Neritic Carbonate Sediments in a Temperate Realm

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Southern Australia

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Cover illustration: Force 6, the Southern Ocean, Great Australian Bight, October 1998 from RV *JOIDES Resolution*. The seafloor beneath these cold, stormy waters is the site of prolific temperate water carbonate sediment production and accumulation.

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To
Vic Gostin & Chris von der Borch

The Pioneers

Preface

Carbonate sediments deposited on shelves and ramps across the globe and in the geological record have traditionally been viewed as tropical, warm-water deposits (Bathurst 1975; Wilson 1975; Tucker and Wright 1990; James and Kendall 1992). Although it has been recognized for more than 50 years that carbonate sediments do accumulate in cool-water temperate and cold, polar environments (Chave 1952), it is only in the last several decades that these sediments have been studied seriously in the modern ocean (Nelson 1988a; James 1997; Pedley and Carannante 2006). This relative neglect is largely because they occur in environments that are difficult to document. The mid latitudes are stormy and the waters are cool but above all the shelves are mostly deep and so not amenable to research using SCUBA. The system must, as a result, be studied by remote sensing, chiefly through shipborne sampling, acoustic profiling, towed imaging and tethered water characterization. Scientific appreciation of the temperate carbonate depositional realm has thus lagged behind our understanding of the warm-water tropical environment. A direct consequence of this knowledge gap is that actualistic cool-water depositional models are not being routinely considered when interpreting the older rock record.

The Australian continent with its old, topographically subdued landscape, has a continental shelf that is almost entirely covered with carbonate sediment. The southern part of the continental shelf is the largest area of temperate, cool-water carbonate deposition in the modern world. Sediments in this vast southern region, in environments ranging from paralic to deep sea, have been examined by a variety of workers but the resultant information is scattered throughout the scientific literature (von der Borch et al. 1970; Wass et al. 1970; Belperio et al. 1988; James et al. 1992; Boreen et al. 1993; James et al. 1994; James et al. 1997; James et al. 2001; James et al. 2008), or presented as short, general summaries in special publications (James and Clarke 1997) and textbooks (Tucker and Wright 1990).

The purpose of this volume is to amalgamate and synthesize most of this information in one place, utilizing the studies of others, our own surveys, and unpublished data, to arrive at an overall synthesis of this critical region. The focus is on the continental shelf and its deposits. It is designed to serve as (1) a core of information for modern environmental studies, (2) a springboard for future marine geological research, and (3) a solid foundation upon which to build sedimentary facies and sequence stratigraphic models that are applicable to the interpretation of the older rock record.

This research has been funded by grant agencies from two countries, specifically the Natural Sciences and Engineering Research Council of Canada (NPJ), the Australian Research Council (YB), the Commonwealth Scientific and Industrial Research

Organization Division of Oceanography ship funding program, Geoscience Australia, and the University of Adelaide.

This science would not have been possible without the ceaseless efforts of officers and crews of CSIRO and Geoscience Australia vessels often under extremely difficult conditions. We are particularly grateful to Captain Neil Cheshire who skillfully guided us through many trying times and raging seas.

Our colleagues at sea and in the laboratory, Tom Boreen, Lindsay Collins, David Feary, Vic Gostin, Steve Hageman, Lisa Hobbs, Kurt Kyser, Jeff Lukasik, John Marshall, and Chris von der Borch are all silent partners in this endeavour.

The research at sea would have been impossible without the tireless efforts of Tony Belperio, Phil Bock, Kirsty Brown, Frank Brunton, Ric Daniels, Vicky Drapala, Margaret Fuller, Kieth Gaard, Paul Gammon, Karen Gowlett-Holmes, Graham Heinson, Alexandra Isern, Andrew Levings, Bobby Rice, Sam Ryan, Paul Scrutton, Rolf Schmidt, and Tony White. The exacting laboratory analyses were carefully performed by Christina Bruce, Elizabeth Campbell, Morag Coyne, Alexandra Der, Christa Kobernick, Heather Macdonald, and Rowan Martindale. Special thanks go to Isabelle Malcolm whose attention to detail, editing, analysis, and photographic skills helped greatly during the final stages of book production.

We are indebted to Peter Davies, Qianyu Li, Brian McGowran, Paul Taylor, and John Rivers for continuing discussions about our interpretations. Seafloor images from NW Tasmania were acquired with the help of Alan Williams and Bruce Barker.

The original manuscript was kindly read and criticized by Vic Gostin, Brian Jones, Andrew Levings, and John Middleton, to whom we are very grateful for their careful, insightful, and helpful suggestions.

Contents

Chapter 1
Introduction

1.1 Scientific Approach

Global carbonate sedimentation is partitioned into discrete marine realms whose character is determined by seawater temperature (Fig. 1.1). The latitude 25° S, which bisects the Australian continent, is the boundary between tropical, warm-water deposits in the north (e.g. the Great Barrier Reef) and temperate, cool-water sediments in the south (Fig. 1.2). Southern Australia is a classic area of shallow and marginal marine carbonate sedimentation (see review in Gostin et al. 1988). As such, it is one of a suite of modern settings that has been repeatedly utilized, along with Florida, the Bahamas, Caribbean islands, Pacific atolls, the Persian Gulf, and western Australia, as modern analogues for the interpretation of the carbonate rock record throughout geologic time. Thus, southern Australia is a touchstone for those scientists wishing to understand how carbonate sedimentation takes place today but also how it took place throughout geologic history. What has been lacking to date is a synthesis of the modern neritic carbonate sedimentary system that lies offshore from the well-studied marginal marine settings of southern Australia.

The purpose of this book is to document and interpret the origin, distribution, and diagenesis of surficial sediments on this immense cool-water carbonate shelf. It is perhaps useful to recall that the length of this environment is the same as the distance between New York to San Francisco or from the English Channel to the Caspian Sea.

The deposits across this shelf are, to a first degree, the products of modern oceanography, the Pleistocene prehistory of the region, and the organisms that produce the sediment. The first part of the book, comprising four chapters, is devoted to each of these aspects. In order to place the resultant neritic carbonates in a holistic context it is also necessary to describe the numerous coeval marginal marine depositional systems, most of which have been documented by others and are here the subject of a separate following chapter. The core of the book is, however, the chapters on neritic facies and depositional environments, many of which are unique to this continental margin. Yet, despite the universality of these facies and environments, each segment of the shelf has a unique suite of attributes. Thus, later chapters are devoted to analyzing the three major sectors of the southern Australian margin. Although the focus is on deposition, the sediments do not enter the rock record as simple biogenic particles, they undergo profound alteration on and just below the modern sea floor; early diagenesis plays an important part in this system and so a separate chapter is devoted to such matters. Finally, all of these aspects are assessed and discussed, both in terms of the modern sedimentary system and the applicability of our findings to global carbonate sedimentation.

1.2 Scope

The character of the sediments is interpreted in light of our current perception of the modern and late Quaternary biota, climate, oceanography, and geohistory of the area. The vast, latitude-parallel continental margin described herein extends some 4000 km from Cape Leeuwin, Western Australia to South West Cape at the southern tip of Tasmania (Fig. 1.3a). Over this distance there are a myriad of marine environments, each of which has a distinctive array of organisms and carbonate deposits. At the broadest scale, it is made up of a Southwestern

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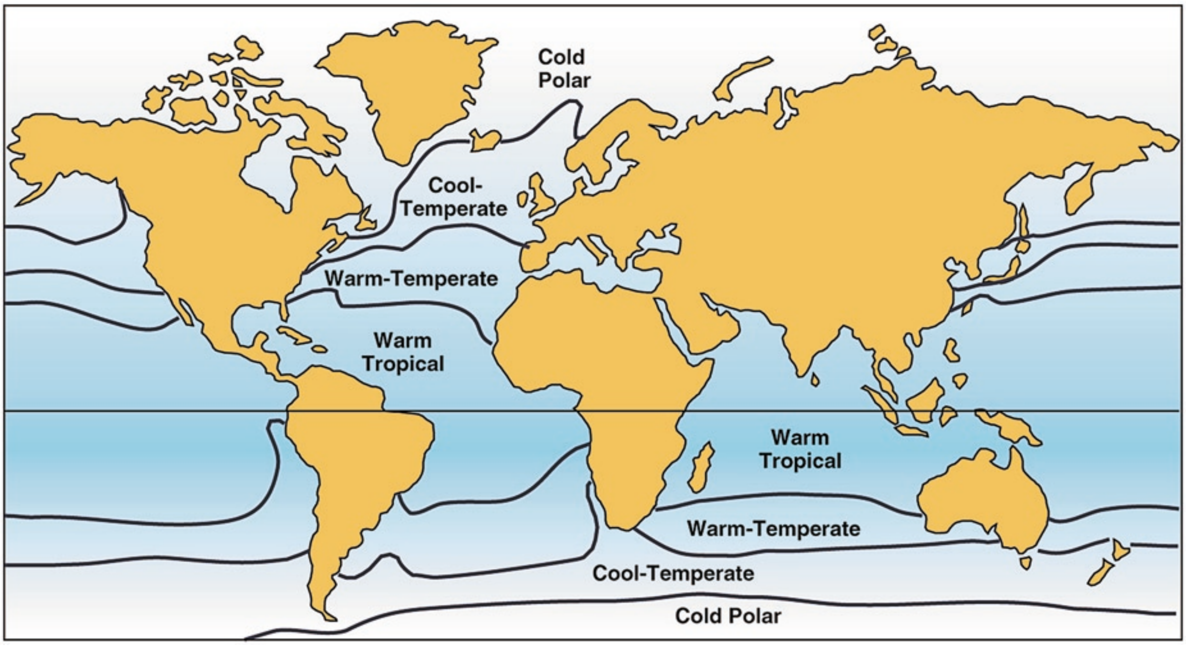

Fig. 1.1 A global map of average surface seawater isotherms delineating different modern carbonate depositional realms. The cool-water realm is differentiated into warm-temperate (15–20°C) and cool-temperate (5–15°C). (After James and Lukasik 2010)

Continental Margin and a Southeastern Continental Margin that pass from one to the other across a complex region of islands and large embayments called the South Australian Sea (Bye 1976) (Fig. 1.3b).

The Southwestern Continental Margin extends from Cape Leeuwin to southern Eyre Peninsula and includes the somewhat narrow Albany Shelf in the very west, but is dominated by the extensive Great Australian Bight. The Bight is, for purposes of documentation, divided into, from west to east, the Baxter, Eyre, and Ceduna sectors. The South Australian Sea is made up of Spencer Gulf, Gulf St. Vincent, Investigator Strait,

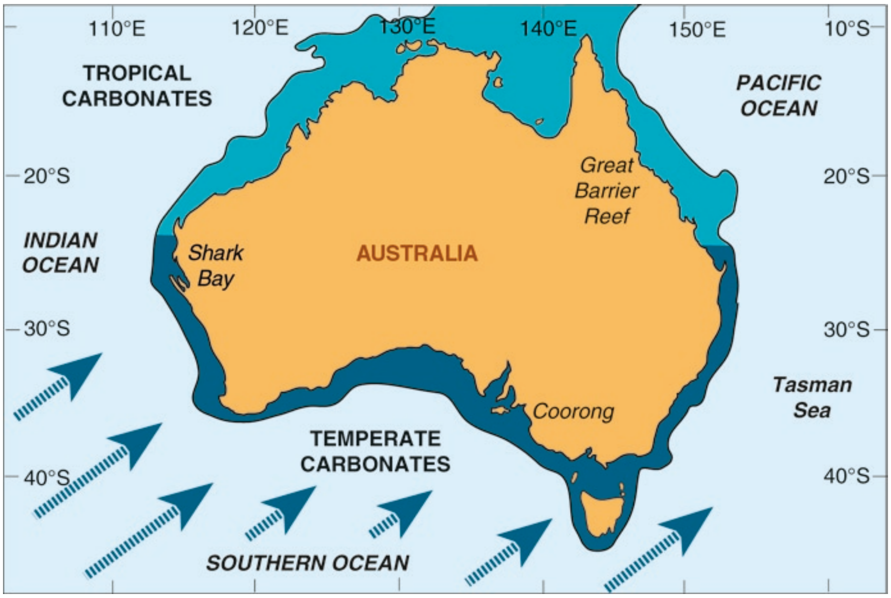

Fig. 1.2 A map of Australia illustrating the surrounding oceans, different neritic carbonate depositional realms (separated by the ~25° S latitude) and the direction of main wave approach (*dashed arrows*). Shark Bay, the Great Barrier Reef, and the Coorong are well known and intensively studied regions of carbonate deposition

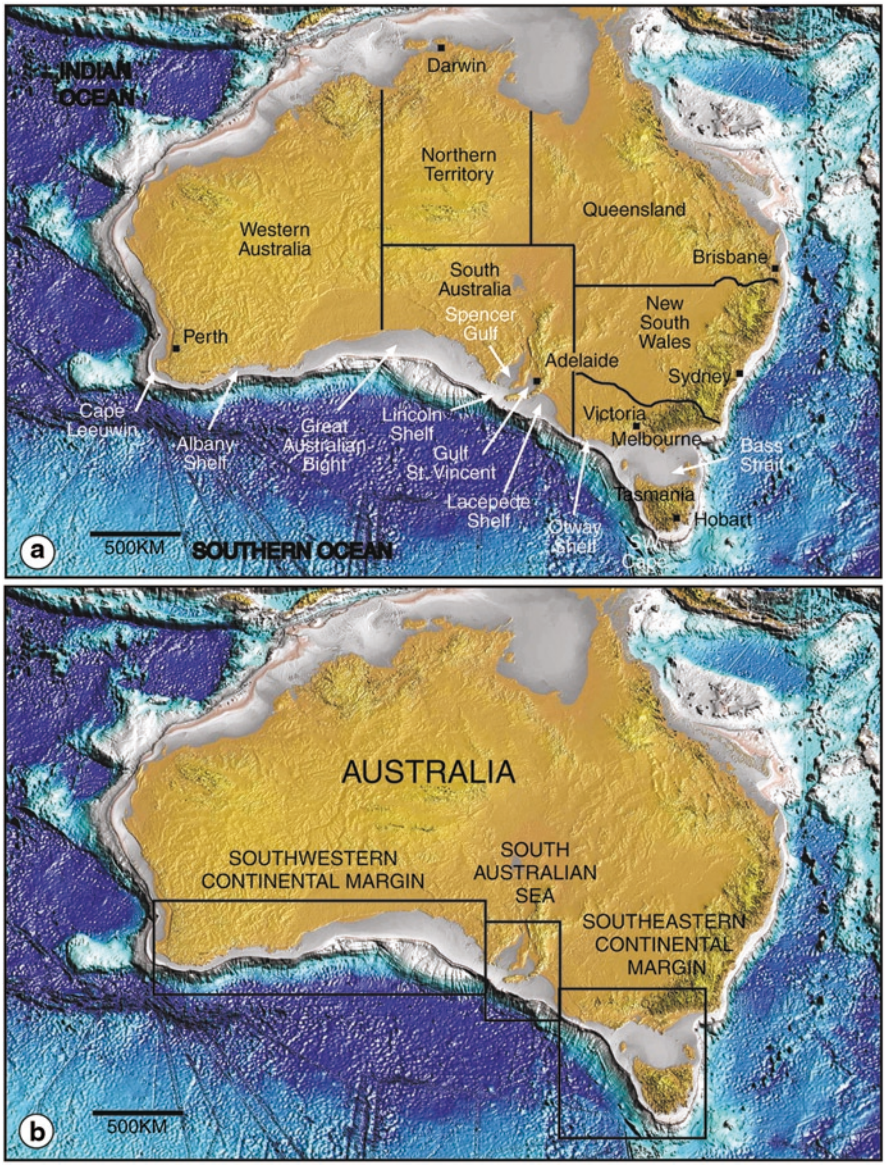

Fig. 1.3 (**a**) A map of Australia and surrounding oceans illustrating the states, major cities, and locations along the southern coast that are noted in this book. (**b**) Map of Australia showing the major sectors of the southern Australian continental shelf discussed in this book. Image courtesy of Geoscience Australia

the Lincoln Shelf, and the expansive Lacepede Shelf. The relatively narrow Southeastern Continental Margin fringes the west coast of Victoria as the Otway Shelf and swings southward along Bass Strait to flank Tasmania as the Western Tasmania Shelf. The scope does not specifically include the continental margin off Western Australia that faces the Indian Ocean or the eastern continental margin off eastern Tasmania, eastern Victoria and New South Wales that face the Tasman Sea.

The environments of sediment accumulation although numerous and varied, can be detailed and integrated under a few broad headings. At the core of this system is the subtidal, open marine seafloor and overlying water column. It is in this neritic sediment factory that stretches from the shoreface to the mid-slope, that most of the carbonate sediment is produced and redistributed. In spite of its largely latitude-parallel orientation, the shelf traverses nearly 15° of latitude, from ~31.5° to ~46° S, and ranges from warm temperate in the west to cool temperate in the east. This sediment factory is also active in the large gulfs and embayments, but because of local oceanographic and climatic constraints it is somewhat different from the open shelf factory. The important marginal marine settings range from spectacular high-energy cliffs to

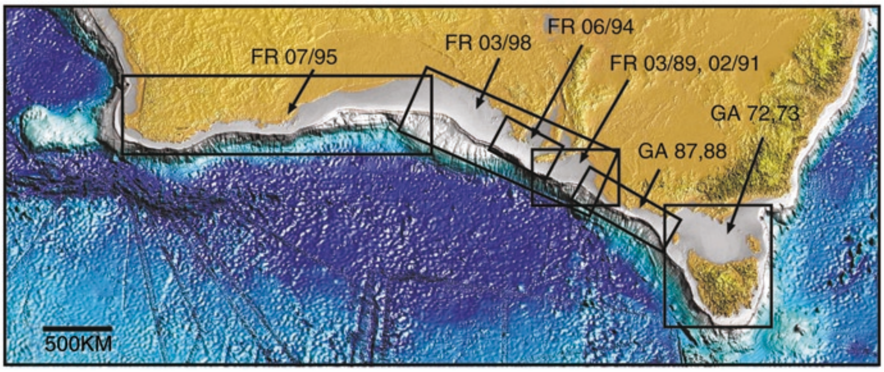

Fig. 1.4 A map of southern Australia. Research cruises (no. = month per year), mainly aboard *RV Franklin*, that enabled complete coverage of the southern continental margin of Australia. Some cruises overlapped previous areas so that seasonal changes in distribution and diversity of the major carbonate producers could be assessed. It also allowed sampling of sites that were not sampled due to weather extremes on previous cruises. Image courtesy of Geoscience Australia

protected muddy tidal flats to strandline dunes and associated saline lakes to fluvial-dominated beaches. Sediment in all of these settings undergoes moderate to significant diagenesis.

1.3 Data Base

The information in this volume comes from documentation of a series of local areas by ourselves, our students, and others over a period of more than 20 years. Research was mainly undertaken during a series of research cruises (Fig. 1.4). The open shelf environment has been documented by James et al. (1992), Boreen et al. (1993), James et al. (1997, 2001, 2008). The slope and associated mounds were described in Passlow (1997), James et al. (2004), von der Borch and Hughes-Clarke (1993), James et al. (2004), Hill et al. (2005), and Exon et al. (2005). The large embayments and their associated marginal facies have been intensively studied (see review for South Australia in Belperio 1995). More terrestrial settings, especially the saline lakes, are also reviewed in Belperio (1995) and Last (1992).

1.4 Data Acquisition and Methodology

The synthesis is principally based on analysis of seafloor sediment samples obtained using CSIRO *RV Franklin* (Fig. 1.5a). These research cruises took place between 1989 and 1998. The first expeditions were to the Lacepede Shelf in 1989 and again in 1991, with the latter focusing on the shelf margin and upper slope. This work was followed by a cruise to the Lincoln Shelf and southeastern Great Australian Bight in 1994. Work in the Great Australian Bight proper began in 1995 by documenting the western half of this huge area. This study was augmented in 1998 by a cruise that collected information from the Lacepede and Lincoln shelves but focused on the eastern part of the Bight. We have not collected samples from the eastern continental shelf ourselves but have generously been given material from the Tasmania continental margin and the Otway Shelf by Geoscience Australia who acquired sediments there in 1971–1972 and 1987–1988 respectively.

Research is based on a total of 1096 sediment samples (Table 1.1). Most of our material was obtained using either a simple pipe dredge (Bleys Dredge) with a volume of ~20 l (Fig. 1.5b), a large epibenthic sled with a 15 cm gape and volume of ~220 l (Fig. 1.5c), a beam trawl (Fig. 1.5d), or occasionally a Smith-McIntyre grab sampler (Table 1.1). Water depths are mostly >30 m, the shallowest operating depth for *RV Franklin*. The pipe dredge and sled were set on the bottom and towed at a speed of 2 knots for 3–5 min, at which time the vessel was stopped and the device retrieved. All sediment samples are, therefore, a mixture of surface and subsurface material to a depth of ~10 cm. A minor amount of the mud fraction may have washed out during retrieval, but enough samples with significant amounts of mud were recovered to indicate that such loss was minimal.

Fig. 1.5 (**a**) *RV Franklin*, the platform used to collect most of the samples and other marine information used in this book, (**b**) the pipe dredge (Bleys Dredge) used to collect most of the bottom sediment samples; hammer is 15 cm long, (**c**) the epibenthic sled being retrieved after sampling; the bag in the center is half full of sediment, (**d**) the material, seafloor biota, and sediment recovered by a beam trawl, (**e**) sediment being analyzed on the stern deck of *RV Franklin.* (Paul Gammon and Kirsty Brown)

Table 1.1 Samples

	Tasmania	Otway Rig Seismic 1987–1988 FR 02-91	Lacepede FR 3-89 FR 2-91	Eucla Rig Seismic 1992	Lincoln FR 06-94	Gab West FR 07-95	Gab East FR 03-98	Total
Grab	272	116	10	11	2	7	1	419
Bleys Dredge	0	0	149	0	52	91	19	311
Epibenthic Sled	0	0	0	0	15	103	91	209
Vibracore	0	24	0	11	0	0	0	35
Garvity Core	0	119	1	0	0	0	0	120
Piston Core	0	0	2	0	0	0	0	2
Total	272	259	162	22	69	201	111	1096

Underwater video images and direct underwater observation via SCUBA confirm these observations. Gravity cores, piston cores and vibracores were taken locally. The materials recovered were, because of operational restrictions, deeper than 30 m water depth (mwd). This information is locally supplemented by shallow-water samples taken using *RV Ngerin* and by materials collected using SCUBA and snorkeling.

Navigation was by Global Positioning System (GPS), transit satellite, radar, and dead reckoning. The average accuracy of navigational fixes varied from meters to several tens of meters. Samples and bottom profiles were widely spaced in order to characterize the entire region. Bathymetry was determined by a precision depth recorder. Surface temperatures and salinities on some cruises were recorded every 10 min, and vertical temperature profiles for selected positions were determined by a conductivity-temperature-depth (CTD) profiler.

Sediment attributes were logged on board (Fig. 1.5e). Images of most samples were taken on deck to ascertain living versus dead biota as well as the size of biota and rocks retrieved. Size fraction separation was done on board. Total samples were taken for further analysis whereas the coarse fraction (>2 mm) was sieved and archived separately. Bulk sample splits are now archived at Geoscience Australia in Canberra and available for future research. Detailed sediment composition was subsequently determined onshore by visual examination, under binocular microscope where appropriate, of sample splits of mud, sand, gravel, and coarser material. Results and facies assignments are tabulated in Appendices A, B, C, and D. Volumetric estimates of various components were made by comparison with standard visual percentage diagrams. Thin sections were prepared as necessary to solve particle identification problems. Scanning electron images were obtained of very fine-grained materials.

Bottom camera stations were located at specific sites after sediment recovery. Images were obtained using either a frame-mounted EG&G camera-flash unit or a 50 mm single lens reflex camera in a watertight housing. Photography during this 10 min drift period enabled coverage over areas that varied from meters to decameters, depending upon the drift rates. Analog videos of sites in the eastern Great Australian Bight were obtained using a camera in a specially designed underwater housing. Images from northern Tasmania were taken from digital videos taken by CSIRO and so are of specific sites.

Chapter 2
Setting

2.1 Geology & Tectonics

2.1.1 Introduction

The southern part of Australia is an ancient terrane that was welded into Gondwana, encompassed within Pangaea, and divorced from the supercontinent during the Mesozoic (Veevers 2000; Johnson 2004). The original tectonic grain, a relict of this long Gondwanan and Pangean prehistory, is predominantly north-south. These structures are, however, truncated by an east-west Mesozoic rift system that has in turn evolved into the modern passive continental margin (Fig. 2.1).

2.1.2 Pre-Mesozoic Craton

Southern Australia is anchored by the Yilgarn Craton and the Gawler Craton (Fig. 2.1). These two Archean-Proterozoic massifs are composed of igneous, metavolcanic, and metasedimentary rocks. The eastern margin of the Gawler Craton is flanked by the Tasman Fold Belt System. This 1,200 km-wide belt (Drexel et al. 1993) comprises, from west to east, the Delamerian Fold Belt, the Lachlan Fold Belt, and the New England Fold Belt (Fig. 2.1). The Delamerian Fold Belt is composed of continental margin Proterozoic and Cambrian sedimentary, metasedimentary, and volcanic rocks that were deformed in the Middle to Late Cambrian and then intruded by Late Cambrian granites (Foden et al. 1990). Today it forms the topographically high Flinders Ranges, Mt. Lofty Ranges, and Olary Arc east and north of Adelaide, and cores much of Kangaroo Island (Foden et al. 2006). The fold belt also underlies much of the Murray Basin.

The eastern part of the continent (Fig. 2.1) is a collage of accreted terranes, linear meridonal sedimentary basins, and volcanic arcs. The western part of the Lachlan Fold Belt is a terrane formed during a protracted period of sedimentation and westward thrusting resulting from repetitive collision of exotic terranes (Birch 2003). Although cratonization of southeastern Australia was largely complete by Middle Devonian, it was quickly followed by intense Late Devonian folding and granite intrusion (Willman et al. 2002). Subsequent rapid unroofing led to erosion and the deposition of middle Paleozoic terrestrial sediments together and post-orogenic acid volcanism. This landscape was scoured by repeated late Paleozoic continental glaciations and locally covered by glacigene and associated cold marine sediments (Fielding et al. 2008).

2.1.3 Australian Southern Rift System

The extensive divergent, passive continental margin of southern Australia, the Australian Southern Rift System (Stagg et al. 1990; Willcox and Stagg 1990; Drexel et al. 1993), is the result of Jurassic to Tertiary rifting and spreading between the Australian and Antarctica plates (Jensen-Schmidt et al. 2002; Duddy 2003; Holdgate and Gallagher 2003; Totterdell and Bradshaw 2004). The initial series of extensional basins formed during Middle-Late Jurassic breakup of eastern Gondwana via extension along the southern margin of Australia as one arm of a triple junction (Fig. 2.2a). This failed rift remained largely quiescent until late Cretaceous when seafloor spreading between Australia and Antarctica began. A major uplift event

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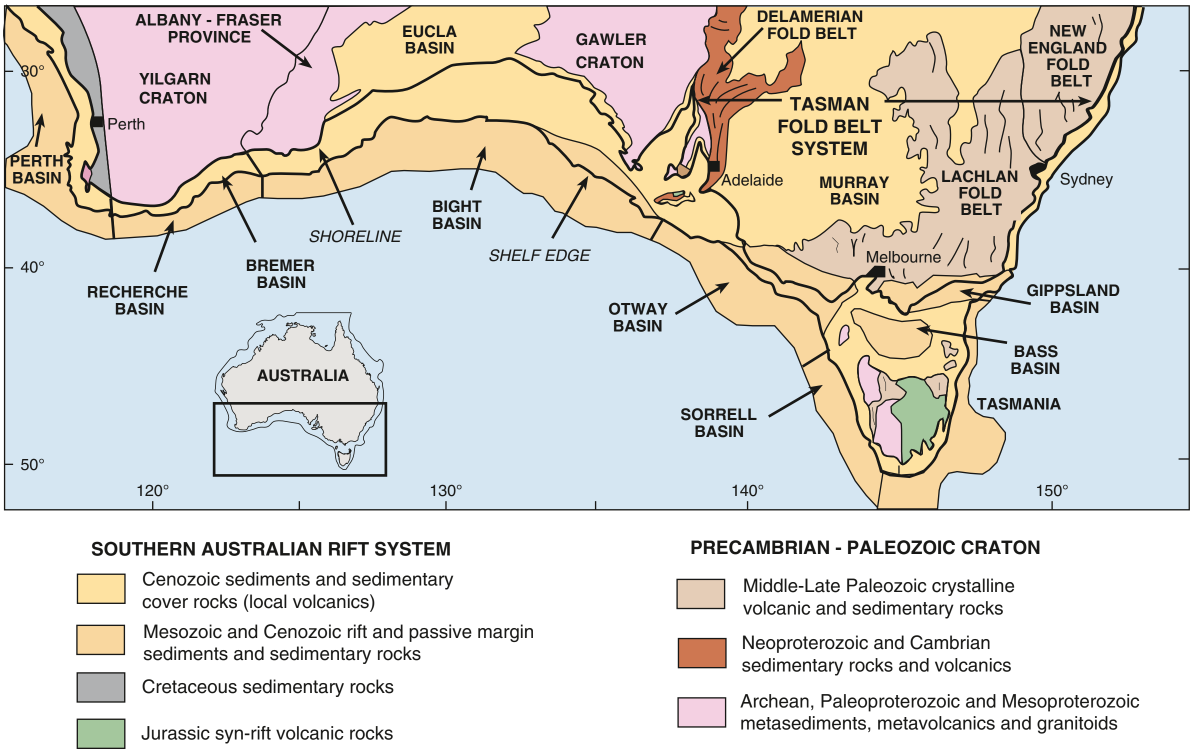


Fig. 2.1 Geological map of southern Australia. Archean-Paleoproterozoic massifs of the Yilgarn and Gawler Cratons dominate the western half of the continent, and are the sources of quartz sediment on the continental margin in this area. The Tasman Fold Belt System, comprising the Delamerian Fold Belt, the Lachlan Fold belt, and the New England Fold Belt comprise most of the eastern part of the continent. These Precambrian-Paleozoic terranes with a predominant north-south tectonic grain are cut by the east-west Australian Southern Rift system. This system comprises local Jurassic volcanics, extensive continental margin rift basins, and Cenozoic cover rocks that accumulated in a series of separate basins. (Recherche Basin to Sorrell Basin)

at ~95 Ma (Cenomanian) probably corresponds to the initial formation of ocean crust south of Australia and initial separation of Australia and Antarctica (Veevers 1986; Veevers and Eittreim 1988) (Fig. 2.2b). Early spreading rates were slow (~9 mm year^{-1}) and largely oriented NW-SE (Fig. 2.2c) but nevertheless resulted in the formation of a narrow, rapidly subsiding seaway between Australia and Antarctica (Fig. 2.2d). Resultant thick Mesozoic sedimentary successions of terrestrial and marine siliciclastic sedimentary rocks are now sequestered in three large roughly east-west, fault-bounded Jurassic-Cretaceous extensional troughs, the Recherche, Bight, and Otway, basins (Figs. 2.1, 2.3) that lie mostly beneath the modern continental shelf and slope in water 200–4,000 m deep.

Spreading rates dramatically increased to ~45 mm year^{-1} during the Middle Eocene coincident with a change of the spreading direction from NW-SE to N-S. Actual continental disconnection was, however, temporally protracted, with final detachment of Tasmania from Antarctica not happening until the Oligocene (~33.7 Ma). Although Tasmania also began to separate from continental Australia, it never completely broke away such that Bass Strait is underlain by a thick sedimentary succession on stretched continental crust; the Bass Basin. This west-to-east, scissors-like opening resulted in a gradually widening Cenozoic marine embayment, the Australia-Antarctica Gulf (Exon et al. 2004). The modern shelf morphology is, however, largely controlled by a series of major Cenozoic basins (Recherche Basin, Eucla Basin, Bight Basin, Otway Basin, and Sorrell Basin) (Lowry 1970; Fraser and Tilbury 1979; Bein and Taylor 1981; Davies et al. 1989; Hocking 1990; Stagg et al. 1990; Hill and Durrand 1993; Totterdell and Bradshaw 2004) whose deposits extend onto the continent proper in a series of epicratonic basins (Bremer, Eucla, Murray, Bass) (Fig. 2.1b).

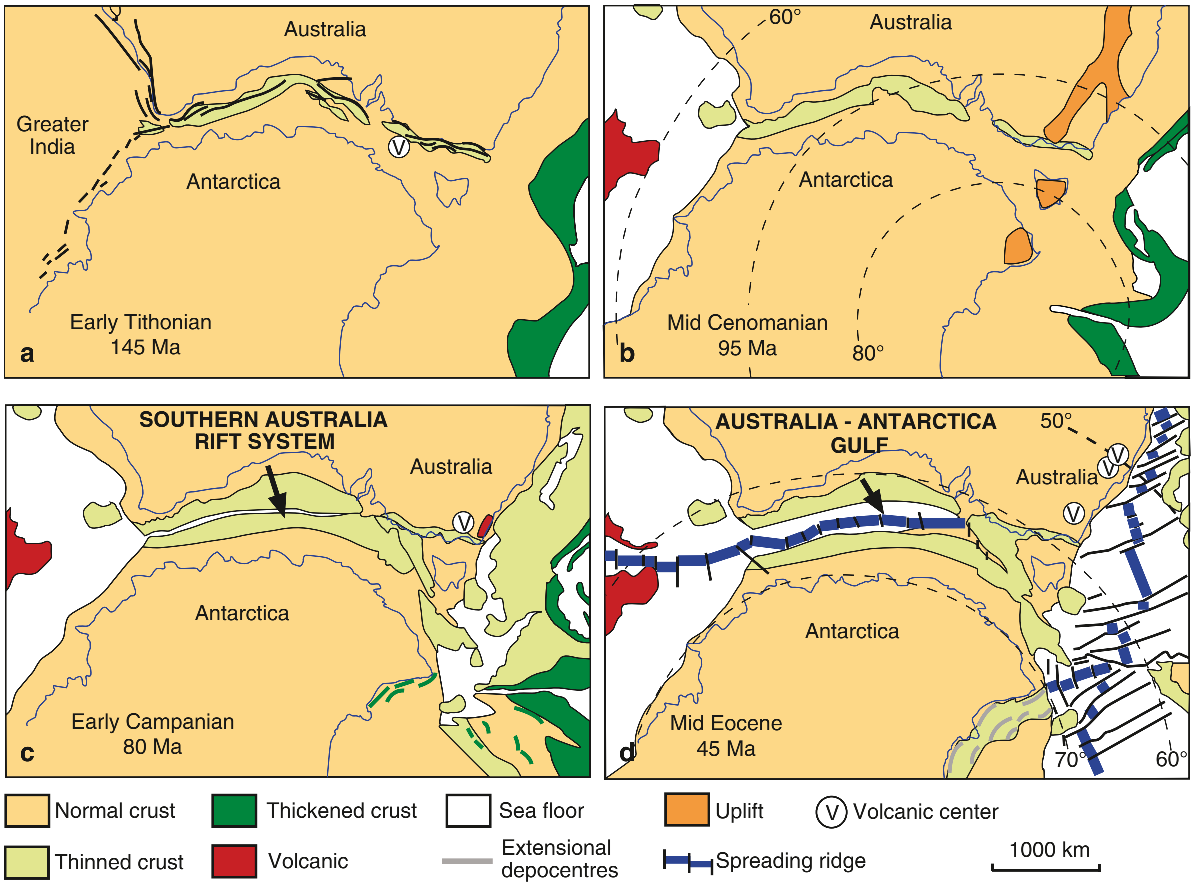


Fig. 2.2 Images depicting different stages in the separation of Australia from Antarctica (after Norvick and Smith 2001). Separation **(c)** began in the west and resulted in the Australia–Antarctica Gulf **(d)** a Paleocene and Eocene embayment that was closed at its eastern end until complete opening and formation of the modern Southern Ocean in the Oligocene

2.1.4 Cenozoic Continental Margin Wedge

The change in drift direction and increase in spreading rate during the Middle Eocene began in the west and was accompanied by left-lateral strike slip as Australia pulled away from Antarctica (Fig. 2.2) until final generation of oceanic crust in the Late Eocene. This change coincided with the first appearance of widespread continental margin and epicratonic carbonate sediments, which continued to be the dominant style of shelf deposition throughout the Cenozoic. The carbonates remained largely cool-water in aspect because, in spite of the fact that Australia had drifted equatorward during the Cenozoic (Fig. 2.4), the surrounding ocean waters remained cool. These epicratonic basin and continental shelf wedge strata have been divided into several discrete successions or sequences (Fig. 2.5), each of which has its distinctive style (Quilty 1977; McGowran et al. 2004). The Middle Eocene to Early Oligocene portion (Succession 2—Fig. 2.5) is characterized by cool-water carbonate and spiculite biosiliceous facies in the west with coeval terrigenous clastic and voluminous coal deposits in eastern Victoria deposited within the elongate Australia–Antarctica Gulf (Fig. 2.2d). The eventual complete separation of Australia, South America, and Antarctica in the early Oligocene led to establishment of the cool Circumantarctic Current and West Wind Drift, isolating Antarctica and profoundly cooling the ocean south of Australia. Following a major eustatic sea level fall due to initial Antarctic glaciation, and profound canyon cutting at the prograding shelf edge (Bernecker et al. 1997), succeeding Late Oligocene to Middle Miocene deposits (Succession 3—Fig. 2.5) are

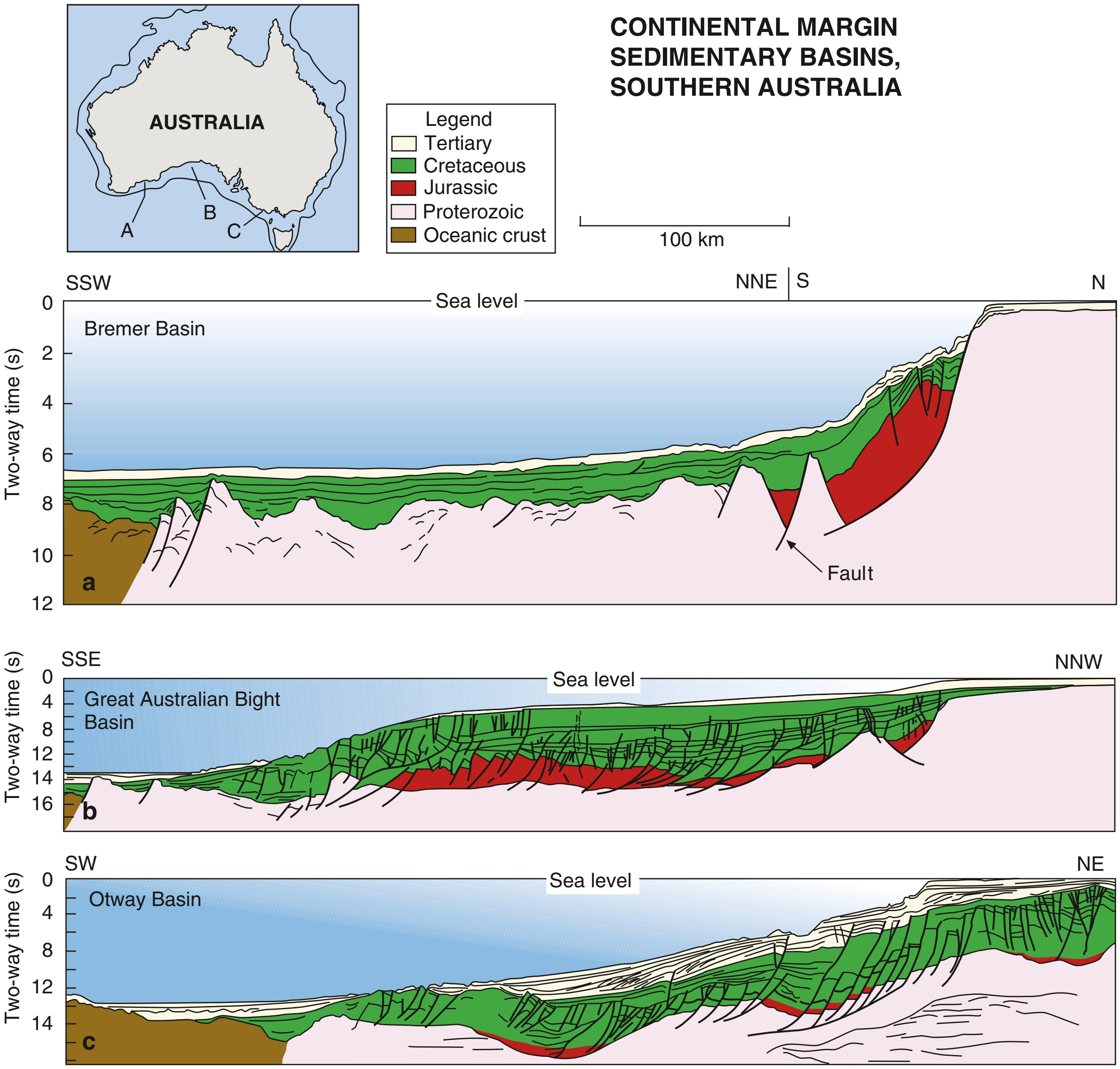


Fig. 2.3 Interpreted seismic sections across the southern Australian continental margin (locations on inset map). Large passive margin basins of the Southern Australian Rift System are filled with Jurassic and Cretaceous siliciclastic sediments, some of which are hydrocarbon rich. The Cenozoic is a relatively thin succession of mainly carbonate sediments and sedimentary rocks in sections **(a)** and **(b)**, whereas the section in the east **(c)** contains significant siliciclastic deposits at the base. (Modified from Stagg et al. 1990)

typified by temperate neritic carbonates, with local coals in the far east (McGowran et al. 2004).

2.1.5 Tectonic Inversion

The quiescent Mesozoic-Paleogene passive margin history was dramatically interrupted in the late Middle Miocene by complete tectonic inversion, wrenching, compression, and associated tectonics (Hill et al. 1995; Sandiford 2003a, b). Large segments of the inner continental margin and most epicratonic basins were uplifted, locally deformed, and exposed; they have remained so to the present day. This event was due to collisions on the northern and eastern margins of the continent. Such deformation was strongest in the east, in Victoria, and progressively less intense westward. Current thinking is that the Otway Ranges were uplifted (for a second time) by late Miocene tectonism at 8–6 Ma

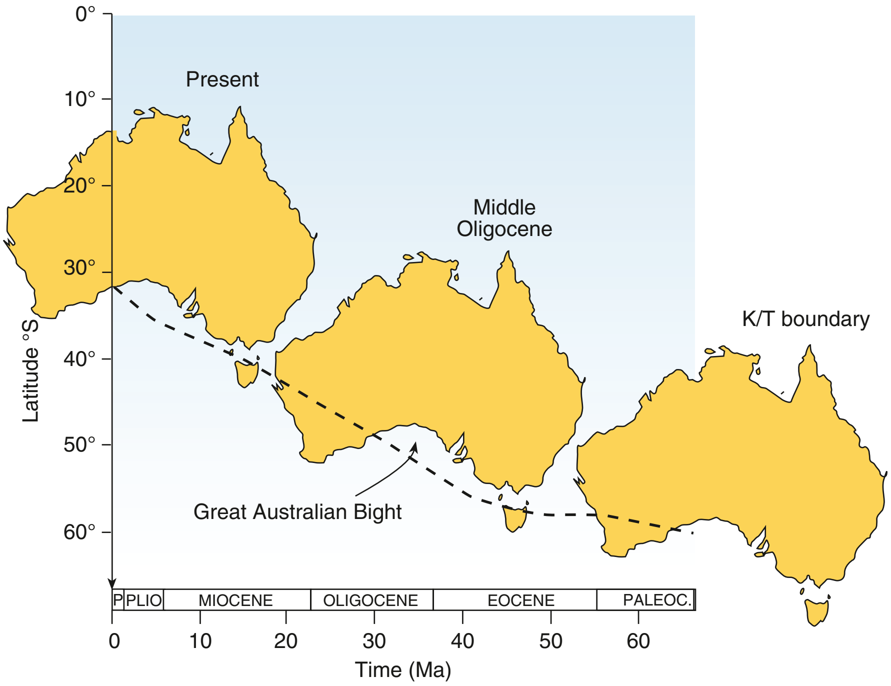


Fig. 2.4 Movement of Australia during the Cenozoic (from Feary et al. 1992). The Great Australian Bight was located at ~60°S during the early Cenozoic and is now positioned at ~32° S. Initial slow northward drift was followed by a change in direction and accelerated movement to the NNW in the middle Oligocene. The continent is still moving in this direction at a rate of ~7 cm year^{-1}

(Dickinson et al. 2002; Sandiford 2003a), either the result of compression between the entire Australian plate and plates of SE Asia or a change in relative plate motion between the Australian and Pacific Plates. All of Victoria is currently under strong E-W and SE-NW compression with evidence of tectonic activity through Pliocene to the Holocene wherein Pliocene strandlines are displaced upward 200–250 m on the west side of the Otway Ranges. Basin inversion was accompanied by Plio-Pleistocene volcanism (the Older Volcanics) (Price et al. 2003), again largely restricted to the east. Such tectonic activity and attendant seismicity continues in South Australia (Greenhalgh et al. 1994) and Victoria with volcanism (the Newer Volcanics) in South Australia documented by aboriginal oral tradition as recently as 1500 BP (Sheard 1986).

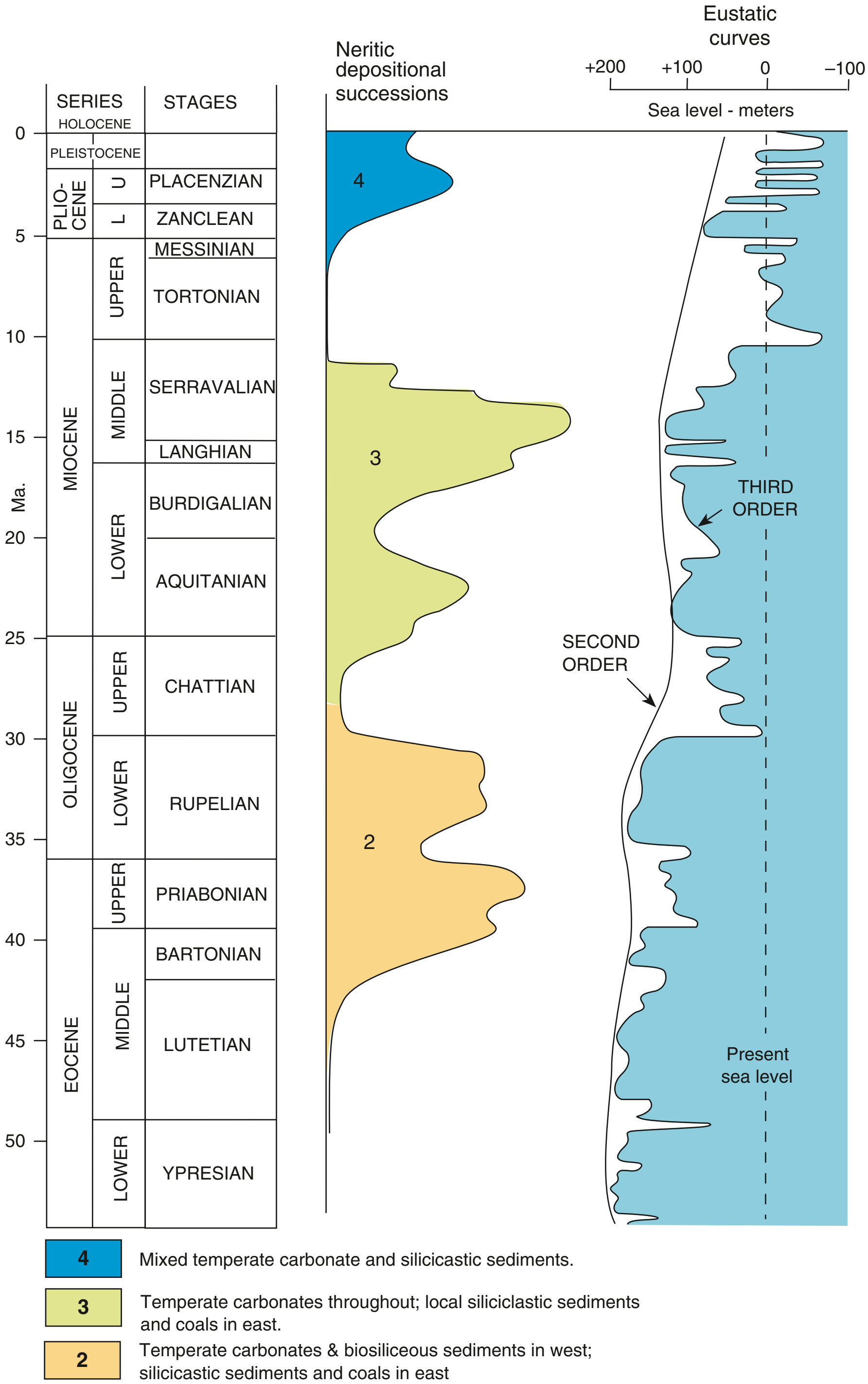
The major episode of uplift that created the Otway Ranges in Victoria, exposed Eocene-Miocene sediments in the epicratonic basins, and resulted in sporadic, ongoing volcanism in the east, was succeeded by Plio-Pleistocene deposition in epicratonic basins and on the outer shelf, whereas little sediment accumulated on the inner shelf. The Pliocene (Succession 4—Fig. 2.5) is typified by mixed siliciclastic–carbonate deposits (Belperio et al. 1988) from oyster-rich estuarine to inboard marine shoreface and grassbed deposits (Brown and Stephenson 1991; Pufahl et al. 2004; James et al. 2006; James and Bone 2007), to local spectacular prograding outer shelf and slope sediments (Feary et al. 2004) and extensive periods of laterization inland. The Pleistocene is, by contrast distinguished by spectacular eolianites that are plastered along many coastlines, especially those that are SW-facing into the prevailing winds and seas (Wilson 1991; Belperio 1995). These sets of aeolianite are locally prograding with evaporites and lacustrine dolomites in interdune corridors (Alderman and Skinner 1957; von der Borch et al. 1975; von der Borch 1976; von der Borch and Lock 1979). Coeval sediments in gulfs and basins are marine (Shepherd and Sprigg 1976; Blom and Alsop 1988; Gostin et al. 1988; Fuller et al. 1994). Outboard the shelf edge and upper slope is (1) gently dipping as a series of impressive prograding clinoforms, (2) steep with numerous submarine canyons or (3) erosional and subject to mass wasting (von der Borch and Hughes-Clarke 1993; Passlow 1997; Feary and James 1998; James et al. 2004; Exon et al. 2005; Hill et al. 2005).

2.2 Meteorology & Climate

2.2.1 Introduction

Meteorology and climate, summarized by Gentilli (1971) have a profound influence on the nature of

Fig. 2.5 A plot of Cenozoic depositional successions in southern Australia, on the shelf and in adjacent epicratonic basins, against geologic time and the global sea level curve (modified from Quilty 1977; McGowran 1997). Deposition reflects the eustatic changes in sea level with succession 2 being a mix of siliciclastic and carbonate sediments whereas succession 3 is mainly carbonate. Succession 4 is again a mixture of carbonate and siliciclastic deposits



sedimentation across the southern Australian marine environment. The continent lies between ~11°S and ~43° S and at this location weather is dominated by the ridge of high pressure produced by descending air at the boundary between the Hadley Cell and the Ferrel Cell. During summer, this boundary moves southward some 5–8° of latitude, at times allowing the tropical belt of low pressure (intertropical convergence) to penetrate the northern coast of Australia (Fig. 2.6b). In winter the high-pressure belt moves northward (Fig. 2.6a) and

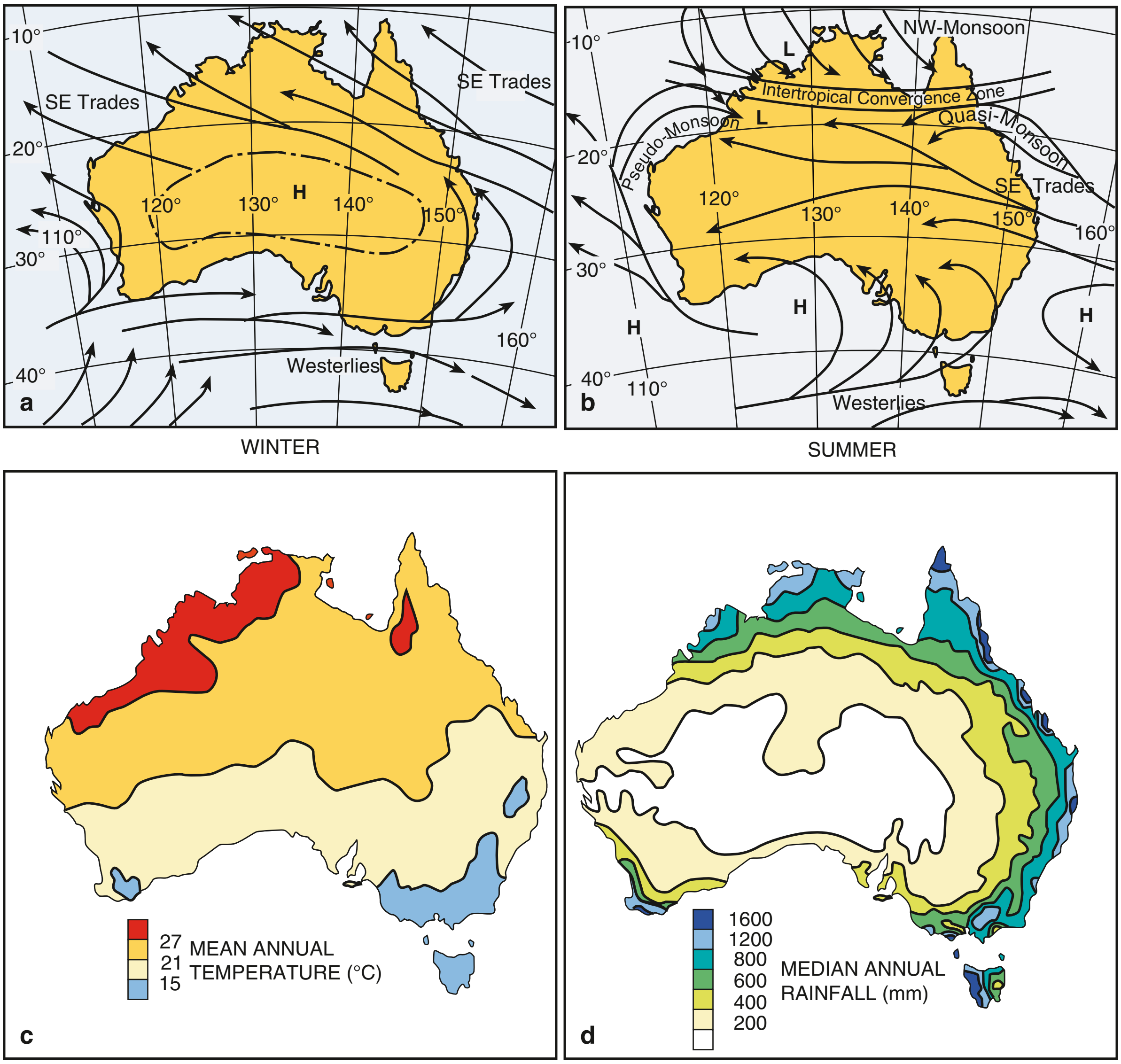


Fig. 2.6 Maps of Australian meteorology (modified from Gentilli 1971). **(a)** A plot of the major intracontinental high and associated wind patterns during winter. **(b)** A plot of the southward movement of the intertropical convergence zone into northern Australia, southward shift of the high pressure system, and associated wind patterns during summer. **(c)** A plot of mean annual temperature. **(d)** A plot of mean annual rainfall illustrating the humid character of the southwestern and southeastern coasts and the semi-arid character of the Great Australian Bight and South Australian Sea

permits the mid-latitude jet stream to meander over the land. Thus, summer circulation is meridonal (N-S) and winter circulation is zonal (E-W).

2.2.2 Anticyclonic Highs

The high-pressure ridge is really a series of highs that move eastward, especially during summer (Figs. 1.2, 1.3). Circulation around each cell is counterclockwise with winds on the south side irregular and often violent. Summer highs bring tropical continental air to the SW and maritime tropical air to the SE. Between highs in summer, there is a quasi-stationary front and light clouds, whereas in winter there is lower pressure, multiple cold fronts, and stormy weather. This winter pressure trough between highs is due to the formation of upper air depressions that often bring copious rain.

The zone of high pressures travels along about 37–38° S latitude in summer (i.e. across Tasmania), and about 29–32° S in winter (i.e. across Pt. Augusta–Sydney). On average, 40 highs pass over Australia per year. These highs originate in the central Indian Ocean and so are warm-air cored. Their magnitude and latitude is related to the speed and latitude of the sub-tropical jet stream. In summer, air from the western edge of the high (flowing south) brings very hot, overheated air from the continental interior that can reach temperatures above 38°C (e.g. 42–43°C). Along the south coast, these north winds are often laden with dust from the continental interior that is a minor sedimentary constituent but potentially important source of nutrients.

As cool SW summer winds travel equatorward, their relative humidity decreases such that upon reaching the hot Australian coast they fail to yield any rain (although there may be a stationary front and cloud). In winter maritime air, upon reaching the colder continent, can release moisture.

In summer, the contrast between the converging airstreams at the margin of 2 consecutive highs is pronounced; northerly flow from the first and southerly flow of the next produces a 'cool change' or dry cold front. Such fronts generally occur ~30 times per year. Winds accompanying such changes are generally 30–60 knots (~60–120 km h^{-1}), but can be violent. The change in temperature may range from 10 to 22°C in 2–4 h.

2.2.3 Mid-Latitude Depressions

These intense lows occur well south of Australia, but they have a strong effect on Australian climate. In summer, they are too far south and weak to affect Australia. During autumn, the frequency of heat-cored highs decreases considerably and the mid-latitude lows travel slightly further north than in summer. By late autumn, zonal circulation is more intense, the jet stream flows faster and enters Australia at a lower latitude, and depressions go past much closer to the southern coast. Well-developed fronts appear across southern Australia, bringing rain. During winter, the closeness of mid-latitude depressions increases rapidly to its mid-July maximum, with an average of three cyclonic centers per month skirting the southwestern coast and passing over Tasmania. Their intensity increases as they move eastward. By spring, the depressions travel further south again and only skirt the southern coast, although still passing over Tasmania.

2.2.4 Tropical Cyclones (Hurricanes)

Tropical cyclones are rare events (av. 3.3 year^{-1}) and are equally prevalent on both eastern and western coasts of northern Australia. They can only travel southward between highs, but if they meet a mid-latitude trough they can intensify or travel south to Tasmania or even New Zealand as a frontal cyclonic depression. The cyclones originate in the Timor Sea, travel southwestwards, veering southwards and then southeastwards with about 10% reaching the south coast. Those along the east coast do not affect the southern margin.

2.2.5 Temperature, Precipitation and Evapotranspiration

Mean annual temperature across most of the western continental margin and the South Australia Sea is between 15 and 21°C. East of Cape Jaffa and in Tasmania it is cooler, ranging between 10 and 15°C (Figs. 1.2, 1.3, 2.6c).

Frontal rains in the south fall mostly in winter. Tropical cyclone rain, when it does appear, comes in the summer or early autumn. The whole of the continent is periodically subject to severe drought. The driest area is in the center of the continent.

In summer, all of the area from Albany to Portland is arid, west of Albany and east from Portland to Melbourne it is semi-arid whereas most of western Tasmania is perhumid (wet) (Fig. 2.6d). In winter, the balance ranges from perhumid west of Esperance and across all of Tasmania, to humid from Esperance east to Cape Pasley and from Streaky Bay east to Melbourne. It is semiarid from Cape Pasley across the Great Australian Bight to Streaky Bay.

In January (summer), mean evaporation across the region ranges from ~200 mm per month in Eucla and Adelaide to ~100 mm per month in Tasmania. In July (winter), it ranges from ~75 mm per month in Eucla to ~25 mm per month in Tasmania.

2.3 Oceanography

2.3.1 Introduction

The continental margin along southern Australia is one of the world's longest, latitude-parallel, zonal, shelves; there are few other such shelves in the modern world. Most are meridonal and so transect major oceanographic boundaries. The shelf faces the continent of Antarctica, with its cold and isolated water masses that drive much of global ocean circulation. The overall region is, from an oceanographic (but not a geological) perspective, called the South Australian Basin.

The region between Australia and Antarctica is commonly referred to as the Southern Ocean, both in the scientific and non-scientific literature. The 2,500–3,500 km–wide body of water is, however, composed of two very different water masses, polar waters surrounding Antarctica and sub-tropical waters adjacent to southern Australia. The Subtropical Convergence Zone, a complex region of fronts, separates these water masses (Fig. 2.7).

The Southern Ocean is not recognized as such by some oceanographers but is instead treated as individual southern segments of the other three oceans (Tomczak and Godfrey 1994). In this view, only the ocean south of the Subtropical Convergence around Antarctica is called the Southern Ocean (Schodlok et al. 1997). It is here that the permanent thermocline reaches the surface. The region is characterized by unimpeded zonal circulation around the polar continent leading to perpetual strong westerly winds and associated strong currents (West Wind Drift–Antarctic Circumpolar Current) (Fig. 2.7), and some of the highest sea states on the globe. Since water circulation is largely from the west, the waters are mostly influenced by the Indian Ocean; Pacific Ocean waters are not present to any significant extent in the region. As a result, waters north of the Subtropical Convergence, and which cover the southern Australian shelf, are treated as part of the SE Indian Ocean. For ease of discussion, the whole region herein is called the Southern Ocean, recognizing other more stringent definitions. The following discussion is a combination of observations, summary articles, and numerical studies.

2.3.2 Sea State

The southern Australian continental shelf overall is swell- and storm-dominated with high (>2.5 m) modal deep-water wave heights (Davies 1980; Short and Hesp 1982; Short and Wright 1984; Hemer and Bye 1999). The dominant wind and swell wave approach is from

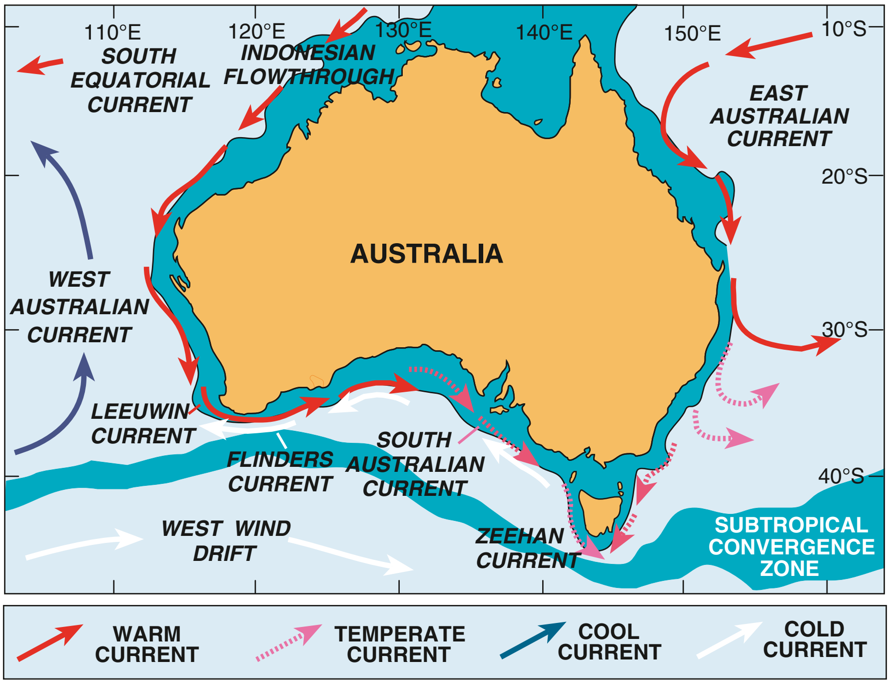


Fig. 2.7 A map of Australia and surrounding oceans highlighting the major current systems