glanville

Table 7.1 Marine isotope stages and inferred palaeosea-levels from the coastal barriers of the Coorong Coastal Plain, southern Australia

Dune range	Marine isotope stage				Shoreline elevation (m)	Uplift-corrected sea level (m)
	Schwebel (1983, 1984)	Belperio and Cann (1990)	Huntley et al. (1993a, b, 1994)	This work		
Central and Northern region						
Robe I/Younghusband Peninsula	1	1	1	1	0.5	0
Robe II	5a	5c		5a		
Robe III	5c		5c	5c		
Woakwine I	5e	5e	5e	5e	10	–
Woakwine II	7a			7e		
Woakwine III	7e			7e		
Woakwine IV	11			–		
Woakwine V	11			–		
West Dairy			7a	7a		
East Dairy/Kongorong		7a	9	7	8	7
Reedy Creek	7e	7e	7e	7e	18	-3
West Avenue	9	9	9a	9	24	-3
East Avenue	11	11	9c	11	26	1
Ardune	11	11	13	11		
Lucindale				11		
Baker	11	13	11c	11	34	-7
Woolumbool/Peacock	13	15	15.3	15	40	-2
Stewarts/Cave	13	17	17	17	45	3
Harper	15	17	13	15/17	45	3
West Naracoorte I	15	19	<780 ka	19	59	-6
West Naracoorte II	15	21		21		
West Naracoorte III	17			–		
West Naracoorte IV	19			–		
East Naracoorte		25–59?	21 or 25	21 or 25	65	
Hynam–Koppamurra				>25		
Black		19		19		
Mount Monster		21				
Coonalpyn		25–59?				
Cannonball Hill Range						

(continued)

Table 7.1 (continued)

Dune range	Marine isotope stage				Shoreline elevation (m)	Uplift-corrected sea level (m)
	Schwebel (1983, 1984)	Belperio and Cann (1990)	Huntley et al. (1993a, b, 1994)	This work		
Mount Gambier region						
Dismal				19	70	
Mingbool				17		
Compton				15/17	50	2 ± 2
Glenburnie				13		
Gambier				11	50	
Caveton				9	38	4 ± 1
Burleigh				7	36	−9 ± 2
MacDonnell				5e	11	
Robe III (Canunda)				5c	0	−14 ± 2

Formation on western Eyre Peninsula, site of the tectonically stable Gawler Craton (Murray-Wallace and Belperio 1991; Murray-Wallace et al. 2016). The long-term uplift rate of 0.07 m/ka was derived by linear regression of the elevation data for the surfaces of back-barrier lagoon facies in a transect across the relict coastal barriers (Belperio and Cann 1990). The uplift rate they determined agreed with the average value Schwebel (1978, 1983, 1984) had derived for the more seaward portion of the coastal plain (i.e. for the barriers seaward of, and including the West Avenue Range).

Belperio and Cann (1990) used the oxygen isotope scheme of Williams et al. (1988) to assign ages to the coastal barriers. They concluded that the dune ranges correlated in the following manner; Robe I (Younghusband Peninsula)—MIS 1; Robe II—MIS 5c; Woakwine I—MIS 5e; West Dairy—MIS 5e; East Dairy—MIS 7a; Reedy Creek—MIS 7e; West Avenue—MIS 9; East Avenue—MIS 11; Ardune—MIS 11; Baker—MIS 13; Peacock/Woolumbool—MIS 15; Stewarts (Cave)—MIS 17; Harper—MIS 17; West Naracoorte I/Black Range—MIS 19; West Naracoorte II/Mount Monster—MIS 21; and East Naracoorte/Coonalpyn Range—MIS 25-59? (Table 7.1).

From Baker Range landwards to the Naracoorte Range, the dune ranges were assigned to different Marine Isotope Stages by Schwebel (1983, 1984) and Belperio and Cann (1990) with a tendency for Schwebel to assign successive barriers to the same marine isotope stage and for Belperio and Cann to correlate the barriers with successive isotope stages (Table 7.1). The assignment of the East Naracoorte/Coonalpyn Range to 'MIS 25-59?' (Belperio and Cann 1990), was to keep an open mind for the age of this barrier complex in view of the absence of firm geochronological evidence, apart from the fact that it predated the Brunhes–Matuyama geomagnetic polarity reversal.

Huntley et al. (1993a) used the ages of oxygen isotope events (i.e. based on the timing of the apex of interglacial events rather than their duration) reported by Imbrie et al. (1984) as a framework for the correlation of their thermoluminescence ages for the barriers (Table 7.1). Notably their chronology for the succession of barriers between the Ardune Range and West Naracoorte I Range reveals three instances where younger dune ranges are considered to have formed in the protected lee settings of older barriers. In this scheme they assigned Baker Range to MIS 11.3 age while the more seaward

Ardune Range was assigned to MIS 13.11. In a similar manner, they assigned Stewarts (Cave) and Harper Ranges to MIS 13.11 and MIS 13.13 respectively as younger dune ranges landward of the older Woolumbool Range (MIS 15.3).

Huntley et al. (1993a) derived model ages for the barriers that involved a variable rate of uplift. They determined an uplift rate of 0.08 m/ka for Naracoorte Range and 0.02 m/ka with an acceleration of −0.0001 m/ka^{-2} for Robe Range. Their model implied that the long-term uplift rate for the Robe area over the past 700 ka was 0.055 m/ka with a modern rate of 0.02 m/ka, which they acknowledged was significantly lower than the values determined by Schwebel (1983, 1984), and Belperio and Cann (1990). Huntley et al. (1993a) adopted this approach in order to correlate the 238 ka highstand with Reedy Creek Range, and the 216 and 196 ka sea levels with Woakwine III and II respectively. They also noted that their thermoluminescene ages appeared systematically older, on average by up to 13% than the dune-model ages up to 500 ka.

While the rate of uplift of the coastal plain as previously stated is slow in a global context, it remains critical in making inferences about palaeosea-level. Based on the elevation of back-barrier lagoon facies immediately backing each barrier, Belperio and Cann (1990) and Belperio (1995) have favoured a uniform rate of uplift throughout the history of the coastal plain of 0.07 m/ka in a line of section between Robe and Naracoorte. Linear regression of the elevation of the back-barrier lagoon facies suggests monotonic uplift over the past 1 Ma.

The uplift-corrected palaeosea-levels reported by Belperio and Cann (1990) and Belperio (1995) for the interval since the Brunhes–Matuyama geomagnetic polarity reversal (781 ka) reveals that sea levels during interglacial maxima rose repeatedly to a broadly common level that did not deviate by more than 6 m from present sea level (Table 7.1). The value of 9 m BPSL for Robe Range III (not II as stated by Belperio and Cann 1990) relates to deposition during the warm interstadial MIS 5c of the last glacial cycle (Huntley et al. 1994) rather than during the interglacial maximum. With the exception of a shelly unit exposed near sea level at Port MacDonnell (Blakemore et al. 2014; and see discussion in Sect. 2.9.9), only aeolian dune facies of Robe Range II and III are preserved above present sea level for the entire coastal plain.

The slow uplift rate of the coastal plain explains the empirical observation that younger back-barrier, estuarine-lagoon facies, not coeval with barrier development may also occur in the lee of some of the coastal barriers across the coastal plain. In these instances, younger estuarine-lagoonal facies rest disconformably on older back-barrier deposits coeval with the barrier successions. Their stratigraphical relationship differs from back-barrier facies coeval with barrier development; the latter interfinger with landward advancing back-barrier dune sediments attesting to their age equivalence. Examples of back-barrier, estuarine–lagoonal facies not coeval with barrier development include the Holocene coquinas in the lee of Robe Range within the Robe-Woakwine Corridor (Cann et al. 1999) and last interglacial (MIS 5e) shelly sands with abundant molluscs such as the cockle *Katelysia rhytiphora* (Murray-Wallace et al. 1999) 13 km landward of the Woakwine Range in the lee of East Dairy Range (MIS 7a), a barrier landform dated by TL at 258 ± 25 ka (Huntley et al. 1993a).

The slow rate of tectonic uplift also explains the composite structure of some of the barriers such as Robe, Woakwine and West Naracoorte Ranges (i.e. that they have not been sufficiently uplifted after the completion of one glacial cycle to have been removed from the influences of marine erosion and coastal sedimentation during a subsequent interglacial maximum). Thus in McCourt Cutting near Beachport, although volumetrically the majority of the sediment within the Woakwine Range was deposited by aeolian processes during the Last Interglacial Maximum (MIS 5e), an older, inner core of sediment of Penultimate Interglacial (MIS 7) age has been identified beneath a marine ravinement surface (Murray-Wallace et al. 1999). Similarly, in Drain L near Robe, a major drainage cutting of the Anderson Scheme, the deeper exposures through the Woakwine Range at this locality reveal that the barrier comprises several separate units separated by 'rounded pebbles, boulders, shells and *Anadara* etc.—Horizon A', 'shells and detritus—Horizon B' and a marine abrasion surface (Hossfeld 1950, p. 247). Sprigg (1952, p. 50) considered that the Drain L exposure through the Woakwine Range indicated '… at least three complete or partial marine submergences.', and Schwebel (1978, 1983, 1984) suggested the presence of five separate components within the Woakwine Range.

7.6 Nature of the Pleistocene Sea Level Record Inferred from the Coorong Coastal Plain

The low gradient and general elevation of the Coorong Coastal Plain land surface renders the landscape particularly sensitive to recording the maximum extent of sea-level rise during interglacials. That the barrier systems are substantial landforms between 20 and 40 m in height above the general level of the coastal plain, and ranging from 2 to 4 km wide in cross-sectional profile, explains why they record the culmination of post-glacial sea-level rise, the ensuing sea level highstand and the early phase of sea-level fall (forced regression). These stratigraphical relationships are evident within the Last Interglacial (MIS 5e) Woakwine Range which reveals a thin transgressive facies with shelly gravel immediately preceding the attainment of the highstand, the period of highstand marked by limited coastal progradation on the seaward side of the barrier and penecontemporaneous landward movement of parabolic dunes under the influence of high energy on-shore winds. The subsequent early portion of a forced regression and relative fall of sea level, manifested by beach ridge development is also evident within the record (Murray-Wallace et al. 1999). Thus, the relative sea level record from the Coorong Coastal Plain is a discontinuous record represented by successive sea level hightsands, in contrast to continuous records based on oxygen isotope profiles from deep sea sediment and ice cores that chronicle ice volume, and as a corollary, glacio-eustatic sea-level changes throughout glacial cycles (Siddal et al. 2006; Rohling et al. 2008).

7.6.1 Uplift-Corrected Palaeosea-Levels Derived from the Coorong Coastal Plain

The uplift-corrected palaeosea-levels determined by Belperio and Cann (1990) reveal that for the past 800 ka, successive interglacial sea-level highstands did not exceed the high sea level of the Last Interglacial Maximum (MIS 5e; Table 7.1), which at sites in southern Australia closest to the Coorong Coastal Plain, but within geotectonically more stable settings, have been found to range between 2.1 ± 0.5 m to 4.8 ± 1 m APSL (Murray-Wallace and Belperio 1991; Murray-Wallace et al. 2016; Pan et al. 2018). The relative sea levels determined by Belperio and Cann (1990) used a value of 2 m APSL for the high sea level of the Last Interglacial Maximum (MIS 5e) to determine the rate of uplift of the coastal plain in the line of section between Robe and Naracoorte.

Based on the data presented by Belperio and Cann (1990), average sea level for all the highstands including warm interstadial Robe Range III (MIS 5c) and the Last Interglacial Maximum (MIS 5e) was 1.5 ± 3 m BPSL (1σ-uncertainty) or 1.8 ± 3 m BPSL (1σ-uncertainty) if the value for MIS 5e is not included. If the inferred palaeosea-level for interstadial Robe Range is excluded, then average sea level for the Middle Pleistocene interglacials and including the Last Interglacial Maximum (MIS 5e) was 1 ± 2 m BPSL (1σ-uncertainty). The uplift-corrected palaeosea-levels are broadly consistent with the oxygen isotope record derived from the EPICA Dome C ice core from Antarctica in terms of the relative intensities of interglacials, although the Dome C record suggests higher sea levels for

MIS 9 and 11 than evident from the Coorong Coastal Plain (Masson-Delmotte et al. 2010).

7.6.2 The Coorong Coastal Plain—A Revised Palaeosea-Level History

Reassessment of the palaeosea-level record from the Coorong Coastal Plain in this study, based on Shuttle Radar Topography Mission (SRTM) imagery, additional survey information and the suite of geochronological information currently available suggest some minor refinements to those inferred by Belperio and Cann (1990; Table 7.1). As summarised in Chap. 6, numerous geochronological investigations have been undertaken within the region since the report by Belperio and Cann (1990). The former study used topographical maps (1:50,000) to derive palaeosea-level information based on the elevation of the upper surface of back-barrier lagoon facies in the immediate lee footslope of the barriers. This approach introduced an uncertainty of ±2.5 m in palaeosea-level estimation.

In the present study the EPICA Dome C ice core record from Antarctica (Masson-Delmotte et al. 2010; Fig. 7.6) is used as a chronological framework for the timing of oxygen isotope stages and their correlation with the geochronologically-derived ages (TL, OSL and AAR) for the coastal barriers. SRTM images were used for estimating regional relative topography (uncertainty ±6 m) and altitude at discrete points (uncertainty ±16 m) in estimations of palaeosea-level. In view of these large uncertainties, critical sites were surveyed by theodolite to South Australian Lands Department bench marks, which involved an uncertainty of ±5 cm. In addition, for determining the rate of uplift of the coastal plain in the line of section between Robe and Naracoorte, a value of 3 m APSL was adopted for the sea level attained during the Last Interglacial Maximum (MIS 5e) based on additional investigations from the tectonically stable Eyre Peninsula in southern Australia (Murray-Wallace et al. 2016), instead of the 2 m APSL value previously adopted (Belperio and Cann 1990). However, in using the revised value for the determination of uplift rate and subtracting it from the maximum elevation of a transgressive lag deposit that extends up to 11.6 m APSL in the central portion of the Last Interglacial (MIS 5e) Woakwine Range (McCourt Cutting site near Beachport), as well as the presence of shallow subtidal *Katelysia* sp., shells in the back-barrier lagoon facies (Murray-Wallace et al. 1999) yielded the same long-term rate of uplift when rounded to two decimal places of 0.07 m/ka. In a similar manner, the calculation of a longer-term uplift rate based on the elevation of the back-barrier lagoon facies in the immediate lee of six Middle Pleistocene age barriers, against the mid-point of Marine Isotope Stages as determined from the EPICA Dome C ice core (Masson-Delmotte et al. 2010), and excluding the Last Interglacial Woakwine Range (MIS 5e) from the calculation yielded an uplift rate of 0.074 m/ka (Table 7.2). This uplift rate is in accord with the findings of Schwebel (1978, 1983, 1984) and Belperio and Cann (1990).

In this investigation palaeosea-level (Psl) was determined based on the following equation:

$$\mathrm{Psl}_t = tu - (h + d)$$

where t is the time (age) of the emergent back-barrier estuarine-lagoon facies, u is the uplift rate, h is the elevation of the feature above present sea level (APSL) and d is the water depth at the time of sedimentation, in this case inferred to be 1.5 m (see Sect. 7.2).

Palaeosea-level inferred for the Penultimate Interglacial (MIS 7) from the Coorong Coastal Plain relates to two events, MIS 7e and MIS 7a (Fig. 7.7). The Penultimate Interglacial Maximum (MIS 7e at 250 ka or 245.6–233.6 in the EPICA Dome C ice core) is represented by Reedy Creek Range dated at 258 ± 25 ka by Huntley et al. (1993a) and 251 ± 48 ka by 'whole-rock' AAR (Murray-Wallace et al. 2001) has an inferred palaeosea-level of 1 m BPSL consistent with the magnitude of this interglacial as determined in the EPICA Dome C ice core (Masson-Delmotte et al. 2010). Belperio and Cann (1990) derived a similar palaeosea-level of

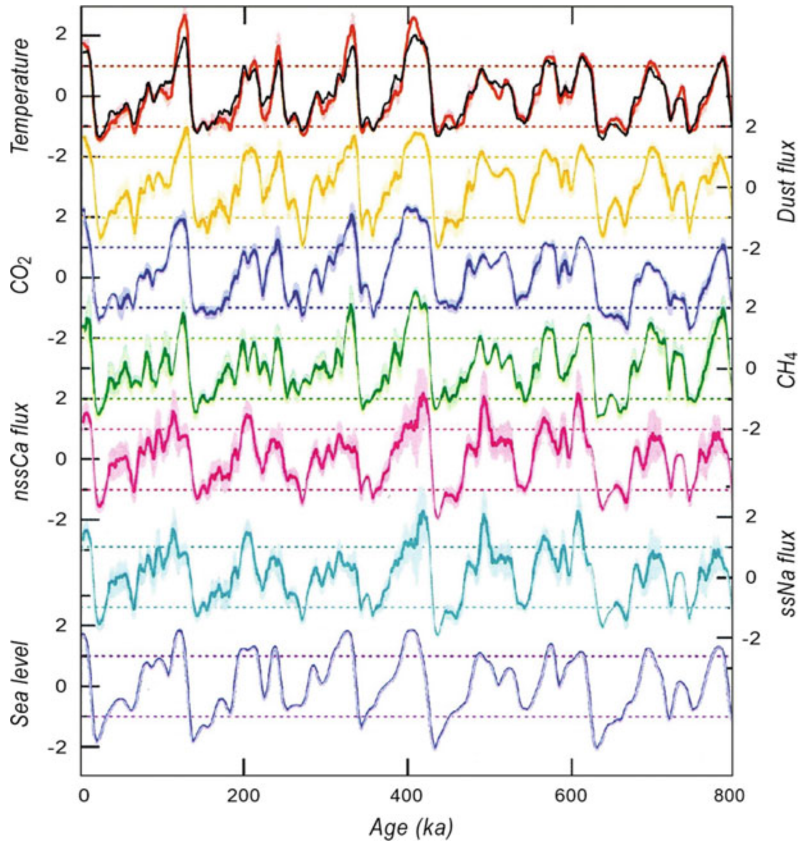


Fig. 7.6 The European Project for Ice Coring in Antarctica (EPICA) Dome C ice core record for the past 800 ka, an oxygen isotope framework for evaluating the record of sea-level highstands from the Coorong Coastal Plain, southern Australia. Adapted from Mason-Delmotte et al. (2010). Reproduced with the permission of Elsevier

Table 7.2 Age and elevation of back-barrier lagoon facies for six Middle Pleistocene Dune Ranges within the chronological framework of the Antarctic EPICA Dome C ice core record

Dune Range	MIS	MIS duration (ka)	MIS mid-point	Back-barrier facies elevation (m)	Inferred uplift rate (m/ka)[a]
Reedy Creek	7e	245.6–233.6	239.6	17	0.071
West Avenue	9	335.6–316.8	326.2	24	0.074
East Avenue	11	424.6–392.0	408.3	29	0.071
Baker	13	529.6–470	499.8	37	0.091
Peacock/Woolumbool	15.1	580–560	570	43	0.075
Harper/Stewarts/Cave	17	720–680	700	45	0.064

[a]Mean uplift rate 0.07 m/ka

0 m (i.e. present sea level) for Reedy Creek Range. Interstadial MIS 7a is represented by the East Dairy/Kongorong Range with an inferred age of 200 ka which records a palaeosea-level of 6.5 m APSL compared with a value of 6 m BPSL as determined by Belperio and Cann (1990). However, if the TL age of 292 ± 25 ka reported by Huntley and Prescott (2001) is used,

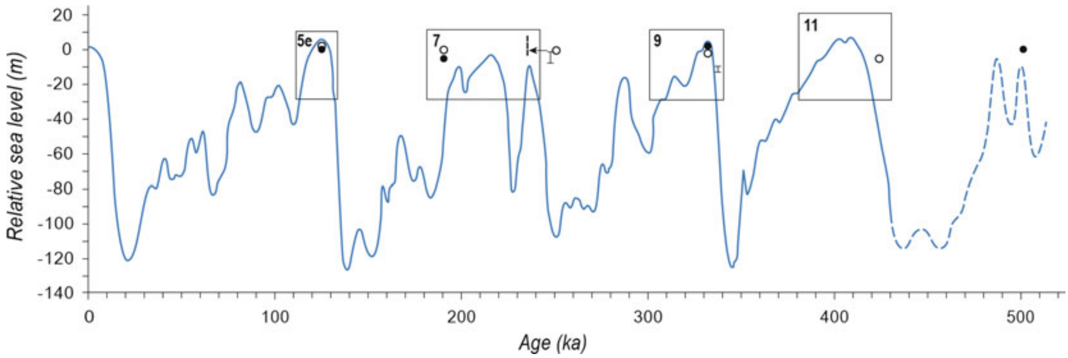


Fig. 7.7 Glacio-eustatic sea levels for the past 500 ka. The primary sea level curve is based on the compilation by Waelbroeck et al. (2002) based on oxygen isotope records from the North Atlantic, Southern Indian and Equatorial Pacific Oceans. The vertical uncertainty bars are based on the palaeosea-level estimates of Schwebel (1983), solid circles are the inferred palaeosea-levels of Belperio and Cann (1990), and open circles from this study based on more recently derived geochronological evidence

then a palaeosea-level of 13 m APSL is suggested which is unlikely given the long-term rate of uplift of the coastal plain.

The Antepenultimate Interglacial (MIS 9; 350 ka in the record of Williams et al. 1988) and bracketed between 335.6 and 316.8 in the EPICA Dome C ice core (Masson-Delmotte et al. 2010), is represented by the West Avenue Range which has been dated at 342 ± 32 ka by Huntley et al. (1993a) and 315 ± 25 ka by Huntley and Prescott (2001). An uplift-corrected sea level of 2.5 m BPSL has been determined for West Avenue Range based on a mean TL age of 329 ka. Belperio and Cann (1990) derived a palaeosea-level of 1 m BPSL for West Avenue Range.

Apart from the Last Interglacial Maximum (MIS 5e), the Pleistocene sea level record from the Coorong Coastal Plain also shows no evidence for significantly higher sea levels for 'warmer interglacials' as has been suggested for MIS 11 (Burkle 1993; Hearty et al. 1999) and suggests that sea levels were similar to the present Holocene interglacial. The EPICA Dome C ice core record reveals that MIS 11 occurred between 424.6 and 392 ka (Masson-Delmotte et al. 2010). This longer duration interglacial (32.6 ka) provided more opportunity for barrier development. East Avenue Range with TL ages of 414 ± 29 ka (Huntley et al. 1993a) and 404 ± 23 ka (Huntley and Prescott 2001) indicates that during MIS 11, a sea level of 2 m BPSL was attained in broad agreement with a value of 3 m BPSL derived by Belperio and Cann (1990). The TL ages support the count from the top approach adopted by Belperio and Cann (1990) in assigning ages to the barrier successions in the absence of direct geochronological evidence for the age of this barrier.

The geochronological results suggest that based on probability, Baker Range more likely correlates with MIS 11 (424.6–392 ka) rather than MIS 13 (529.6–470 ka) as originally suggested by Belperio and Cann (1990). Huntley et al. (1993a) reported a TL age of 456 ± 37 ka for Baker Range. They subsequently reported an OSL age for inclusions within quartz grains of 390 ± 40 ka for this dune range (Huntley et al., 1993b). A whole-rock AAR age of 438 ± 83 ka (Murray-Wallace et al. 2001) and an ESR age for quartz sand of 416 ± 43 ka (Rittner 2013) have also been obtained for this barrier. A pooled-mean age of 424 ± 22 ka for these TL ages implies a palaeosea-level of 9 m BPSL, a value consistent with inferred palaeosea-level from the EPICA Dome C ice core.

Additional geochronological investigations are required to refine the age correlation of Baker Range with oxygen isotope records. The TL and AAR numeric ages have large uncertainties at the 1-sigma level and so Baker Range may have formed during MIS 13 as originally suggested by

Belperio and Cann (1990), as MIS 13 has been bracketed to between 529.6 and 470 ka in the EPICA Dome C ice core record (Masson-Delmotte et al. 2010). Rittner (2013) also reported an age of 612 ± 75 ka for a second sample collected 1 m below the younger ESR sample from Baker Range, which may have resulted from partial bleaching of the sediment.

If Baker Range is accepted as having formed in MIS 11, then it, together with Lucindale, Ardune and East Avenue Range all formed during MIS 11. The Ardune and Lucindale Ranges are physically connected to Baker Range. During this interval paleosea-level fluctuated between 2 m BPSL and 9 m BPSL on the Coorong Coastal Plain. Minor fluctuations in sea level during MIS 11 are required to account for the relative spacing of these successive dune ranges, as over the course of this 32.6 ka-long isotope stage, the coastal plain would have only experienced 2.3 m of uplift. The formation of these four coastal barriers involved up to 16 km of coastal progradation. The shoreline margin of East Avenue Range is some 13 km seaward of the shoreline of Baker Range.

The Peacock and Woolumbool Dune Ranges were correlated with MIS 15 with an inferred palaeosea-level equivalent to present by Belperio and Cann (1990), based on a count from the top approach for assigning ages to the dune ranges. No geochronological studies have been undertaken on these dune ranges and the inferred age and palaeosea-level can only be regarded as preliminary.

Harper Range was assigned to MIS 17 by Belperio and Cann (1990). Huntley et al. (1993a) reported a TL age of 585 ± 44 ka for this dune range, and although they correlated it with MIS 13, it would seem that correlation of their TL age with MIS 15 is more appropriate. A 'whole-rock' AAR age of 693 ± 132 ka was obtained for the same barrier (Murray-Wallace et al. 2001). MIS 17 has been bracketed to between 720 and 680 ka with a duration of 40 ka in the EPICA Dome C ice core record (Masson-Delmotte et al. 2010). Although the AAR numeric age has a very large uncertainty, the mid-point age value falls within the range of MIS 17 (i.e. close to the mid-point of MIS 17 at 700 ka) while the TL age and associated uncertainty does not fall within the defined range for MIS 17. A correlation with MIS 17 is favoured here as originally proposed by Belperio and Cann (1990). An uplift-corrected palaeosea-level of 2 m APSL was determined based on the AAR age of 693 ka compared with 1 m BPSL by Belperio and Cann (1990).

The West Naracoorte Range is situated in the footslope of the Kanawinka Fault, a fault-line scarp. It is the oldest of the Middle Pleistocene barriers and its sediments are of Normal magnetic polarity indicating that the barrier is younger than 781 ka. At Wrattonbully Quarry, now the site of a major winery, the West Naracoorte Range comprises two depositional sequences separated by an undulating unconformity (West Naracoorte I and II; Fig. 2.11). Huntley et al. (1993a) were unable to derive a TL age for West Naracoorte Range I, as the analytical results did not conform to acceptability criteria, but in a subsequent study Huntley et al. (1994) derived a TL age of 800 ± 100 ka from West Naracoorte I from the Wrattonbully Quarry site. Belperio and Cann (1990) assigned the West Naracoorte Range I/Black Range to MIS 19 with an inferred age of 720 ka and uplift corrected sea level of 1 m APSL. According to the chronology of the EPICA Dome C ice core, MIS 19 is now defined as extending between 791.6 and 769.6 ka, while MIS 17 is bracketed between 720–680 ka (Masson-Delmotte et al. 2010). Electron spin resonance ages of 752 ± 57 ka and 702 ± 81 ka, obtained by Rittner (2013), suggest that West Naracoorte Range I correlates with MIS 17 rather than MIS 19 as proposed by Belperio and Cann (1990). Rittner (2013) also reported an ESR age of 828 ± 75 ka for West Naracoorte Range II, which given the large uncertainty may imply correlation with MIS 19 which is bracketed between 791.6 and 769.6 ka (Masson-Delmotte et al. 2010). A palaeosea-level of 4.5 m BPSL has been derived for West Naracoorte Range I based on the TL age of 800 ka.

The East Naracoorte Range is situated on the up-thrown block of the Kanawinka Fault and because of the unknown timing of movement on the fault it has not been possible to infer a palaeosea- level associated with this barrier. The sea level associated with the East Naracoorte Range pre-dates the Brunhes-Matuyama boundary of 781 ka.

In summary, there are some differences in the ages and associated palaeosea-levels inferred from the coastal plain barrier system based on the studies of Belperio and Cann (1990), Huntley et al. (1993a) and as currently understood in terms of barrier ages and the oxygen isotope record of the EPICA Dome C ice core (Masson-Delmotte et al. 2010). It must be stressed, however, that the revised interpretation may be subject to further refinements as additional geochronological information becomes available. In many respects there remains a paucity of information about the ages of some of the barriers. A higher density of geochronological sampling, as well as wider sample replication is critically needed. Some barriers such as the Marmon Jabuk, Cannonball Hill, Coonalpyn, Mount Monster, Black, Hynam-Koppamurra, Woolumbool and Peacock Ranges remain undated.

The East Avenue Range is here correlated with MIS 11 as favoured by Schwebel (1983, 1984) and Belperio and Cann (1990) rather than MIS 9.3 by Huntley et al. (1993a) and with a revised palaeosea-level of 2 m BPSL. Baker Range is correlated with MIS 11 as suggested by Huntley et al. (1993a) with a revised palaeosea-level of between 9 m BPSL based on a pooled-mean age of 424 ka. Harper Range is correlated with MIS 17 as suggested by Belperio and Cann (1990) and not MIS 13 as favoured by Huntley et al. (1993a) and a palaeosea-level of 2 m APSL is determined. Finally, West Naracoorte Range I is also assigned to MIS 17 rather than MIS 19 (Belperio and Cann 1990), or MIS 15 (Huntley et al. 1993a) with an inferred paleaosea-level of 4.5 m BPSL. West Naracoorte Range II is provisionally assigned to MIS 19 but in the absence of palaeosea-level indicators it is not possible to infer a former level for this barrier succession. Rittner (2013) derived an ESR age on quartz of 828 ± 75 ka for West Naracoorte Range II suggesting a correlation with MIS 21.

The luminescence ages (TL and OSL) if taken at face value, suggest a non-linear progression in the formation of barriers across the coastal plain and also raise a fundamental philosophical question in Quaternary geochronology. As multiple barriers have formed across the slowly uplifting coastal plain, intuitive reasoning would suggest that successive barriers formed in a progradational sequence with successively younger interglacials as proposed by Belperio and Cann (1990), and that younger barriers are consistently encountered in a seaward direction. The Stewarts/Cave Range was dated at 725 ± 100 ka (Huntley and Prescott 2001) correlating with MIS 17. This dune range is seaward of Harper Range, which they correlated with MIS 13 (their TL age regarded here as inviting correlation with MIS 15). Irrespective of whether the TL age of 585 ± 44 ka is correlated with MIS 13 or 15, it raises the difficulty of a younger barrier having formed landward of an older barrier. This seeming anomaly raises the question of the accuracy of ages (i.e. deviation from 'true age') and the need for greater replication in geochronological measurements in general for the coastal plain succession. As the Bridgewater Formation barriers represent the development of landforms in a time-series, the age of the features obviously fall under greater scrutiny than in the dating of an isolated feature of unknown age and without a firm morphostratigraphical context. Accordingly, it raises the question of just how many replicate samples should be analysed to confidently define the age of a barrier landform? This question becomes more critical in the case of composite barriers.

7.6.3 Some Reflections on Sea Level History During the Last Interglacial Maximum (MIS 5e)

Sedimentary successions deposited during the Last Interglacial Maximum (MIS 5e) are particularly well-developed along the coastline of southern Australia (Murray-Wallace and Belperio 1991; Belperio et al. 1995; Bourman et al.

2016; Murray-Wallace et al. 2016; Pan et al. 2018). Away from areas of known neotectonic activity, a sea level of between 2.1 ± 0.5 and 4.8 ± 1 m APSL has been inferred for the Last Interglacial Maximum (Murray-Wallace et al. 2016; Pan et al. 2018). The question of the nature of sea level history during the interglacial in this region is more problematic and the stratigraphical characteristics of the Woakwine Range may enhance the understanding of this topic.

As outlined in earlier chapters, a substantial portion of the Woakwine Range formed during the Last Interglacial Maximum, manifested by large scale aeolian deposition (transgressive parabolic dunes with high angle slip faces on their lee side, which in the McCourt Cutting represent approximately 80% of the physical barrier structure above the surface of the surrounding coastal plain). Deep drainage cuttings such as Drain L near Robe (Hossfeld 1950; Sprigg 1952) and the McCourt Cutting near Beachport (Murray-Wallace et al. 1999) provide insights about the facies architecture and depositional history of this coastal barrier, that contribute to the global debate concerning sea level history during the Last Interglacial Maximum (MIS 5e).

It is not possible to uniquely define a eustatic (ice-equivalent) sea level from the Woakwine Range in view of the long uplift history of the coastal plain and the potential for circular reasoning, as the elevation of the subaqueous facies of the barrier has been used in the determination of uplift rate. Within McCourt Cutting, a 1 km-long drainage channel, a basal transgressive facies unconformably overlies an older aeolianite correlated with MIS 7 (Murray-Wallace et al. 1999). The transgressive facies comprises a thin gravel lag with stringers of angular flint pebbles derived from the Oligo-Miocene Gambier Limestone and calcarenite cobbles and boulders in a very poorly sorted, medium- to very coarse-grained skeletal carbonate sand. Shell fragments up to 2 cm long, including fragments of oysters and the columella and opercula of the gastropod *Turbo* sp., are also present. The transgressive lag is exposed over a horizontal distance of 100 m on the seaward side within the central portion of the cutting (300–400 m within the cutting from the western, seaward side of the barrier landform). The transgressive facies at approximately 370 m within the cutting is near-vertical and the form of the older calcarenite resembles a small sea stack (Fig. 2.6c). Analogous landforms are common along the actively eroding modern coastline near Robe. The unconformity rises up to 11.65 m APSL (Murray-Wallace et al. 1999).

The facies architecture of the Woakwine Range as revealed within the McCourt Cutting provides evidence for only one sea level highstand during MIS 5e. The basal transgressive facies is overlain by a progradational succession of subtidal and intertidal shoreline facies. On the landward side of the barrier coeval aeolian over-wash and landward migrating transgressive dune facies, in what morphostratigraphically represents the early history of barrier development during the Last Interglacial Maximum, was dated at 117 ± 8 ka by TL (Murray-Wallace et al. 1999).

As discussed in Chap. 2, the Drain L Cutting within the Woakwine Range near Robe, reveals a more complex stratigraphical architecture with at least three (Sprigg 1952), or four (Hossfeld 1950) and possibly up to five depositional episodes suggested (Schwebel 1978, 1983, 1984). The question of whether these sedimentary units relate to more than one phase of marine inundation during the Last Interglacial Maximum (MIS 5e) rests on the stratigraphical significance attached to the bounding discontinuities within the calcarenite successions of the Bridgewater Formation at this locality. Thin stringers of conglomerate associated with the upper two erosional truncations in Drain L contain the bivalve mollusc *Anadara trapezia* an index fossil of the Last Interglacial Maximum (MIS 5e; Murray-Wallace et al. 2000).

Hossfeld (1950) suggested four phases of development for the Woakwine Range based on his examination of the exposures within Drain L. The basal unit of calcarenite termed ‘Woakwine A’ by Hossfeld (Fig. 2.17b) is considered here to correlate with the MIS 7 inner core of aeolianite within the McCourt Cutting. The upper bounding surface of Woakwine A is considered here to represent a marine abrasion surface which has removed any trace of calcrete or pedogenic features that would otherwise attest to subaerial exposure of this unit at times of lower sea level. A critical point, central to this interpretation is a TL age for the older aeolianite of 151 ± 13 ka within the McCourt Cutting. The TL sample was collected from a calcarenite unit capped by a hardground, and the sediment was strongly indurated, in marked contrast to the overlying last interglacial succession. The overlying units Woakwine B, C and D with interbedded shell and detritus layers which bifurcate in a landward direction, as identified both by Hossfeld (1950) and Sprigg (1952), are considered here to represent lateral facies variations rather than having a higher level of genetic significance, either temporally or in terms of relative sea-level history. The absence of calcrete profiles at the upper bounding surfaces of Woakwine B and C suggests that they formed within a relatively discrete period of time and were not subaerially exposed. The upper-most unit of aeolian dune facies, 'Woakwine D' is capped by an indurated calcrete profile. On this basis, it is concluded that the succession formed during only one major depositional event.

A drill hole (Penola #4 in Schwebel 1978 and termed BMR#4 in Schwebel 1984) located near the crest of the Woakwine Range, approximately 2 km north-east of Lake Eliza, provides additional information about the stratigraphical character of this barrier. The drill hole intercepted the top of the Oligo-Miocene Gambier Limestone at 31.93 m below the crest of the Woakwine Range (25.1 m APSL) indicating that the limestone, representing the local basement to the Quaternary succession occurs at 6.83 m BPSL (Schwebel 1978). The land surface in the immediate lee of the Woakwine Range in this locality ranges between 3 and 4 m APSL. Schwebel identified four discontinuities within the core, inferred as erosion surfaces at heights of 7.5 m APSL, 0.14 m BPSL, 2.67 m BPSL and 4.92 m BPSL respectively. The surfaces are more highly indurated and are associated with rounded flint pebble conglomerate, whole and fragmentary fossil molluscs and pervasive iron staining. Schwebel (1978, 1984) concluded that the two upper erosion surfaces correlated with those exposed in Drain L. Based on the presence of these discontinuities, Schwebel concluded that the Woakwine Range comprised five separate units which he assigned Roman Numerals; Woakwine I through to Woakwine V; Woakwine I representing the youngest unit correlating with the Last Interglacial Maximum (MIS 5e). Based on the available stratigraphical information, it is concluded here, that the lowest two units (Woakwine IV and V) relate to deposition during MIS 7.

Evidence for the single sea level highstand during the Last Interglacial Maximum (MIS 5e) within the Woakwine Range at McCourt Cutting is consistent with other occurrences of the Glanville Formation in southern Australia (Howchin 1888; Ludbrook 1976; Cann 1978; Belperio et al. 1995; Murray-Wallace et al. 2016; Pan et al. 2018). In all exposures of the Glanville Formation for over 2000 km of coastline in South Australia, the formation comprises subtidal and intertidal facies that range in total thickness between 1–4 m (Belperio et al. 1995). The absence of major diastems, subaerial exposure surfaces, palaeosols, protosols, or relict sedimentary units within the formation, preclude the occurrence of two highstand events during the Last Interglacial Maximum (MIS 5e) within this far-field region.

7.7 The Quaternary Sea Level Record of the Coorong Coastal Plain in a Global Context

There are two principal means of evaluating the palaeosea-level record derived from the Coorong Coastal Plain. Several coastal regions around the world with long Pleistocene records of relative sea-level changes, spanning at least four interglacials, such as Barbados, the Bahamas, Sumba Island in Indonesia and the Huon Peninsula in Papua New Guinea, provide a direct comparison with the palaeosea-level record derived from the Coorong Coastal Plain. As with the Coorong Coastal Plain, these are discontinuous records which document interglacial and interstadial sea-level highstands but do not preserve evidence for sea-level lowstands, particularly glacial maxima. The rationale for selecting these palaeosea-level records for comparison, is that they provide insights about the relative magnitude of successive interglacial highstands, rather than a reference framework for sea level heights in absolute terms.

Another means of evaluating the palaeosea-level record of the Coorong Coastal Plain is based on indirect comparisons with deep sea sediment and ice core-based oxygen isotope records of fluctuating ice volumes, and as a corollary, glacio-eustatic (ice-equivalent) sea-level changes. These records are more continuous in nature and provide insights about the magnitude and complexity of relative sea levels between highstands.

7.7.1 Pleistocene Sea Levels Inferred from Oxygen Isotope Records

Since the pioneering work of Emiliani (1955), Shackleton and Opdyke (1973, 1976) and Hays et al. (1976) on the application of oxygen isotopes for inferring long Quaternary records of ice volume change, seemingly countless studies have investigated the oxygen isotope composition of foraminifers from deep sea sediment cores from all of the ocean basins. The Deep Sea Drilling Project (DSDP), and its successors, the Ocean Drilling Program (ODP) and the International Ocean Discovery Program (IODP) have been instrumental in fostering this research. Valuable summaries are provided by Cronin (2010), Bradley (2015), Lowe and Walker (2015), and Summerhayes (2015). This large body of research has shown a generally coherent pattern in the timing of global ice-volume and sea-level changes, although the inferred magnitude of some isotopic events appears to vary geographically in response to local ocean temperatures and salinities. The palaeoclimatic observations derived from deep sea sediment core records have also been corroborated from several ice core records from Greenland and Antarctica, such as the GRIP (Greenland Ice Core Project) cores (Dansgaard et al. 1993) and the EPICA (European Project for Ice Coring in Antarctica) Dome C ice core (Fischer et al. 2010). Ice cores, particularly the GRIP and NGRIP $\delta^{18}O$ records have provided very detailed information about the complexity of Greenland Interstadial events during the last glacial cycle of potential global applicability (Blockley et al. 2012).

One of the most influential records of long-term ice-volume change, and as a corollary, glacio-eustatic sea-level change, is based on the oxygen isotope record derived from the planktonic foraminifer *Globigerinoides sacculifera* from Equatorial Pacific Ocean deep sea core Vema 28-238 (Shackleton and Opdyke 1973). The piston core was collected from the Solomon (Otong Java) Plateau in a present water depth of 3120 m. The 16 m core record spans essentially the past 1 Ma given that the Brunhes–Matuyama boundary at 12 m is dated at 781 ka rather than 690 ka as understood at the time of publication. The oxygen isotope record is of interest given the proximity of the core location to the Huon Peninsula emergent reef complex in Papua New Guinea, and the eastern margin of the Australian continent. The Vema 28-238 oxygen isotope record suggests that MIS 5e and 9 were the warmest interglacials during the entire core record, closely followed by the present Holocene interglacial and MIS 11. All the marine isotope stages before MIS 11 appear to be less intense interglacials and therefore characterised by lower sea-level highstands. The record from the Coorong Coastal Plain indicates that sea levels ranged from 1 m BPSL to 1 m APSL for the barriers older than MIS 11 as inferred by Belperio and Cann (1990). The revised record reported above indicates that for the barriers where geochronological results are available, the following palaeosea-levels apply; East Avenue Range (MIS 11 sea level of 2 m BPSL), Baker Range (MIS 11 sea level of 9 m BPSL), Harper Range (MIS 17 sea level of 2 m APSL) and West Naracoorte I Range (MIS 17 sea level of 5 m BPSL).

One of the widely cited long Quaternary oxygen isotope records, is the LR04 $\delta^{18}O$ (benthic) stack, a composite of 57 deep-sea sediment core records for the past 5.3 Ma with a precision of 0.06‰ (Lisiecki and Raymo 2005; Fig. 7.8). The record is based on cores principally from the North and South Atlantic Ocean, equatorial Pacific Ocean, as well as cores from the Indian Ocean and South China Sea. The stacked record shows the Last Interglacial Maximum (MIS 5e) and MIS 11 as the warmest interglacials in the past 1 Ma, and that they were similar in magnitude, reinforcing the evidence from core Vema 28-238 (Shackleton and Opdyke 1973). The record also indirectly indicates that the sea-level highstand of MIS 9 was of a similar magnitude to MIS 5e and MIS 11 but did not quite attain the same ice volume. The inferred palaeosea-levels for these highstands from the Coorong Coastal Plain are broadly in accord with these observations. In contrast, the LR04 stack suggests a significantly lower sea level for the penultimate interglacial (MIS 7e) whereas the inferred sea level for MIS 7e based on Reedy Creek Range is equivalent to present sea level. The LR04 stack also reveals that MIS 15, 17, 19 and 21 were all of broadly similar intensity, characterised by smaller ice volumes than MIS 5e, 9 and 11. The revised Coorong Coastal Plain relative sea level record is in accord with these observations with relative sea level ranging between 1 m BPSL for MIS 17 and 1 m APSL for MIS 21.

Waelbroeck et al. (2002) inferred relative sea levels for the late-Middle Pleistocene to the Holocene based on the analysis of oxygen isotope records from deep sea cores from the North Atlantic, Southern Indian Ocean and Equatorial Pacific Ocean. Their composite relative sea level curve revealed that sea levels of the interglacial maxima MIS 7 and MIS 9 were as high, or slightly higher than present sea level. In this respect, their inferred sea level for MIS 7 is significantly higher than indicated in the LR04 stack. Palaeosea-levels from the Coorong Coastal Plain suggest that sea level was equivalent to present during MIS 7e and at 1 m BPSL during MIS 9.

The EPICA Dome C ice core record from Antarctica spans the past 800 ka and also provides critical insights about the intensity of glacials and interglacials (Masson-Delmotte et al. 2010). The EPICA Dome C ice core reveals that the interglacial maxima between 800 and 400 ka ago were less intense than the more recent interglacials (MIS 11, 9, 7e and 5e). The revised record from the Coorong Coastal Plain suggests that based on a TL chronology, sea level was below present during MIS 7e, 9 and 11, and in particular, 1 m BPSL at 250 ka, 2.5 m BPSL at 329 ka and 9 m BPSL at 424 ka. If the mid-points of the EPICA Dome C-derived isotope stages are adopted, palaeosea-level as registered on the Coorong Coastal Plain, remained below present during these isotope stages; specifically 2 m BPSL during MIS 7e and 3 m BPSL and 2 m BPSL during MIS 9 and 11 respectively (rounded off to the nearest metre).

7.7.2 Pleistocene Sea Level Records from Other Coastal Regions

While the magnitude of a sea-level highstand for a specific oxygen isotope stage may vary regionally and globally due to glacio-hydro-isostatic adjustment processes, the relative heights of sea level attained for different interglacial maxima is more likely to be replicated in general terms, particularly where there is a substantial difference in ice volume between interglacials. Accordingly, the comparison of long Quaternary records of sea-level changes from other regions with the record from the Coorong Coastal Plain is instructive.

Located to the north of the Java Trench within the subduction province of the Indonesian archipelago in a region of active andesitic volcanism, Sumba Island, preserves a long record of Pleistocene relative sea-level changes (Pirazzoli et al. 1993). A sequence of up to 11 raised coral reef terraces occur at Cape Laundi on the northern coast of Sumba Island. The terraces range between 100 and 500 m wide and extend

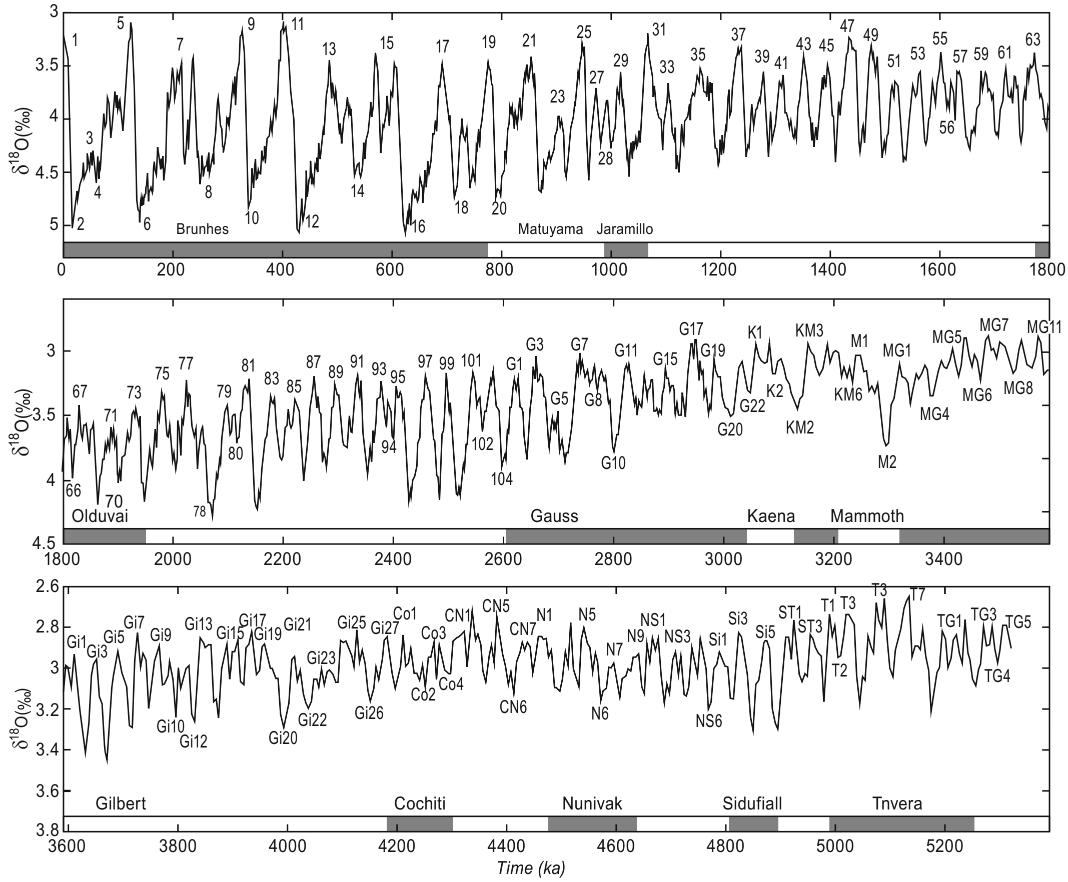


Fig. 7.8 The LR04 $\delta^{18}O$ (benthic) stack, a composite of 57 deep-sea sediment core records of oxygen isotope data (Lisiecki and Raymo 2005)

up to 475 m APSL. The terraces are well-defined features backed by prominent changes in slope, erosional scarps and in some places, shoreline notches. The Last Interglacial (MIS 5e) reef complex occurs at 19 ± 1 m APSL. Assuming a relative sea level of 6 m APSL for the Last Interglacial Maximum, Pirazzoli et al. (1993) derived an uplift rate of 0.49 ± 0.01 mm/year, which they assumed remained constant during the formation of the entire emergent reef complex. They suggested that the highest reef in the complex correlated with MIS 27 with an age of approximately 0.99 Ma. In view of the moderate rate of uplift of the reef complex, some of the terrace surfaces are of polycyclic origin and re-occupied by younger interglacial sea levels, rendering a definitive palaeosea-level record for the entire sequence of terraces more problematic. Pirazzoli et al. (1993) concluded that sea level was close to present during MIS 13 and 15 which was in accord with the palaeosea-levels originally inferred by Belperio and Cann (1990) for Baker Range (MIS 13 with an inferred palaeosea-level of 1 m BPSL) and Peacock/Woolumbool Range (MIS 15 with an inferred palaeosea-level equivalent to present sea level).

The inferred palaeosea-levels for MIS 17 (20 ± 10 m BPSL), MIS 19 (15 ± 10 m BPSL) and MIS 23 (between 25 and 40 m BPSL) from the Cape Laundi reef complex are significantly lower than inferred from the Coorong Coastal Plain for this broad period of time (MIS 17 at

1 m BPSL; MIS 19 equivalent to present sea level; MIS 21 at 1 m APSL; Belperio and Cann 1990).

Barbados has long featured in investigations of Quaternary sea-level changes (Mesolella et al. 1969; Matthews 1973; Schellmann and Radtke 2004a, b). Early interest in the sea-level record of Barbados centred on its correlation with the southwestern Pacific Ocean sea-level record inferred from the Huon Peninsula on Papua New Guinea (Steinen et al. 1973). Barbados is situated in the Caribbean Sea approximately 150 km east of the Lesser Antilles. The 430 km^2 island represents the subaerial portion of an accretionary prism, comprising highly deformed marine muds that have accumulated associated with the subduction of the North American Plate beneath the Caribbean Plate (Schellmann and Radtke 2004a, b). Mud diapirism within this fore-arc ridge setting since late Eocene time has been instrumental in the early development of the island. Approximately 85% of Barbados is covered by Pleistocene coralline limestone that ranges from 15 to 130 m in thickness and extends up to 300 m APSL as a series of emergent reef complexes. Resulting from the differential uplift of the island, the Quaternary sea level record of Barbados extends back in time to about 650 ka on the northern portion of the island and about 400 ka in the south.

Based on the meticulous field investigations and electron spin resonance dating of fossil corals by Schellmann and Radtke (2004a, b) a detailed record of sea-level highstands principally for the past four interglacial maxima was derived from Barbados. The inferred palaeosea-levels depend on the assumed value of sea level for the Last Interglacial Maximum (MIS 5e), which in turn influences the inferred rate of uplift. Conscious of this issue, Schellmann and Radtke (2004a, b) calculated rates of uplift based on assumed sea levels of 0, 2 and 6 m APSL for MIS 5e. The oldest dated site at Guinea situated at 192 m APSL and dated at 640 ka was correlated with MIS 17/19 with and inferred palaeosea-level of −22 m which is significantly lower than the inferred sea level of 4 m APSL in the revised sea-level record from the Coorong Coastal Plain reported herein.

The Barbados palaeo-sea level record derived by Schellmann and Radtke, (2004a, b) revealed that sub-Milankovitch sea-level oscillations were responsible for some of the emergent reef terraces. For example, during the Last Interglacial Maximum (MIS 5e), three morphologically distinct reef terraces formed. They include the Maxwell Hill Terrace (22 m APSL), Rendezvous Hill I (36 m APSL) and Rendezvous Hill II (39 m APSL). Uplift-corrected sea levels for the two younger MIS 5e terraces depend on the assumed palaeo-sea level at the time of formation of the Rendezvous Hill II Terrace. If Rendezvous Hill II formed at 6 m APSL then uplift-corrected sea levels for the Rendezvous Hill I and Maxwell Hill Terraces are 4 m APSL and 8 m APSL respectively (Schellmann and Radtke 2004a, b).

The palaeosea-level record from Barbados for MIS 7, 9 and 11 also reveals the presence of three distinct terraces during each of these interglacials. Assuming a value of 6 m APSL for sea level during the Last Interglacial Maximum (MIS 5e) yielded inferred sea levels of 10 m BPSL, <1 m and 4 m APSL for the penultimate interglacial (MIS 7). The revised palaeosea-level for MIS 7e from the Coorong Coastal Plain is 2 m BPSL. Sea levels of 1, 7 and 8 m APSL were derived for the Antepenultimate Interglacial (MIS 9) from Barbados in contrast to 3 m BPSL for the Coorong Coastal Plain. Inferred palaeosea-levels of 11 and 18 m APSL for MIS 11 from Barbados are significantly higher than 2 m BPSL from the Coorong Coastal Plain.

The Bahamas have also been extensively studied in investigations of palaeosea-level (Carew and Mylroie 1997; Kindler and Hearty 1997; Hearty 1998). The Bahama Islands comprise successions of aeolianite interbedded with palaeosols and protosols with adjoining reefal units. As with the Coorong Coastal Plain, the aeolianite successions of the Bahamas formed during periods of sea-level highstands resulting from the higher rates of carbonate production on the adjacent shelf environment while palaeosols and protosols formed at times of lower sea level.

Fig. 7.9 Sequential development of the Coorong Coastal Plain, southern Australia. The inferred relict shoreline trends are based on the geochronologically-defined barrier ages and their mapped occurrence is based on SRTM imagery. In the northern portion of coastal plain, the barriers young in a seaward direction with the oldest barrier represented by number *21*—Marmon Jabuk Range. Successively younger barriers include; *20*. Cannonball Hill Range; *19*. Coonalpyn Range; *18*. Mount Monster Range; *17*. The Black Range; *16*. Hynam Range; *15*. East Naracoorte Range; *14*. West Naracoorte Range; *13*. Harper Range; *12*. Stewarts/Cave Range; *11*. Woolumbool Range; *10*. Peacock Range; *9*. Baker Range; *9a*. Lucindale Range; *8*. Ardune Range; *7*. East Avenue Range; *6*. West Avenue Range; *5*. Reedy Creek Range; *4*. East Dairy Range; *3*. West Dairy Range; *2*. Woakwine Range and; *1*. Robe Range. In the Mount Gambier region of the coastal plain, the successively younger barriers that are more easily recognised in SRTM images include; *25*. Gambier Range; *24*. Caveton Range; *23*. Burleigh Range; *22*. MacDonnell Range and; 1. Robe (Canunda) Range

Up to eight parasequences have been identified on the Bahamas (Hearty 1998). Sea level during MIS 7 has been suggested to have reached up to near present sea level based on beach sediments at 0 and 2 m APSL on New Providence Island (Hearty 1998), compared with 2 m BPSL from the Coorong Coastal Plain. A rise of sea level by up to 20 m APSL has been inferred for the Bahamas during MIS 11, based on the presence of thin beach units. This is in marked contrast to the Coorong Coastal Plain with an inferred palaeosea-level of 2 m BPSL for this interval.

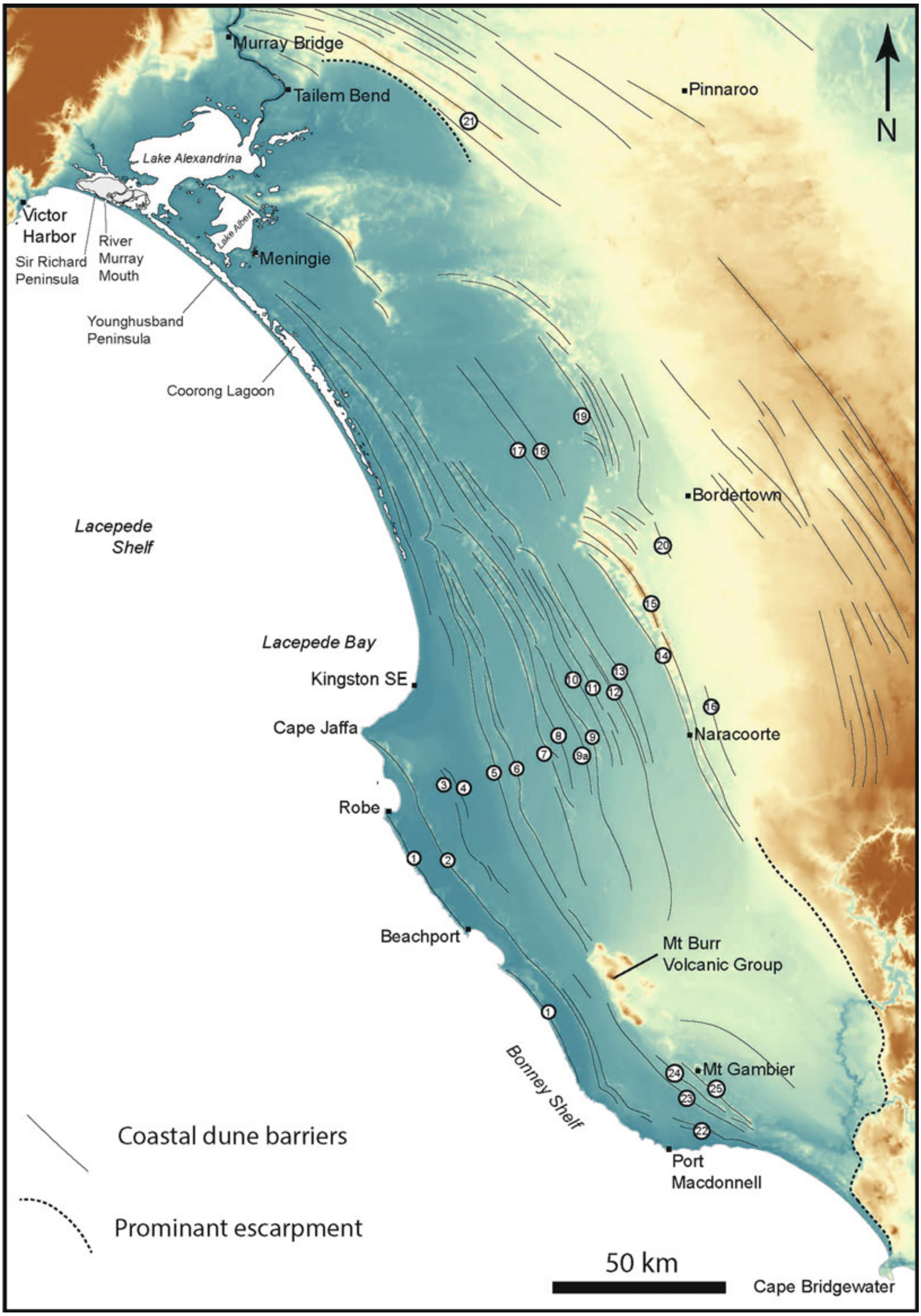
7.8 Quaternary Evolution of the Coorong Coastal Plain

The Coorong Coastal Plain underwent progressive epeirogenic uplift during the Quaternary with the locus of maximum uplift centred in the region between the Pleistocene Mount Burr Volcanic Group and the Holocene volcanoes, Mounts Gambier and Schank. Approximately 80 m of uplift occurred close to these volcanic provinces over the past 500 ka. The combined processes of glacio-eustatic sea-level changes superimposed on a gently rising coastal plain resulted in the remarkable preservation of up to 20 well-defined coastal barriers relating to deposition predominantly during interglacials, but with some warm interstadials also represented in the stratigraphical record.

As the coastal plain prograded, the plan-form geometry of the coastal barriers progressively changed reflecting the subtle but ongoing influence of the gently warping basement topography to the Pleistocene Bridgewater Formation (Fig. 7.9). Warping is genetically associated with in situ stresses within the Indo-Australia Plate within the region and Pleistocene to Holocene intra-plate volcanism.

In the southern portion of the coastal plain the early Middle Pleistocene barriers of Harper Range and the Stewarts and Cave Ranges curved in an arcuate manner as they nucleated against the archipelago of volcanic islands associated with the Mount Burr Volcanic Group. Progressive barrier development and longshore sediment transport led to the formation of a major tombolo (cuspate foreland) that extended some 44 km to the south-west from the West Naracoorte Range. The broad shape of the embayment to the immediate north-east of the Mount Burr Volcanic Group during this period is reminiscent of the modern and Holocene Lacepede Bay between Kingston SE and Cape Jaffa. To the south-east of the Mount Burr Volcanic Group, the Dismal and Mingbool Ranges curved in an arcuate-form to the southern-most portion of the Mount Burr Volcanic Group.

With the passage of time the general configuration of the coastline changed and by the time West Avenue Range (c. 342–315 ka; MIS 9; barrier number 6 in Fig. 7.9) and Reedy Creek Range (250–200 ka; barrier number 5 in Fig. 7.9) had formed, the Mount Burr Range ceased to influence the regional configuration of the coastline to the north-west. The younger barriers to the north of the Mount Burr Volcanic Group became more linear in form and correlative sediments of Reedy Creek Range were deposited on the seaward side of the Mount Burr Volcanic Group, in particular, seaward of Mounts Muirhead, Burr, Lookout, Watch and


Murray Bridge
Tailem Bend
Pinnaroo
N
Lake Alexandrina
Victor Harbor
Sir Richard Peninsula
River Murray Mouth
Lake Albert
Meningie
Younghusband Peninsula
Coorong Lagoon
Lacepede Shelf
Bordertown
Lacepede Bay
Kingston SE
Cape Jaffa
Naracoorte
Robe
Beachport
Mt Burr Volcanic Group
Bonney Shelf
Mt Gambier
Port Macdonnell
Coastal dune barriers
Prominant escarpment
50 km
Cape Bridgewater

The Bluff. In contrast, in the south-east in the Mount Gambier sector of the Coorong Coastal Plain, the Mount Burr Volcanic Complex ceased to influence coastal barrier configuration by the time of formation of the Gambier Range of presumed MIS 11 age (barrier number 25 in Fig. 7.9). In the line of section between Robe and Naracoorte, the coastal plain prograded by up to 90 km, over an 800 ka period.

7.8.1 Orbital Forcing and Global Climatic Events: The Early-Middle Pleistocene Transition and the Mid-Brunhes Event

The Early-Middle Pleistocene Transition is a major event in the geologically recent history of the Earth involving a global reorganization of climate states. It represents the most significant climate change event during the Quaternary. A substantial increase in the magnitude of global sea-level changes accompanying glacial cycles (increasing by approximately 50 m), such that the change from full glacial to interglacial conditions, involved a global sea-level rise of some 125 m, occurred during this period (Clark et al. 2006). This led to feedbacks within Earth surface environments, particularly as substantial portions of the continental shelves were subaerially-exposed during glacial maxima. Decreased production of North Atlantic Deep Water most likely resulted from increased northern hemisphere glaciation. The global extinction of at least 50 species of deep-sea benthic foraminifers occurred during this interval (Hayward et al. 2005). Thicker loess successions are evident in northern Eurasia after 1 million years ago and deserts in China expanded significantly after 1.2 million years ago (Head et al. 2008).

The sequence of inferred climate changes that occurred during the Early-Middle Pleistocene Transition have been well-defined in longer-term marine-based oxygen isotope records, such as the LR04 benthic $\delta^{18}O$ stack (Lisieck and Raymo, 2005: Fig. 7.8). However, less is known about how these changes were manifested in other environmental settings, particularly marginal marine environments.

The Early-Middle Pleistocene Transition involved a progressive shift from glacial cycles of 41,000-year duration (obliquity-dominated) to high-amplitude, quasi-periodic cycles lasting approximately 100,000 years (Fig. 7.8). In terms of the more recent history of the planet, the Early-Middle Pleistocene Transition represents a significant period in which the Earth's climate system adjusted, from less intense and shorter-term glacial cycles to more intense glacial cycles of longer duration (periods of maximum continental ice sheet development and lower sea levels) and interglacials (periods of climatic amelioration and sea levels as high, or higher than present). The Early-Middle Pleistocene Transition is generally considered to have occurred between about 1.2 million years ago (Ma) and 700 thousand years ago (ka) (Head and Gibbard 2005, 2015; Fig. 7.8). It represented the culmination of a 50 million year period of progressive cooling of the Earth's climate, from a 'hothouse' world, free of continental ice, to the modern world's climate system.

As revealed in marine-based oxygen isotope records, during the Early-Middle Pleistocene Transition glacial cycles changed from broadly symmetrical peaks to cycles characterised by greater asymmetry (saw-tooth pattern), culminating in the glacial cycles of the past 700 thousand years in which full glacial conditions were defined by major troughs in oxygen isotope records at the culmination of each cycle (e.g. Stages 2, 6, 8, 10, 12, 14, 16 in Fig. 7.8; Head et al. 2008; Maslin and Brierley 2015). Significantly, the orbital forcing parameters did not change substantially during the Early-Middle Pleistocene Transition implying that non-linear feedback mechanisms were responsible for the transition in the spectral climate signature. The non-linear forcing of the global climate system is also expressed in slow formation of ice sheets and their rapid melting at the end of glacial cycles. Several hypotheses have been advanced to explain the transition including changes in the dynamic behaviour of ice sheets (Clark et al. 2006) and an overall decline in atmospheric CO_2 (Maslin and Ridgwell 2005).

Significant landscape changes also occurred in Australia during the Early-Middle Pleistocene Transition. In the Murray Basin–Coorong Coastal Plain region of southern Australia, a significant change from quartz-rich coastal barrier ridge deposition (Pliocene Loxton-Parilla Sands of the Murray Basin) to the formation of the coastal barriers comprising temperate carbonate, bioclastic sediment (Pleistocene Bridgewater Formation) of the Coorong Coastal Plain (Bowler et al. 2006). This transition coincides with an increase in the intensity and geographical range of aridity within the continent, which on the southern margin, with the decline of river discharge to the coasts over successive glacial cycles, has favoured the prolific production of temperate carbonate sediments within the region (James and Bone 2011). A similar transition is evident within the Perth Basin in south-west Western Australia represented in a shift from the siliciclastic Bassendean Sand to the younger, temperate carbonate Tamala Limestone (Kendrick et al. 1991).

The Early-Middle Pleistocene Transition was followed by the Mid-Brunhes Event a period of carbonate dissolution within the world oceans during Marine Isotope Stage 11 (MIS 11; Cronin 2010). The climate change event leading to the interglacial MIS 11 following the termination of glacial MIS 12 (Termination V at 430 ka) represents one of the most extreme glacial-interglacial transitions in the past 5.3 Ma (Fig. 7.8). MIS 11 is also regarded as one of the longest interglacial intervals in the Quaternary (past 2.59 Ma) spanning a period of approximately 32.6 ka (424.6–392 ka ago) as defined in the European Project for Ice Coring in Antarctica (EPICA) Dome C Antarctic ice core record (Masson-Delmotte et al. 2010; Fig. 7.6). Present geochronological and geomorphological evidence suggests that during the 'super-interglacial' MIS 11 four barriers formed on the Coorong Coastal Plain; the Baker, Lucindale, Ardune and East Avenue Ranges.

7.9 Summary and Conclusions

Investigations of the sea-level history and associated environmental changes of the Coorong Coastal Plain of southern Australia, illustrate the contrasting research paradigms that have prevailed for over the past 150 years, in explaining the origin of the relict shoreline complexes. These changing approaches and research frameworks for interpreting landscape evolution, parallel changing world views about the nature of long-term climate and sea-level changes.

The initial investigations of Woods in the 1860s concluded that the coastal plain had been uplifted in recent Earth history and that the successive shoreline ridges represented periods of quiescence in uplift rather eustatic sea-level changes. This perspective reflected the lack of empirical evidence for substantial changes in sea level occurring in unison at a global scale, and is now understood in terms of glacio-eustatic sea-level changes driven by the fluctuating volumes of continental ice sheets and valley glaciers.

As evidence amounted for world-wide changes in sea level (Suess 1888) and the emergence and acceptance of the Glacial Theory (Agassiz 1840; Geikie 1894) and in particular the four-fold model of Quaternary Alpine Glaciation (Penck and Brückner 1909), research undertaken in the mid-twentieth century by Paul Hossfeld, Reg Sprigg, Norman Tindale, Bob Crocker and Bernard Cotton involved the correlation of the successive coastal barrier landforms of the Coorong Coastal Plain with the four-fold model of Quaternary Alpine Glaciation. The investigations by Reg Sprigg, however, that also involved the assignment of ages to the barriers based on the Croll-Milankovitch Hypothesis was prescient for anticipating future developments in astrobiochronology. Technological developments following the Second World War resulted in oxygen isotope stratigraphy and a significantly improved level of understanding of the complex nature of glacio-eustatic sea-level changes during the Quaternary. These major advances were accompanied by the ability to assign numeric ages to the barrier landforms based on a range of newly developed geochronological methods that included luminescence dating (thermoluminescence and optically stimulated luminescence), amino acid racemization, electron spin resonance, uranium-series and radiocarbon dating and palaeomagnetism.

The application of these geochronological methods has provided novel approaches to assigning ages to the successive barriers to quantify the relative sea-level history. However, these analytical approaches are not without limitations and illustrate the need for further replication to more confidently assign ages to some of the barriers. The results of some of the geochronological investigations have challenged the notion of a simple progradational sequence of barriers throughout the Quaternary. Such a perspective is geomorphologically difficult to reconcile, however, as it is difficult to envisage a younger barrier forming landward and in the lee of an older barrier, as high wave energy conditions are required to entrain sediment landwards from the inner continental shelf to form barrier structures.

Despite these complexities, the Coorong Coastal Plain preserves one of the world's longest records of Quaternary sea-level changes within a terrestrial setting. The sea-level record, which is dominantly a record of glacio-eustatic sea-level changes, documents the onset of interglacial and warm interstadial sea-level highstands, barrier development during the highstand, and forced regressions at the end of highstands manifested in many instances by beach ridge deposition on the former, seaward side of barriers.

The palaeosea-level record of the Coorong Coastal Plain reveals that interglacial sea levels for the past 800 ka successively returned to a common sea level datum that ranged between 9 m BPSL to 4 m APSL.

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Epilogue

Since the 1860s researchers have examined the regional landscapes, sedimentary successions and evolutionary history of the Coorong Coastal Plain in southern Australia. The research interests have been diverse although predominantly focusing on long-term coastal landscape evolution over contrasting temporal and spatial scales. Broader research topics have included coastal barrier development; depositional processes in sedimentary carbonate environments, dune and estuarine-lagoonal environments, soil formation, Quaternary sea-level changes, neotectonism, volcanism, karst landform development, fossil vertebrates and megafaunal extinctions, and the rich Holocene archaeological record of the region. In addition, the coastal plain has also served as an important testing ground for refining several geochronological methods.

Several distinctive and remarkable attributes of the Coorong Coastal Plain include its spatial scale, the magnitude of skeletal carbonate sediment production on the adjacent continental shelves, the physical size and lateral continuity of the individual coastal barrier landforms, their vast number extending across the coastal plain and Murray Basin, and the subtle nature of the epeirogenic uplift and ubiquitous calcrete development which have been instrumental in preserving the coastal landforms.

Numerous environmental controls are responsible for the spatial distribution of sedimentary environments and their resultant sedimentary facies within the region. Sedimentary processes such as the role of waves, tides, wind, in conjunction with sediment supply, climate, tectonics, sea-level changes, biological activity, water chemistry and volcanism have all contributed to produce the highly distinctive barrier landforms and associated sedimentary environments of the coastal plain. The high wave energy dissipative beach environments, combined with strong on-shore winds has influenced the landward concentration of the mixed quartz-bioclastic sand from the adjacent Lacepede and Bonney Shelves, to form the highly distinctive barrier landforms of the region. The terrigenous-clastic sedimentary component (quartz and heavy minerals) is predominantly extra-basinal in origin and brought by the River Murray to the Lacepede Shelf, particularly during periods of lower sea level. There, the terrigenous-clastic sediments are physically intermixed with the intra-basinal temperate carbonate sediments, and with the passage of time, brought landward by periodic glacio-eustatic sea-level rises and the continued landward translation of sediment in the inner-shelf environment above storm-weather wave base during sea-level highstands. The Mediterranean climate has enhanced the development of thick pedogenic carbonate profiles (calcretes) which have acted as armour, protecting the original morphology of the regional landforms. The climate of the region has also influenced sedimentation in other nuanced ways. The seasonal precipitation of dolomite in some back-barrier, saline lake environments resulting from an annual desiccation cycle is but one example.

The legacy of Quaternary sea-level changes is one of the most enduring geomorphological expressions of the Coorong Coastal Plain. In a global context the region appears unique in terms

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of the number of relict barrier shoreline complexes preserved in an emergent coastal region. Up to 20 barriers have been identified within the Bridgewater Formation in the 90 km transect across the coastal plain from Robe to Naracoorte, and at least 600 barrier ridges in the Pliocene Loxton-Parilla Sands (McLaren et al. 2011) occur inland to the landward margin of the Murray Basin (Murravian Gulf of Sprigg 1952). The barriers of the Bridgewater Formation comprise thin packages of transgressive facies associations overlain by regressive sublittoral and beach facies. Volumetrically the largest component of each barrier, however, is the landward advancing aeolian dune and sand-sheet unit consisting of transverse and parabolic dunes, blowout, coppice, barchan and barchanoid ridges. Although the majority of barriers each formed during a single period of high sea level, as suggested in early drilling of the barrier structures (Cook et al. 1977), some are composite structures such as the Robe, Woakwine and Naracoorte Ranges. The interplay of successive sea level highstands at a similar elevation and a presumed constant rate of uplift of the low gradient coastal plain have been the principal factors determining whether the barriers form as single features or composite structures, the latter having formed in more than one interglacial or warm interstadial (e.g. Robe Range). The overall end product, the Bridgewater Formation, is a regressive depositional sequence having resulted from multiple episodes of marine transgression and forced regressions on an emergent coastal plain.

Although located in a trailing edge, passive continental margin and within an intra-plate setting, the Coorong Coastal Plain has experienced a modest uplift history with up to 70 m of uplift in the past 1 million years (centred on the Naracoorte region). Despite the slow rate of uplift in a global context, it has been sufficient to isolate interglacial barrier shoreline landforms from the erosional influences of younger interglacial sea level highstands. In this sense, uplift above ultimate base level and pervasive regional calcrete development have acted as the principal means of preserving the sedimentary record, rather than rapid subsidence of the sedimentary sequences beneath storm-wave base. Although the overall mechanism for the epeirogenic uplift of the coastal plain is still not completely understood, the Pleistocene and Holocene intraplate volcanic complexes have locally contributed to the uplift.

Successive periods of high sea level during interglacials and warm interstadials in conjunction with epeirogenic uplift have predominantly controlled the spatial distribution of the barriers across the low gradient coastal plain. In some areas, however, a variable and uneven, antecedent bedrock topography, related to partially exhumed granitic intrusions, has locally determined the resultant geometry of the barriers in plan-view. This control on resultant depositional landforms has in turn influenced the spatial arrangement of the sedimentary facies so that barrier-lagoonal landform associations have a distinctive geometry that is replicated during successive interglacials. Collectively, these environmental controls on coastal sedimentation have ensured that the Pleistocene Bridgewater Formation has a relatively high preservation potential in the geological record. The two main agents of destruction of the coastal sedimentary record is the potential erosion that may occur resulting from the coincidence of sea level highstands and processes of karstification. The former is spectacularly illustrated with up to 2 km of shoreline retreat and coastal erosion of Robe Range during the past 7000 years of the Holocene sea level highstand. The latter is more concentrated in the southern sector of the coastal plain near Mount Gambier in the region of higher rainfall and occurs at a significantly slower rate and smaller spatial scale.

The history of geological and geomorphological investigations within the region also reveals the evolving intellectual perspectives and the role of successive paradigms in understanding Quaternary coastal landscape development. In a sense these represent different world views of seeing landscapes. Tenison Woods (1862) considered the relict beaches to have resulted from periodic phases of quiescence in uplift rather than an expression of sequential eustatic-changes, for at that time, an integrated framework of sea-level changes associated with the waxing and waning of continental ice sheets had not been fully elucidated. With the emergence of the Glacial Theory (Agassiz 1840) and the recognition of potentially several glacial events in the Quaternary, a framework emerged for repeated sea-level changes. Based on a study of glacial outwash terraces with terminal moraines in the Bavarian plateau south of Ulm, Augsburg and Munich, Penck and Brückner (1909) concluded that there had been four glaciations in Europe during the Quaternary Period; Günz, Mindel, Riss and Würm. Simultaneous research on the Mediterranean coasts identified ‘staircases’ of marine terraces which were considered to be a direct expression of sea-level changes and thus reinforced the notion of a four-fold model of Quaternary Alpine glaciation and a progressively falling sea surface throughout the Quaternary. This Mediterranean framework of Quaternary sea-level changes was used by Hossfeld (1950) and Sprigg (1952) to assign ages to the barriers of the Coorong Coastal Plain. Sprigg (1952) also invoked the Croll-Milankovitch Hypothesis to assign ages to the barrier successions, acknowledging the role of orbital-forcing as a mechanism for explaining glacio-eustatic sea-level changes.

Palaeoclimatic research acknowledging multiple glaciations and interglaciations in the Quaternary, significantly enhanced the understanding of long-term coastal landscape development of the Coorong Coastal Plain and Murray Basin. Technological developments during the latter twentieth century improved the sophistication of research questions that may be addressed and revealed that the four-fold model of Quaternary Alpine glaciation significantly under-estimated the number of glaciations in the Quaternary. In the early 1970s the mutual development of oxygen isotope analyses on benthic and planktonic foraminifers from deep sea cores (a proxy of long-term continental ice-volume and temperature changes, and as a corollary, glacio-eustatic sea-level changes) and the correlation of the derived time-series data with the record of inferred sea-level changes from emergent reef complexes (Shackleton and Opdyke 1973, 1976; Chappell 1974; Hays et al. 1976), provided compelling evidence for the nature of sea-level changes in the late-Middle Pleistocene through to the current Holocene interglacial. A new paradigm had emerged. Particularly significant was the recognition, in broad view, that interglacial highstands attained a similar datum, rather than a progressively falling sea surface as originally considered for the Mediterranean Basin. This in turn further refined the understanding of the long-term landscape evolution of the Coorong Coastal Plain.

Technological developments in geochemistry and geochronology since the mid-twentieth century have also significantly enhanced the understanding of the landscape dynamics of the region. Although this has fostered a more nuanced appreciation of the nature and rates of geological processes that have fashioned this distinctive landscape, many questions remain. Developments in geochemistry and geochronology, particularly the increasingly more sophisticated analytical techniques permitting the analysis of samples of smaller mass have enhanced the nature of specific research questions that can be examined in these landscapes. The advent of radiocarbon dating by accelerator mass spectrometry and uranium-series dating by thermal ionisation mass spectrometry has enabled significantly smaller samples to be analysed with greater precision compared with earlier instruments. In a similar manner, the use of reverse-phase, high performance liquid chromatography has enabled single foraminifers from the Pleistocene aeolianites of the Bridgewater Formation to by analysed using amino acid racemization (Blakemore et al. 2015), and highlights the potential of the method for Holocene successions using the fast racemizing amino acid, aspartic acid for improved age resolution. The development of geochronological methods such as luminescence dating, electron spin resonance, amino acid racemization, radiocarbon and uranium-series dating, as well as palaeomagnetism, have all contributed to an enhanced understanding of the timing of specific events in coastal landscape development within the region.

It is clear that electron capture methods such as luminescence and electron spin resonance will remain important geochronological tools for dating the barrier successions, as the aeolian dune facies represent an excellent medium for dating by these methods. The spatial scale of dune trough- and tabular-cross bedding in outcrops, provide unambiguous evidence for aeolian sedimentary processes. This increases the probability that the sampled quartz sand has been adequately bleached in a subaerial environment to ensure valid geochronological results. This combined with the fact that the sediments can generally be relatively easily sampled by a hand-auger within quarries and borrow pits will ensure the continued success of these methods. The remarkably consistent radiation dose of 0.5 Gray/ka in the Bridgewater Formation sediments across the coastal plain (Huntley et al. 1993a, b; Murray-Wallace et al. 2002) also renders the succession particularly suited for luminescence analyses and enhances the wider age range for dating.

There remains the need for greater replication in geochronological analyses from specific landforms given the large analytical uncertainties in some of the earlier luminescence measurements, which frustrated correlations with oxygen isotope records of long-term climate changes. Similarly, the ages of many of the barrier landforms rests on the validity of single geochronological analyses. It is imperative that single grain OSL measurements be applied to the complete sequence of barriers across the coastal plain as this will provide major insights about the nature of sediment dynamics and the magnitude of sediment reworking during successive interglacial highstands. Further developments in luminescence dating using thermal transfer and other emerging analytical protocols may also determine the age of barriers that appear to have formed shortly before or during the 'Early-Middle Pleistocene Transition' (1.2 Ma to 700 ka ago). The Early-Middle Pleistocene transition is a major event in the geologically recent history of the Earth involving a global reorganization of climate states. It involved the progressive shift from glacial cycles of 41,000 years duration (obliquity-dominated) to high-amplitude, quasi-periodic cycles lasting approximately 100,000 years. In the Coorong Coastal Plain–Murray Basin region the Early-Middle Pleistocene Transition is manifested by a gradational change from the more landward siliceous and ferruginous barrier ridges of the Loxton-Parilla Sands of Pliocene age to the mixed quartz-carbonate successions of the Pleistocene Bridgewater Formation. One of the major challenges, however, will be increasing the analytical precision and applicable age range of luminescence methods for this window of time. Further developments in electron spin resonance will also be of considerable value in dating these successions.

The regional landscapes of the Coorong Coastal Plain also illustrate the contingent nature of Earth history. The plate tectonic induced separation of the continents of Australia and Antarctica led to the deposition of extensive sequences of Paleogene-Neogene cool water carbonates along substantial portions of the southern Australian margin. The Oligo-Miocene Gambier Limestone of the Gambier Embayment, Otway Basin, as well as in part, the Pleistocene Bridgewater Formation have been significant repositories for the preservation of Pleistocene vertebrate taxa, due to the karst weathering of these limestones. The cave deposits in part chronicle the extinction of some elements of the Pleistocene megafauna. The explosive phases of volcanism during the Pleistocene (Mount Burr Volcanic Group) and Holocene (Mounts Gambier and Schank) was intensified by the interaction of ascending magmas with groundwater in this karst province. One geological event gives rise to a succession of cascading events. An interesting question in the realm of geo-philosophy, is if we were able to repeat the experiment which commenced in the Cretaceous, would broadly similar coastal landscapes grace the southern margin of the Australian continent today?

Different approaches have been adopted for defining palaeo-sea level from the barrier complexes. Fixed sea-level indicators (that always form within a well-defined elevation related to tidal datum) have included the surface elevation of the planar landscape on the seaward side of barriers to infer palaeosea-level (Sprigg 1952), the elevation of the contact between high angle aeolian cross-bedding and low angle beach cross-stratification (Cook et al. 1977), and the surface elevation of back-barrier estuarine-lagoon facies in the immediate lee of barriers (Belperio and Cann 1990). Relational indicators of palaeo-sea level, which form at a range of elevations above or below the intertidal zone and, accordingly are of lower reliability, include the presence of palaeosols indicating that former sea level was below a given datum, or the lowest position of beach-dune sediments within a barrier indicating the minimum elevation of palaeo-sea level (Schwebel 1978). Despite these contrasting approaches to quantifying palaeosea-level, a wider spatial coverage will enhance the overall understanding of Quaternary sea-level changes within the region.

The Coorong Coastal Plain provides insights about the relative intensity of different interglacial events in the Quaternary. The age-height relationships of the back-barrier estuarine-lagoon facies reveal that interglacial sea levels occurred within a broadly common band-width of ±7 m. The record also reveals that the sea levels of the Last Interglacial Maximum (MIS 5e) were the highest attained on the coastal plain over the past 800,000 years. The transition to more intense glacial cycles (Early-Middle Pleistocene Transition) was characterised by lower sea levels and a more seaward position of the shoreline during glacial maxima. This resulted in a wider sweep of the continental shelf and the entrainment of additional bioclastic sediment in a landward direction at times of rising sea level to form the larger coastal barriers which characterise the Pleistocene Bridgewater Formation. In contrast, the lower amplitude glacial cycles before the Early-Middle Pleistocene Transition account for the smaller sediment volumes in the barriers of the Pliocene Loxton-Parilla Sands.

The differential durations of interglacial maxima is also geomorphologically expressed in the coastal plain. For example, during the 'super-interglacial' MIS 11 (424.6 to 392 ka ago) up to four barriers formed which include the Baker, Lucindale, Ardune and East Avenue Ranges. The relative positions of these barrier landforms within the landscape reflect subtle changes in relative sea level during MIS 11. These landforms also reveal that sea level during MIS 11 was significantly lower in this region compared with some other reported occurrences of shoreline successions of this age (Bowen 2003). In contrast, during all the other interglacials of the Middle and Late Pleistocene, only single barrier structures formed.

There still remains much to be done in understanding aspects of the long-term landscape development of the Coorong Coastal Plain and its rich palaeoenvironmental history. This book represents a first step in documenting the complexity of the evolutionary history of the region. There are numerous avenues for further research that immediately come to mind. Many of the smaller scale barrier landforms need to be dated to improve the understanding of the nuances of geomorphological changes and the complexity of the palaeosea-level record, particularly for the Pleistocene. With the passage of time it may be possible to derive a more complete understanding of warm interstadial events of glacial cycles as they appear to be preserved in the record of the coastal plain.

Additional studies examining the facies architecture of the Bridgewater Formation will refine interpretations of relative sea-level, particularly investigations of the buried palaeosols within these successions which formed at times of lower sea level and may reveal a rich palaeoclimatic record, particularly in terms of the intensification of aridity during the Quaternary. Constraining the duration of palaeosol development will be a fascinating line of inquiry. Other profitable areas for future research across the coastal plain include detailed stratigraphical analyses of lunettes within some of the inter-barrier depressions. Lunettes, source-bordering dunes found on the down-wind, eastern sides of lakes in southern Australia have provided rich sources of evidence for changing palaeoenvironments particularly for the last glacial cycle. The lunette as a distinctive landform, first described by Hills (1940), has since been shown to chronicle rich palaeoclimate records with high lake levels favouring the selective deposition of sand, while dry lake surfaces led to the deflation of lake surfaces and deposition of silt and clay aggregates in the leeward margins of the lakes, thus providing insights to distinct episodes of climate change and contrasting degrees of surface water flow (Bowler et al. 2006). Many of these landscapes also provide rich archaeological records as seen elsewhere in southern Australia.

One final thought for reflection. In the first volume of his autobiography, Sprigg (1989, pp. 261–262) reflected on the complexity of the Quaternary geology of the Coorong Coastal Plain and the merits and delights of studying the region. He noted;

> What worries me, is that so few others have yet attempted to fully extend studies of the S. E. stranded beach systems. A rich province for continuing research beckons, requiring ever more sophisticated age-dating techniques. … I wish I had another one hundred years to go, Geology sure is fun!

His words are as prescient now as the day they were written concerning the joys of working within the region.

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