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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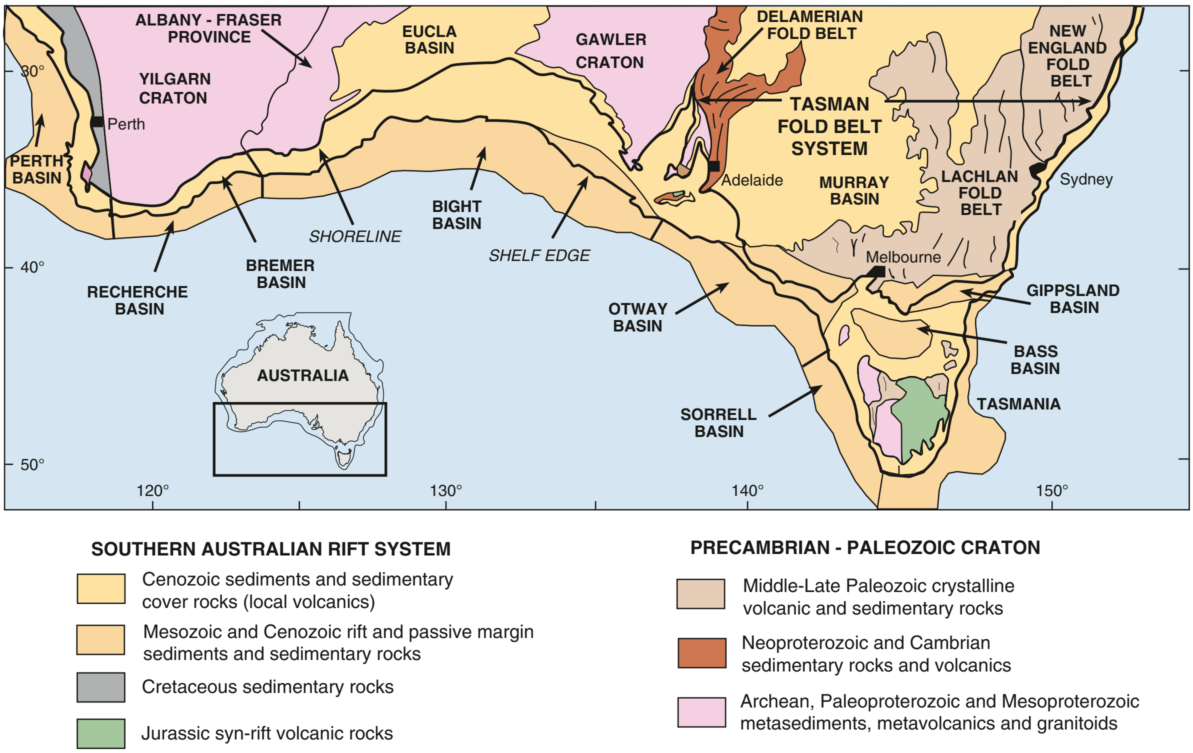

Fig. 2.1 Geological map of southern Australia. Archean-Paleoproterozoic massifs of the Yilgarn and Gawler Cratons dominate the western half of the continent, and are the sources of quartz sediment on the continental margin in this area. The Tasman Fold Belt System, comprising the Delamerian Fold Belt, 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).

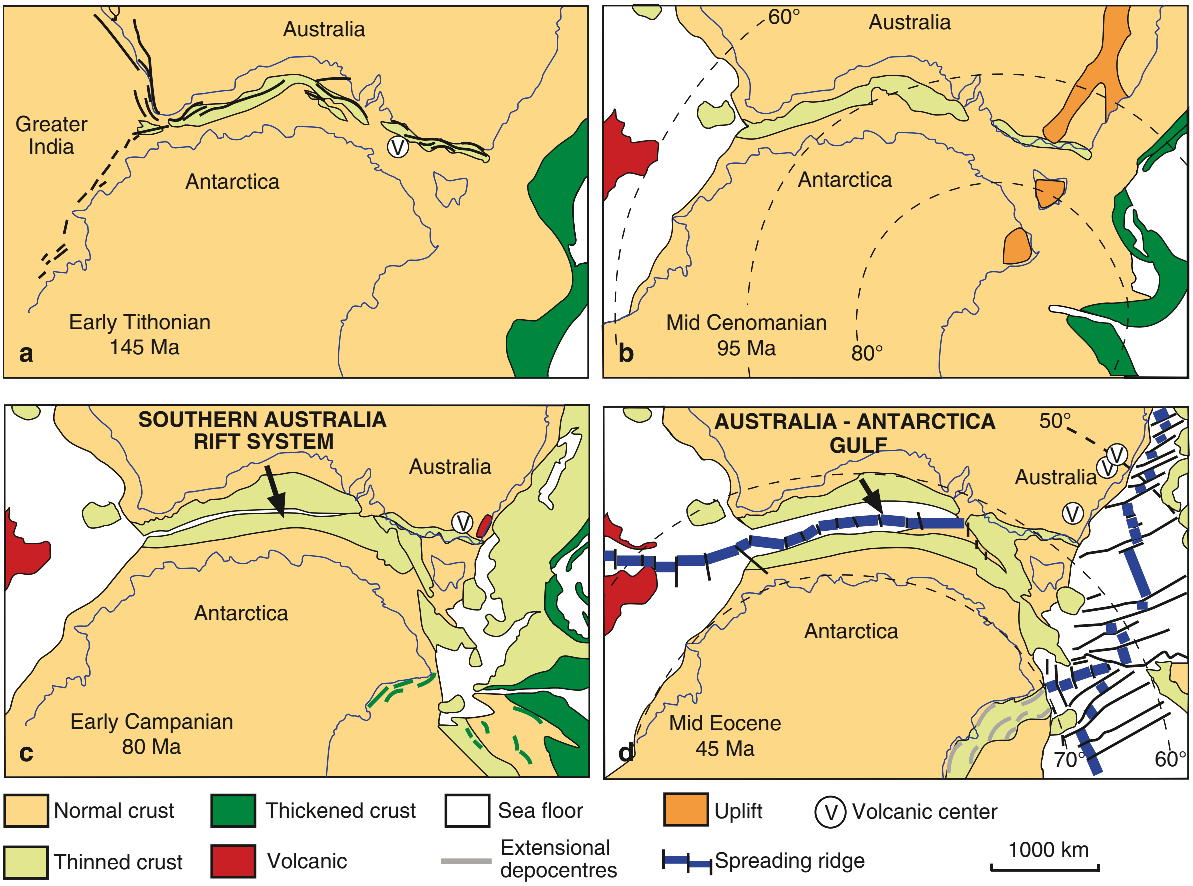

Fig. 2.2 Images depicting different stages in the separation of Australia from Antarctica (after Norvick and Smith 2001). Separation **(c)** began in the west and resulted in the Australia–Antarctica Gulf **(d)** a Paleocene and Eocene embayment that was closed at its eastern end until complete opening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

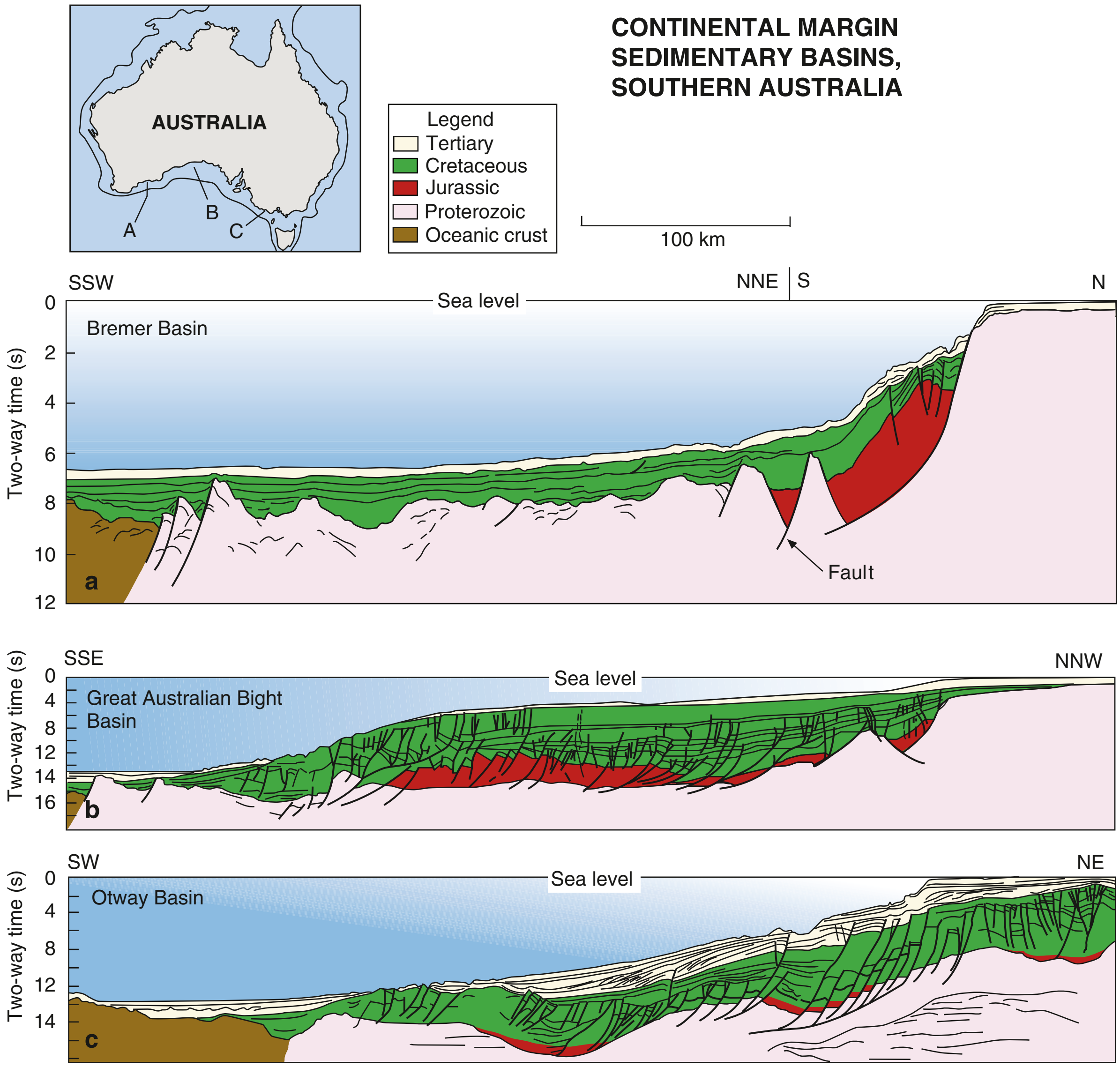

Fig. 2.3 Interpreted seismic sections across the southern Australian continental margin (locations on inset map). Large passive margin basins of the Southern Australian Rift System are filled with Jurassic and Cretaceous siliciclastic sediments, some of which are hydrocarbon rich. The Cenozoic is a relatively 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

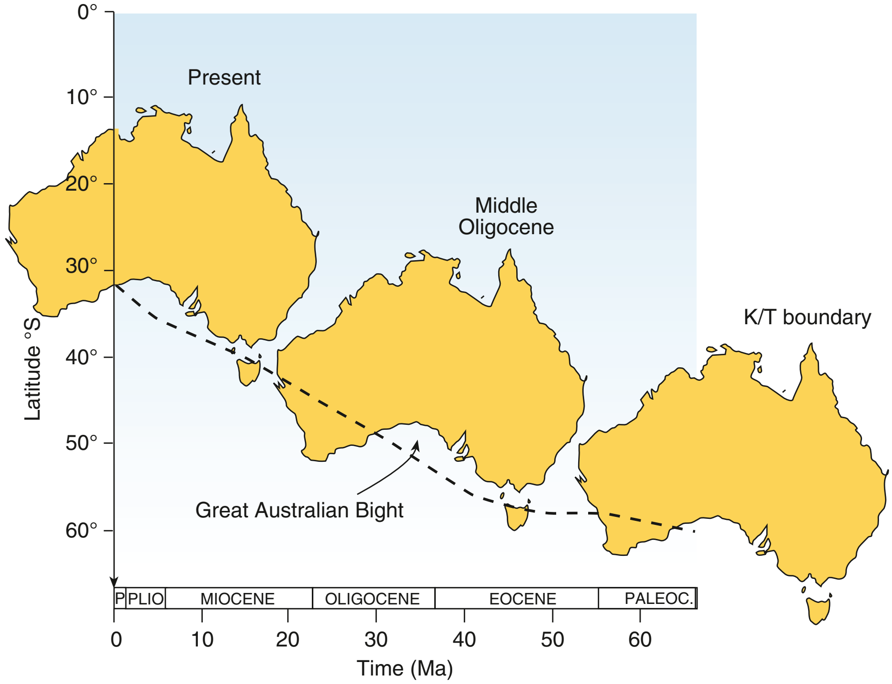

Fig. 2.4 Movement of Australia during the Cenozoic (from Feary et al. 1992). The Great Australian Bight was located at ~60°S during the early Cenozoic and is now positioned at ~32° S. Initial slow northward drift was followed by a change in direction and accelerated movement to the NNW in the middle 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

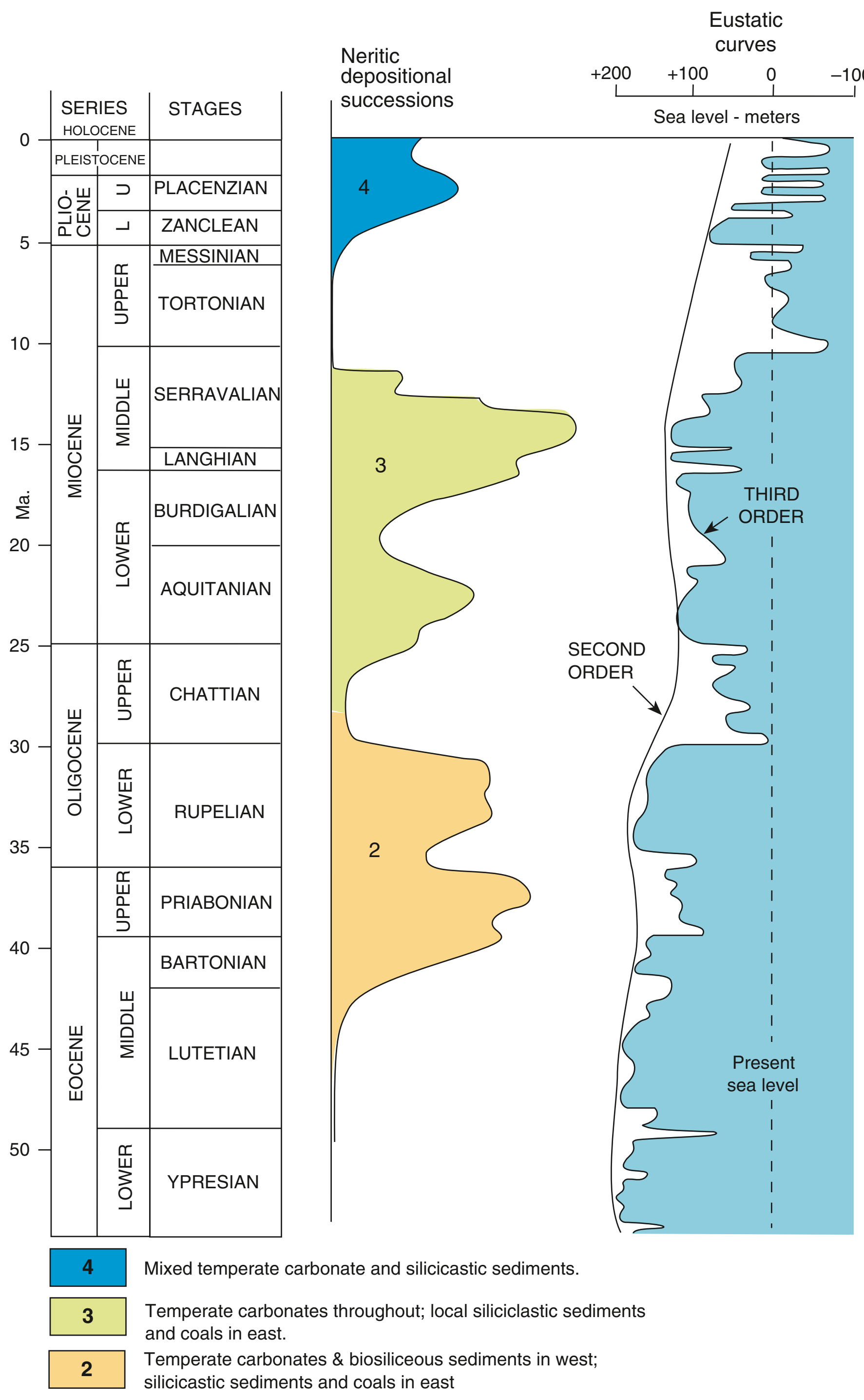

Fig. 2.5 A plot of Cenozoic depositional successions in southern Australia, on the shelf and in adjacent epicratonic basins, against geologic time and the global sea level curve (modified from Quilty 1977; McGowran 1997). Deposition reflects the eustatic changes in sea level with succession 2 being a 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

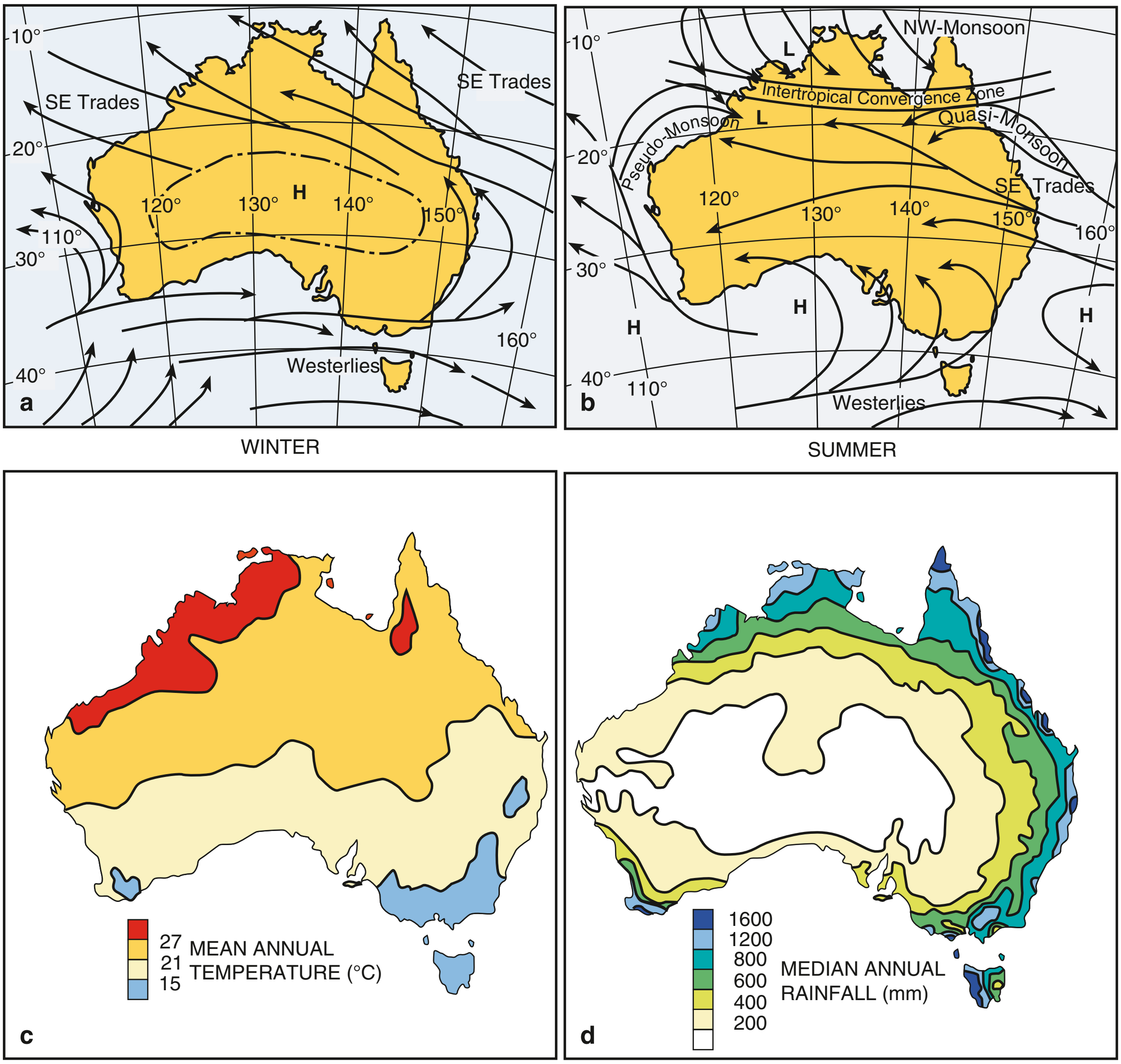

Fig. 2.6 Maps of Australian meteorology (modified from Gentilli 1971). **(a)** A plot of the major intracontinental high and associated wind patterns during winter. **(b)** A plot of the southward movement of the intertropical convergence zone into northern Australia, southward shift of the high pressure 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

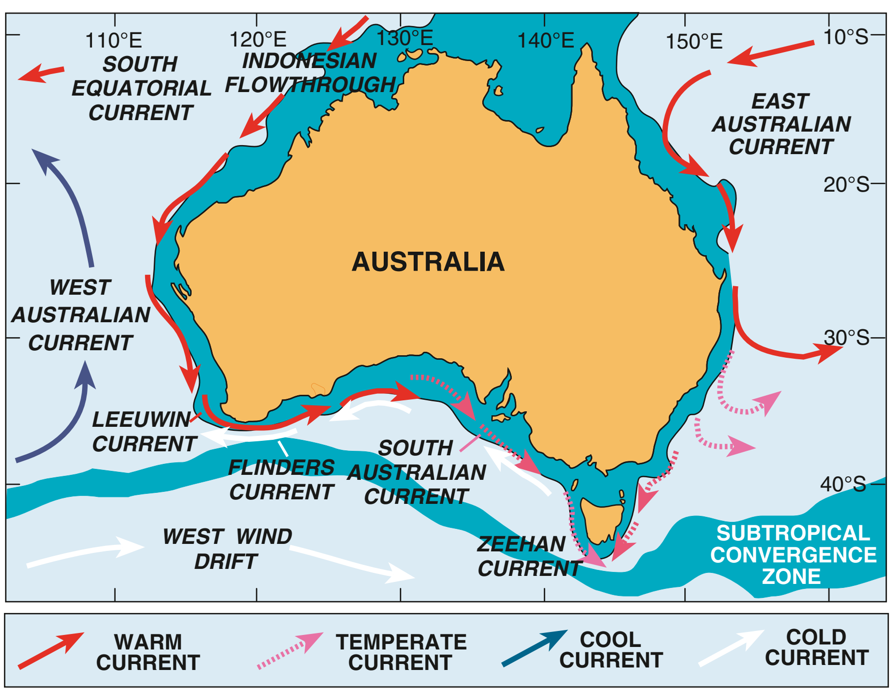

Fig. 2.7 A map of Australia and surrounding oceans highlighting the major current systems

the southwest, year-round. Wave drift is onshore with a mean speed of 0.15 $cm\,s^{-1}$ (over a period of a month, organisms would be advected onshore ~400 km). The importance of this wave drift conveyor belt is not yet known. Wave height will exceed 3 m for 30–60 days of the year; will exceed 6 m for 0–10 days; will exceed 8 m 1.3% of the time.

For typical swells there is refraction around Kangaroo Island. A westerly swell penetrates directly into Investigator Strait and is refracted northward into Spencer Gulf along the western shore of Yorke Peninsula; models predict 6 m swells; swells in the surf zone of Adelaide beaches would be 0.4–0.7 m with velocities of 1.0–0.6 $m\,s^{-1}$ (Bye 1976).

The two critical sedimentological interfaces in this hydrodynamically energetic region are storm wave base and swell wave base. Swells move onshore, generally from the southwest year round whereas storm waves are most intense during winter and spring (June to November). Swell period off southwest Australia ranges between 10 and 20 s with peak energy at 14 s and so waves would interact with the seafloor to depths of ~160 mwd Collins (1988). Storm wave periods are somewhat shorter, ranging between 8 and 10 s with peak energy at 8.5 s and so they come in contact with the seafloor at depths shallower than ~60 mwd. This relationship is more or less the same ±10 mwd across most of the southern Australian continental margin. Thus, swell base is, except for extremely intense storms, deeper than normal storm wave base. The seafloor <~60 ± 10 mwd is swept constantly by swell waves and episodically by storm waves. Collins (1988) has usefully called this the 'zone of wave abrasion' wherein sand grains are almost in continuous motion. Sediment movement by swell waves augmented by occasional storms waves is also active between ~60 and ~140 mwd, but less so. These calculations fit well with actual seafloor images that show rippled seafloor sands to ~140 mwd but seldom deeper. The seafloor below 140 mwd to the shelf edge is typically muddy with only local degraded bedforms in the shallower parts. These bedforms are partially obliterated by infaunal burrowing, attesting to their episodic nature.

2.3.3 Oceanographic Zones

The south to north transition from polar Antarctic to subtropical Australian waters is complicated and is marked by several fronts or narrow areas of rapid spatial temperature and salinity change. These are the Polar Front, Subantarctic Front and Subtropical Front (Fig. 2.8a). It is the water masses generated and subducted at these fronts that are potential upwelling waters along the south Australian margin.

2.3.3.1 Antarctic Region or Zone

The Antarctic Zone lies south of the Polar Front. The Polar Front Zone, where water temperatures change northward from 4 to 10°C is complex and composed of the Subantarctic Front and the Polar Front. The Polar Front is where surface temperatures change northward from ~4 to 8°C and salinities change from ~34.2 to <33.9‰. The Subantarctic Front is where temperatures change from 8 to 10°C and salinities increase from 34.3‰ to 34.7‰.

2.3.3.2 Subantarctic Region or Zone

This zone is bounded by two fronts, the Subtropical Convergence (~40° S) and the Polar Front (~50° S) and contains another, the Subantarctic Front (~45° S). It has also been called the Subantarctic Water Ring (Longhurst 1998). The northernmost zone is in the vicinity of the Antarctic Circumpolar Current and is located between the Subtropical Front and Subantarctic Front. Its most prominent feature is a water layer of nearly homogeneous thickness, extending from the surface to 400 mwd, called Subantarctic Mode Water (see below). The Subtropical Front is a current band with predominantly eastward flow associated with the southern boundary of the major subtropical gyres and marks the southern boundary of the Subtropical Convergence. The waters here warm rapidly from 8 to10°C and the salinity increases from 34.2 to 34.8‰.

2.3.3.3 Subtropical Convergence Zone

On the poleward side of the Subtropical Convergence the cold, low-salinity Antarctic Intermediate Water converges with and slides beneath the warm, high salinity, subtropical surface water at the Subtropical Front. The Subtropical Convergence divides anticyclonic water circulation of the southern Atlantic, Pacific, and Indian

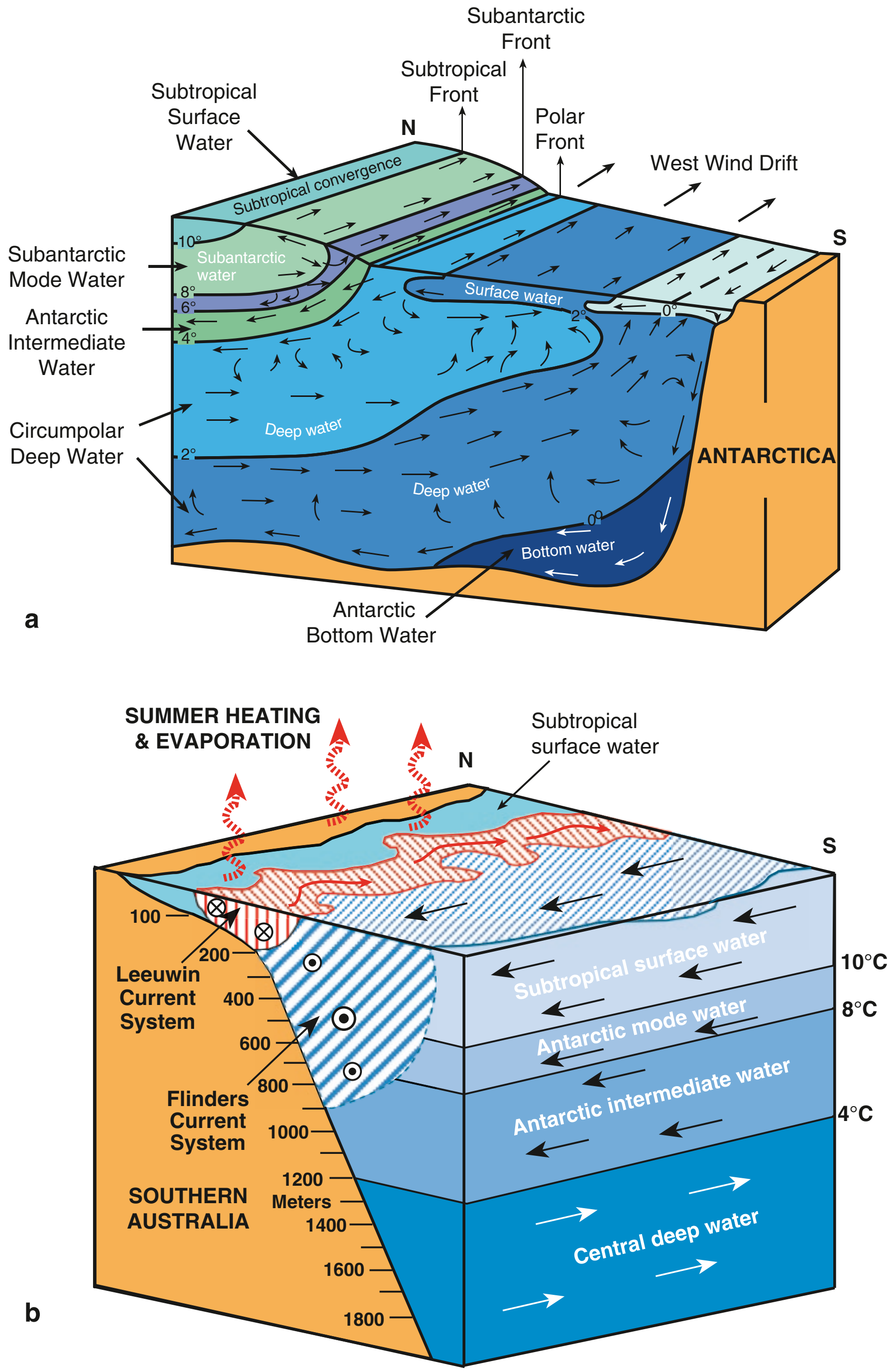

Fig. 2.8 Isometric blocks illustrating the major water masses described in the text **(a)** off Antarctica (after Sverdrup et al. 1942) and **(b)** off Southern Australia (synthesized from McCartney 1982; Condie and Dunn 2006; Middleton and Bye 2007). The Leeuwin Current System flows from west to east whereas the Flinders Current system flows from east to west

oceans from the cyclonic circulation of the Antarctic Circumpolar Current and can be traced almost continuously around the globe.

The Subtropical Convergence in the Australian-Antarctic sector lies north of the Subtropical Front and between ~35° and 45°S and is where surface waters increase in temperature from ~10°C to locally 18°C over a distance of <5 km. Increasing sea surface temperature and salinity occurs with decreasing latitude. The water spreads northward along isopicnals (a process called subduction). Subduction proceeds by the injection of surface water into intermediate depths by Ekman Pumping along isopicnals of its own density (Tomczak and Godfrey 1994). This is common in the subtropics because of negative wind curl.

The zone forms a mixed layer nutrient discontinuity where sharp gradients in nitrate concentration (<0.5 µmol in the north and 8–10 µmol in the south) results in high chlorophyll biomass. The phytoplankton is a mixture of southern diatom-dominated and northern calcareous—phytoplankton dominated forms.

2.3.4 *Water Masses*

The South Australian Basin is filled with five stacked water masses, which from the deepest to shallowest are (Fig. 2.8a) Antarctic Bottom Water, Circumpolar Deep Water, Antarctic Intermediate Water, Antarctic Mode Water, and Subtropical Surface Water (Tomczak and Godfrey 1994; Condie and Dunn 2006) (Table 2.1).

2.3.4.1 Antarctic Bottom Water

The deepest water in the Australian-Antarctic Basin (sometimes called the South Indian Ocean Basin), results from the sinking of cold and dense nearsurface water off Antarctica, (rich in solutes excluded during ice formation), that descends to >4,000 mwd and mixes with the Circumpolar Deep Water. Its origin is mostly in the Ross Sea and off Adelie Land. It is high in dissolved oxygen and low in nutrient content and maximum salinity and spreads to the east along

Table 2.1 Intermediate and deep water masses of the Southern Ocean

Subantarctic Mode Water	ESPERANCE		CEDUNA	
Potential Temperature (°C)	9.0–9.5		8.5–9.5	
Salinity (‰)	34.65–34.7		34.60–34.65	
Dissolved Oxygen (µmol l^{-1})	255 (N)–290 (S)		250(N)–285 (S)	
Oxygen Saturation (%)	89 (N)–100 (S)		88 (N)–100 (S)	
Phosphoate (µmol l^{-1})	0.9–1.2		1.0–1.2	
Nitrate (µmol l^{-1})	14–18		14–20	
Silicate (µmol l^{-1})	2.0–6.0		3.0–6.0	
Antarctic Intermediate Water				
Potential Temperature (°C)	3.5–5.5		3.1–6.3	
Salinity (‰)	34.30–34.40		34.50–34.32	
Dissolved Oxygen	190–2-5		200–220	
Oxygen Saturation	65–70		66–72	
Phosphate (µmol l^{-1})	1.9–2.2		1.9–2.3	
Nitrate (µmol l^{-1})	28–34		30–34	
Silicate (µmol l^{-1})	22–35		20–39	
Circumpolar Deep Water	Lower 1250–2250 mwd	Upper 2250–4500 mwd	Lower 1250–2250 mwd	Upper 2250–4500 mwd
Potential Temperature (°C)	2.0–0.5	2.0–3.5	2.0–0.5	2.0–3.0
Salinity (‰)	34.73–34.71 max 34.75 @3 km	34.55–34.73	34.73–34.71 max 34.75@2.7 km	
Dissolved Oxygen	180–220	180–170 O_2 min (<170) 1500–1700 mwd	180–210	180–200 O_2 min (<175) 1200–1500 mwd
Oxygen Saturation	55–62	53–55 O_2 min <51	53–62	53–60 O_2 min <51
Phosphate (µmol l^{-1})	2.2–2.4	2.2–2.5 O_2 min >2.5	2.4–2.5	2.4–2.5 O_2 min >2.5
Nitrate (µmol l^{-1})	36–38	36–38	34–36	34–36
Silicate (µmol l^{-1})	90–125	50–90	100–120	60–100

Compiled from Schodlok et al. (1997)

the sea floor. The water temperature is <0.5°C and the salinity <34.7‰. Dissolved oxygen is >220 μmol l^{-1}, >62% saturation. Nutrients are about the same as the overlying Circumpolar Deep Water whereas silicate is ~125 μmol l^{-1}. This water mass has little effect on the southern Australian continental slope or shelf.

2.3.4.2 Circumpolar Deep Water

Low in dissolved oxygen, this is the most prominent water mass in the Southern Ocean. In this region, it originates as the North Indian Ocean Deep water and spreads southward from the western Indian Ocean at depths of 1,000–2,000 m to mix with North Atlantic Deep Water east of Africa and form Central Deep Water that is characterized by low dissolved oxygen and high nutrients. In this area it can be divided into two parts, upper (1,250–2,250 mwd) and lower (2,250–4,500 mwd) (Table 2.1). The upper part has nutrient levels higher than anywhere else in the water column.

2.3.4.3 Antarctic Intermediate Water

For many years it has been known that this water mass is formed as high salinity North Atlantic Deep water and Circumpolar Deep water together move upward from depths greater than 2,000 m, come to within 200 m of the surface in the Antarctic Zone where they mix with nearsurface waters. Recent studies have also found much evidence that Subantarctic Mode Water is also another precursor of Antarctic Intermediate Water (Carter et al. 2009). The mixture of these waters is warmed and diluted by rain and snow, resulting in low salinity, and is then subducted northward near the polar front between the Polar Front and the Subantarctic Front.

This relatively nutrient-rich water forms an intermediate depth temperature and salinity minimum layer with high oxygen content that flows northward at depths of ~800–1000 m (Lynch-Stieglitz et al. 1994). It is slightly denser than Subantarctic Mode Water (see below). The winter deep mixed layers are isolated from the surface during the summer by a seasonal thermocline. The sinking occurs in a stepwise path northward. This water intersects the south Australian slope at ~600–1200 mwd (Middleton and Cirano 2002; Wood and Terray 2005) and with Sub Antarctic Mode Water feeds into upwelling circulations over the shelf during the Austral summer. It has a temperature of 4–8°C and salinities of 34.30–34.50‰, fresher than the Subantarctic Mode Water positioned above it, although in upwelled circulations is sometimes reheated to 14°C (Levings and Gill, in press).

2.3.4.4 Subantarctic Mode Water

This large, nearly homogeneous layer formed between the Subantarctic Front and the Subtropical Front is called a thermostad or pycnostad because temperature and salinity variation with depth is very small. The water body results from deep winter convection due to erosion of the seasonal thermocline and exposure of this layer to the cold atmosphere. Convective overturning and thus ventilation results in high dissolved oxygen (~95%–McCartney 1977, 1982). It is tracked throughout southern hemisphere oceans as water with an oxygen maximum.

Adjacent to the Australian continental slope this water has descended to ~450–700 mwd but is much thicker and extends to the surface south of the subtropical front. It has a temperature of ~8–10°C and salinity of 34.60–34.70‰ (Table 2.1). In the Subantarctic Ring Longhurst (1998) referred to this as an oligotrophic regimen even though it is a relatively high-nitrate but low chlorophyll signature, probably because of low Fe supply.

2.3.4.5 Surface Waters

Surface waters, those shallower than ~400 mwd are complex, especially on and adjacent to the continental shelf proper where they are a combination of Subtropical Surface Water, waters introduced from offshore Western Australia, evaporated waters, and upwelled waters. Subtropical Surface Water is also called Southern Subtropical Surface water, Tropical Surface Waters, Subtropical Surface Water and Indian Central water (Condie and Dunn 2006; Woo and Pattiaratchi 2008). Herein called Subtropical Surface Water, it is between 10 and 22°C, has intermediate relatively high salinity (35.1–35.9‰) and intermediate oxygen content (220–245 μmol l^{-1}) and a weak minima of dissolved N, Si, and P. Details of the water in different areas are discussed in subsequent chapters.

2.3.5 *Current Systems*

2.3.5.1 General Aspects

Waters that overlie the shelf and upper slope, because they are relatively shallow, are strongly affected by seasonally changing climate, both in terms of their composition and movement. In summer, the high-pressure ridge that is maintained over the area induces a consistent pattern of southeasterly winds; in winter when the anticyclone moves north over central Australia there is a predominantly westerly wind regimen. The autumn change from an easterly to westerly wind pattern causes, (1) a change in the character of Ekman transport, and (2) a switch in the direction of coastal currents from east to west. Southeasterly summer winds along the northern edge of the high pressure cells drive waters offshore via Ekman transport, lower coastal sea level by ~25 cm, induce a westward coastal current, and locally upwell waters towards the coast (Herzfeld and Tomczak 1997; Middleton and Platov 2003; Levings and Gill in press).

This situation reverses in winter as the westerly winds force downwelling to depths of 600 mwd over the shelf break, raising coastal sea level ~25 cm, and generating an easterly nearshore current. This is a rare example of downwelling currents driven by seasonally reversing winds (Middleton and Cirano 1999; Cirano and Middleton 2004)

2.3.5.2 Open Ocean

Water movement south of the Subtropical Convergence Zone is perpetually to the east in the form of the West Wind Drift or Circumpolar Current (Figs. 2.7, 2.8). The Circumpolar Current is the largest mass transport of all ocean currents. Driven by a circumpolar belt of westerly winds and associated frequent storms, this current comprises all water masses south of the Subtropical Front and travels eastward at a velocity of 0.05–0.15 $m\,s^{-1}$ (~0.2 knots). North of the Subtropical Front water movement in the upper 1,000 m is largely westward. Movement of Subantarctic Mode Water adjacent to the Australian continental margin is westward (McCartney 1977; Schodlok et al. 1997). To the south it may be anticyclonic; east in the south, north adjacent to Tasmania, and west along the shelf edge (McCartney 1977, 1982) or west north of the Subtropical Front, east in the centre, and west adjacent to the shelf (Schodlok et al. 1997).

2.3.5.3 Continental Margin

There is a considerable amount of information available concerning water masses and circulation across the continental margin. The two dominant features are a warm, mixed surface layer underlain by cooler Antarctic Intermediate and Subantarctic Mode Water (Newell 1961, 1974; Wyrtki et al. 1971; Bye 1972, 1983; Callahan 1972; Rochford 1977; Lewis 1981; Godfrey et al. 1986; Hahn 1986; Harris et al. 1987; Schahinger 1987; Cresswell and Peterson 1993; Hufford et al. 1997). The mixed surface layer flows in a generally east-southeast direction and is known as the Leeuwin Current off west Australia, the South Australian Current off South Australia and Victoria, and the Zeehan Current off west Tasmania. The underlying counter current of Antarctic Intermediate Water and Antarctic Mode Water flows in a generally north westward direction at a depth of about 400–600 m (Wood and Terray 2005) and is known as the Leeuwin Undercurrent off west Australia and the Flinders current off western Tasmania, western Victoria and South Australia (Middleton and Cirano 2002). This current feeds into shallower shelf circulations during summer when alongshore winds from the southeast in combination with coriolis force advects the mixed surface layer offshore and triggers a compensatory upwelling of Antarctic Intermediate Water and Antarctic Mode Water from greater depths (Hahn 1986; Schahinger 1987; Levings and Gill in press).

2.3.5.4 Flinders Current System

Monthly mean wind stress curl south of Australia is positive during summer and winter and leads to Ekman pumping and downwelling throughout the region. Calculations indicate that such downwelling ought to result in northward transport and that this should be deflected westward into an upwelling favourable boundary current that flows westward along the southern shelf; the Flinders Current (Bye 1972, 1983; Middleton and Cirano 2002; Middleton and Bye 2007), a northern boundary current. This may be the only such current on the globe. There are but a handful of real observations about the Flinders Current (Cresswell and Peterson 1993; Wood and Terray 2005) and most of what is understood comes from an integration of these measurements and mathematical modeling.

The Flinders Current is sourced from the Subantarctic Zone where Subantarctic Mode Water (cool, high oxygen, moderate nutrient levels) and Antarctic Intermediate Water (very cold, relatively fresh, high nutrient levels) flow north across the Subtropical Front (Fig. 2.8a) and then west along the Australian continental slope (McCartney and Donohue 2007; Currie et al. in press). The Flinders Current is also thought to be fed by the Tasman outflow, that flows westward around the southern tip of Tasmania (Cirano and Middleton 2004). Upwelled waters would therefore come mostly from Antarctic Intermediate Water (and Subantarctic Mode Water).

The Flinders Current flows throughout the year, even though coastal winds and currents reverse. The current runs beneath the Leeuwin Current during winter (Cirano and Middleton 2004), but during summer locally upwells onto the shelf and is present as a shallow current. Flow is strongest in summer due to increased Sverdrup transport. The Current intensifies from east to west, can extend from the surface to 800 mwd, and flows year-round with a velocity of ~16 cm s^{-1} (0.3 knots). Maximum westward speed is 20 cm s^{-1} (~0.4 knots) off Cape Pasley between 400 and 600 mwd; decreasing to zero at 1000 mwd. It should be thickest in summer with the bottom boundary layer extending some 50 km out from the shelf.

2.3.5.5 Leeuwin Current System

The western and southern margins of the continent are characterized by a unique series of strong warm shallow-water (<200 mwd) currents that flow south and east along the shelf edge in a narrow band for almost 5500 km (Ridgway and Condie 2004) from Northwest Cape to the southern tip of Tasmania (Fig. 2.8).

Leeuwin Current The wind-dominated circulation pattern generates a shelf-edge jet that changes with the season. The Leeuwin Current (Godfrey and Ridgway 1985; Cresswell 1991) is a narrow (<100 km), shallow (<200 m) stream of comparatively warm, (17–19°C), low-salinity (35.7–35.8‰) nutrient-depleted oceanic water of tropical origin that flows southward at relatively high velocity (0.1–1.4 m s^{-1}; 0.2–3.0 knots, ~20 km per day) along the western Australian continental slope and eastward into the Great Australian Bight (Pearce 1991). Temperature decreases from 26.3°C at the northern origin to 21.5°C at Cape Leeuwin to 18°C in the Great Australian Bight.

The Leeuwin Current originates off northwest Australia where the Indonesian Throughflow creates a warm-water pool. This in turn drives a meridonal pressure gradient that through geostrophy drives an onshore transport towards the western Australian coast. This situation results in a strong alongshore pressure gradient that provides the driving mechanism for a poleward flowing boundary current. The flow is driven by a large-scale meridonal pressure gradient that generates onshore geostrophic transport that is sufficient to exceed Ekman transport induced by equatorward wind stress. This is a unique current because it flows against the prevailing winds and transports warm, low-salinity, oligotrophic tropical water southward along the western Australian coast and then eastward across the Great Australian Bight. The strong alongshore pressure gradient is usually sufficient to overwhelm the effects of coastal, wind-forced upwelling. It has a strong seasonal cycle with greatest strength in the autumn and early winter, associated with weakening of alongshore winds from the southwest. It flows into the Great Australian Bight to about 120° E (off Esperance), although in many years it may penetrate further east.

There is also a substantial alongshore steric height gradient eastward from Cape Leeuwin capable of driving the Leeuwin Current eastward (it is here that the Leeuwin Current flows fastest). The influence of the Leeuwin Current diminishes eastwards such that off the eastern Great Australian Bight (135° E) it only drives ~15% of the flow. Ridgway and Condie (2004) concluded that fortuitously, the west coast pressure gradient delivers the Leeuwin Current to the southern margin just in time for the winds to change to winter westerlies and drive it eastwards.

As the Leeuwin Current propagates southward along the western coast of Western Australia it passes over the high-salinity subsurface core of the South Indian Central Water and the associated mixing makes it progressively more saline and cooler (Webster et al. 1979). Thus, there is a seasonal increase in the salinity of the Leeuwin Current as it approaches Cape Leeuwin (due to this drawing up of the South Indian Central Water), such that after rounding Cape Leeuwin the Leeuwin Current is more saline than surrounding waters. The saline water is, however, slowly lost through energetic mixing with fresher offshore waters. The Leeuwin Current appears to reach a longitude of ~138° E (south of Kangaroo Island) before its temperature-salinity signature is swamped by the Great Australian Bight outflow onto the slope.

South Australian Current The Leeuwin Current merges with the South Australian Current in autumn (Black 1853) as a plume of warm (2–3°C above the surrounding waters), saline water from the Great Australian Bight. The South Australian Current water forms in summer and moves east and off the shelf just as the winter winds start to blow from the west, driving it eastward. The current reaches its maximum flow during May, June, and July. Wind stress curl that leads to the anticyclonic gyre in the Great Australian Bight is intensified off Eyre Peninsula. In the western Great Australian Bight, seaward surface Ekman transport and Flinders Current shoreward transport converge to form a ridge over the shelf edge resulting in an eastward current over the shelf break and downwelling to 100 mwd. Temperature patterns of the Leeuwin Current indicate that the saline pulse from the Great Australian Bight travels 3000 km in ~2.5 months (speed of 0.4 cm s^{-1}, ~1 knot).

Zeehan Current Further east, there is a strong southeasterly flow off western Tasmania, called the Zeehan Current (Baines et al. 1983). The current is seasonally reversing, and steric height measurements show that the strongest flow is in winter and spring (June to November), although there is a southward flow all year round. Once the full winter state has been established with a positive sea level anomaly, the jet of warm water moves progressively eastward until it reaches the coast of Tasmania in July. Surface water decreases in temperature as it moves east from 18.3°C in the Great Australian Bight to 14°C along the Tasmania coast. The higher salinity water that is entrained into the flow comes from the Great Australian Bight and not from Spencer Gulf, Gulf St. Vincent, or the Indian Ocean. The winter outflow of cool and very saline waters from Spencer Gulf intrudes onto the shelf and slope and finds its own density level at 250–300 mwd; too deep to be incorporated into the shallower flow.

2.3.6 Tidal Currents and Internal Waves

Tidal currents on the southern Australian shelf are small (<10 cm s^{-1}, <0.2 knots) but are locally amplified somewhat in the gulfs. The nature and role of internal tides and solutions is unknown but inertial wave currents off the Bonney Coast are relatively large (20 cm s^{-1}; 0.4 knots) (Middleton and Bye 2007).

2.3.7 Seasonal Variability and Trophic Resources

Prevailing westerlies reverse during summer months and this together with coastal heating leads to the formation of warm waters in the Great Australian Bight and South Australian Sea. These east and southeasterly winds result in weak coastal currents that flow westward. Wind stress curl can lead to an anticyclonic gyre in the Great Australian Bight as well as the formation of the South Australian Current. For over 25 years it has been known that summer coastal upwelling occurs along the narrow continental shelf adjacent to the Bonney Coast between Cape Jaffa and Portland (Rochford 1977; Lewis 1981; Schahinger 1987; Griffin et al. 1997). Simultaneous upwelling also occurs along wider segments off western Victoria (Levings and Gill in press), south of Kangaroo Island, at the mouth of Spencer Gulf (Hahn 1986), and along the western coast of Eyre Peninsula (Kämpf et al. 2004; Middleton and Bye 2007) but does not usually shoal to the surface and is often masked in sea surface temperature images by the warm surface layer.

Strong winter westerlies and cooling lead to intense downwelling throughout to 200 mwd or more as well as the formation of dense coastal waters in the Great Australian Bight and the South Australian Sea. There is no upwelling during winter. Dense waters that have been evaporated during the summer and subsequently cooled exit the Great Australian Bight and Spencer Gulf as gravity currents to equilibrium depths of ~200 m. Winter cooling also leads to the formation of cold and dense waters (14–15°C, 36‰) in shallow waters of the Lacepede Shelf.

2.4 Synopsis

The southern part of Australia is a passive continental margin presently covered by cool-water carbonate sediments. The strongly seasonal climate varies from arid to humid. The ocean that covers the shelf lies north of the subtropical convergence zone and is a high-energy, swell dominated hydrodynamic regimen.

1. Southern Australia is composed of two major Precambrian cratons bounded on the east by the Tasman Fold Belt System, a series of Neoproterozoic to late Paleozoic continental margin and accreted terranes. The tectonic grain is predominantly north-south. This fragment of Gondwana is truncated by the Southern Australian Rift System, an east-west, Mesozoic–Cenozoic structure involving rift and drift coincident with separation of Australia from Antarctica. Marginal rift basins and subsequent shelf deposits in this system comprise Jurassic to Cretaceous siliciclastic sedimentary rocks overlain by Cenozoic limestones. The entire region underwent tectonic inversion and uplift in the middle Miocene resulting in reduced shelf accommodation and exposure of the Paleogene and early Neogene limestones in a series of shallow epicontinental basins.
2. A strong, mid-latitude, high-pressure cell dominates weather in Australia today. The high lies over the southern Australian coastline during summer resulting in an overall semi-arid climate. It shifts northward during winter, allowing a succession of low-pressure systems with accompanying rains and strong westerlies to dominate weather across the region. This pattern results in an overall climate that is arid to semi-arid across the Great Australian Bight and South Australian Sea but becomes progressively more humid southward in Victoria and around Tasmania.
3. Waters on the continental shelf are largely sub-tropical and separated from cold Antarctic waters by the Subtropical Convergence Zone. There is unimpeded zonal water circulation from the west (West Wind Drift). The sea state is swell–dominated with high wave heights and long period swells. Storm wave base is estimated to lie on average at ~60 m water depth (mwd) whereas swell wave base extends to ~140 mwd.
4. The ocean south of Australia comprises five stacked water masses:
   - *Antarctic Bottom Water:* very cold, high salinity waters with high dissolved oxygen and high nutrient levels—it has little affect on the Australian shelf or slope.
   - *Circumpolar Deep Water:* 4500–1250 mwd, cold, moderate salinity waters with low dissolved oxygen but very high nutrient levels—it has little effect on the Australian shelf or slope.
   - *Antarctic Intermediate water:* 1250–800 mwd, intermediate temperature, nutrient-rich water with high oxygen contents but low salinity levels that are recognizable as a salinity minimum throughout the Southern Ocean.
   - *Subantarctic Mode Water:* 800–450 mwd, a homogeneous, intermediate temperature (8–10°C), low oxygen, intermediate salinity water mass with moderate nutrient levels adjacent to the southern Australian continental margin.
   - *Subtropical Surface Water:* <450 mwd, a relatively warm (10–22°C) water mass with intermediate oxygen content and low nutrient levels that is complex and locally saline because of intense seasonal evaporation.
5. Current systems are strongly affected by climatic seasonality. The autumn change from an easterly to westerly wind pattern results in a change of Eckman transport and a switch in coastal currents. The regimen is over all downwelling with local cool summer upwelling. Nearsurface environments are affected by two currents systems:
   - The *Flinders Current System* is an upwelling-favourable northern boundary current that extends from the surface to ~800 mwd and flows from south of Tasmania westward and northward, generally outboard of the shelf edge to Cape Leeuwin. It is composed of Antarctic Intermediate Water and Subantarctic Mode Water that is cool, well oxygenated, and with moderate nutrient levels.
   - The *Leeuwin Current System* is a seasonal phenomenon that flows eastward along the

entire length of the continental shelf edge. It is composed of relatively warm, nutrient-depleted subtropical surface waters, and generally prevents upwelling. The system comprises Leeuwin Current waters in the west, South Australian Current waters in the center, and Zeehan Current waters in the east.

6. Upwelling of waters from the Flinders Current occur in summer but are localized to the Bonney Shelf, off Kangaroo Island, near the mouth of Spencer Gulf, and along the eastern coast of Eyre Peninsula. There is no upwelling during winter because of the strong westerlies.
7. Spencer Gulf and Gulf St. Vincent are inverse estuaries in which strong summer heating and evaporation form saline waters at the head of each gulf. These waters cool in winter and flow oceanward as dense saline bottom currents.

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