Chapter 2

Tectonic Setting of Australia

The Australian continent comprises a number of different tectonic blocks: Archaean and Proterozoic blocks in the western and central parts and relatively younger units (Phanerozoic) in the east. The Archaean Cratons are some of the Earth's oldest regions and carry information from the very early geological history of the Earth when the supercontinents were present and the tectonic processes possibly different from today (Betts et al., 2002). The separation of Australia and Antarctica, once part of the supercontinent Gondwana, began around 160 Ma ago along the southern margin of the Australian continent. The process led to crustal thinning at the margin and the separation was complete by around 95 Ma ± 5 Ma.

Another important feature of the continent is the geological boundary, between the Precambrian units in central Australia and Phanerozoic units in the east. This boundary is referred to as the Tasman Line. Since there is limited outcrop much of the transition has to be inferred from indirect evidence such as gravity and magnetic lineations. The Tasman Line concept is still a major source of debate regarding its age, current position and past position in Gondwana reconstructions (Direen & Crawford, 2003; Kennett et al., 2004).

A geological summary map of the Australia is given at figure 2.1 which emphasizes the major blocks, with their age and inferred boundaries under sedimentary cover (heavy dashed lines).

2.1 Archaean Cratons

2.1.1 West Australia

The Pilbara and Yilgarn Cratons located in the west cover the majority of West Australia.

The Pilbara Craton, which is one of the oldest blocks in Australia, preserves tectonic evolution features formed between *ca* 3.65 and 2.0 Ga (Betts et al., 2002). The crustal growth in the east Pilbara occurred between 3.65

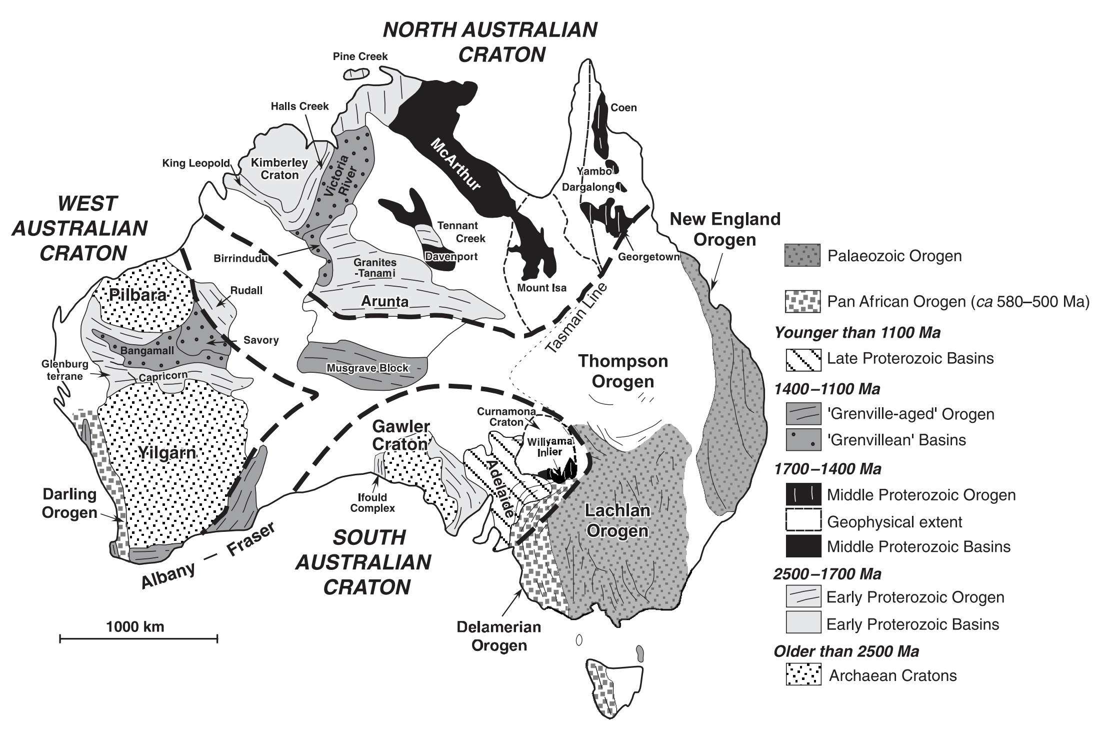

Figure 2.1: Terrane map of the Australian Continent emphasizing the major blocks (Betts et al., 2002).

and 3.15 Ga and shows dome structures in a granite-greenstone lithology. This may indicate a different style of continental crust formation at this time than at present. However, the evolution of the western parts is comparable to present day tectonic processes. For the creation of the large domes in the eastern and the central parts of the Pilbara Craton, different models are proposed for the class processes in the Archaean era. For example, the convective overturn model is used to explain 100 km-scale granitoid domes (Collins et al. (1998) and Collins & Van Kranendonk (1999)). Additionally, Zegers et al. (1996) observed large shear zones which evolved in an extensional environment (Betts et al., 2002).

The Hamersley Basin, which comprises the most of the southern Pilbara Craton developed during the Late Archaean and Palaeoproterozoic and mainly contains banded iron formations deposited between 2.6 and 2.45 Ga (Betts et al., 2002) which are of major economic significance.

The Yilgarn Craton is the largest known remnant of Archaean continental crust in Australia (Myers, 1997); it is important economically because of its vast deposits of gold and other minerals. The composition of the Yilgarn Craton is primarily low metamorphic grade granite-greenstone rocks which were formed between *ca* 3.73 and 2.55 Ga (Betts et al., 2002). The Narryer Terrane which is located in the northwestern part of the craton forms the oldest part of the Yilgarn Craton (3.73 Ga) where the layered megacrystic anorthosites and associated amphibolites were intruded by sheets of 3.6 Ga granites (Betts et al., 2002; Myers, 1997). The Murchison, Southern Cross and southwest Yilgarn terranes exhibit metavolcanic rocks (3 Ga) intruded by sheets of granite at 2.9 Ga including residues of older continental crust. The Eastern Goldfields, which is another component of the Yilgarn Craton, is younger than the other parts of the craton, here the granite-greenstone is formed from volcanic rocks and granites aged between 2.7 Ga and 2.6 Ga (Myers, 1997). Similar to the evolution of the Pilbara Craton, convective overturn and modern plate tectonic style processes are debated for the early evolution of the Yilgarn Craton.

2.1.2 South Australia

A further significant region of Archaean crust within Australia is the Gawler Craton of South Australia. The correlation of South Australia and East Antarctica prior to break-up Gondwana, using geochemical evidence, suggests that the Gawler Craton was once part of the early Mesoproterozoic Mawson Craton that formed most of the East Antarctic Shield (Fitzsimons, 2002). It now forms the central part of the South Australian Craton with gneiss exposures along the southern and northwestern margins and an age of 2.7 Ga (Daly et al., 1998). Ages of inherited zircons suggest that the craton was derived from crustal rocks as old as 3.15 Ga. Deformation and metamorphosis occurred during the Sleafordian Orogeny which began *ca* 2.55 Ga and was accompanied by granite intrusive events (Fanning, 1997). Electromagnetic constraints (Thiel et al., 2005) suggest that the southern Gawler Craton was subject to compressional and extensional events that led to the development of a half-graben and extensive shear zone.

2.2 Proterozoic Provinces

2.2.1 West Australia

The Pilbara and Yilgarn Cratons were joined during the Early Proterozoic by the Capricorn Orogen. This shows a complex tectonic history with multiple phases of deformation, metamorphism and granite formation (Occhipinti, 2004; Reddy & Occhipinti, 2004). The development of the Capricorn Orogen is inferred to be the collision of the northern and the southern blocks of the craton where the Pilbara and Yilgarn Cratons are situated (Occhipinti, 2004). In addition to this, after completion of this phase, the orogen remained an intracratonic site of lithospheric weakness (Cawood & Tyler, 2004). The age of the the Capricorn Orogeny is constrained as 1830-1780 Ma (Occhipinti, 2004). However, the formation of the region was a sequence of different processes. Major deformations happened in Opthalmian Orogeny (2.2 Ga), Glenburgh Orogeny (2.0 Ga), Capricorn Orogeny (1.8 Ga) and an unnamed event (1.6 Ga) (Cawood & Tyler, 2004; Occhipinti, 2004). The Capricorn Orogen contains highly plutonic igneous rocks and graded metamorphic rocks in the Gascoyne Complex. The other regions are mostly volcano-sedimentary, sedimentary basins (Cawood & Tyler, 2004). The Bangamall basin, located within the Capricorn region, formed in the Middle-Late Proterozoic.

The Albany-Fraser Orogen runs between the West Australian and South Australian Cratons towards Central Australia and is summarized in the section on Central Australia.

2.2.2 North Australia

The Northern part of Australia is made up of several blocks which together form a Proterozoic craton: the Kimberley Craton in the west, the Arunta Block in the south, the McArthur Basin in the north and the Mt. Isa Block in the east. The Kimberley Craton is not well exposed but may have included Archaean components (Graham et al., 1999) during formation or major reworking during the early Palaeoproterozoic. The Kimberley region amalgamated with the rest of the North Australian Craton during the Halls Creek Orogeny (1.82 Ga, Betts et al. (2002)). Archaean basement is exposed within the Pine Creek inlier, located to the northeast of the Kimberley Craton (Needham et al., 1998). The Arunta Block is Proterozoic in age. Exposure is again relatively poor, but the oldest known rocks in the region are 1880 Ma. It is likely to have formed as an orogenic province and contains the remnants of an accretionary margin that existed on the southern margin of the North Australian Craton at this time. The McArthur Basin is a later, Middle Proterozoic, rift basin which is host to economically important diamond deposits Betts et al. (2002). The Mt. Isa Block in the east is a relatively well-studied region and an important source of information on Proterozoic tectonic processes (Betts et al., 2006). Its evolution spanned 400 million years, beginning *ca* 1900, including two major tectonic events, intracontinental basin evolution and magmatism.

2.2.3 South Australia

The South Australian Craton is also made up of several blocks which amalgamated during the Proterozoic: the Gawler Craton in the centre, the Adelaide successions in the east, the Curnamona Province in the north east and the Coompana Block in the west (Parker, 1993). The Curnamona Craton is not well exposed but has been delineated by aeromagnetic data. The limited exposed basement is a late Palaeoproterozoic metasedimentary and metavolcanic succession (Robertson et al., 1998) and may be linked to the eastern Mt. Isa block suggesting a common history in the Palaeo-Mesoproterozoic (Giles et al., 2004). The Adelaide successions consist of Late Proterozoic and earliest Palaeozoic sediments, but evidence from inliers suggests that they overlie older basement (Belperio et al., 1998). They lie within the Adelaide Geosyncline rift basin (Myers et al., 1996) and deposition continued until folding and metamorphism occurred associated with the Palaeozoic Delamarian Orogeny (Belperio et al., 1998). The Coompana Block, to the west of the Gawler Craton, is buried beneath recent sediments and best observed at the southeast of continent along the eastern edge of Eyre Peninsula It is likely to be an old continental fragment which collided with the Gawler Craton *ca* 1650 Ma (Fitzsimons, 2002).

2.2.4 Central Australia

The major composite cratons of West, North and South Australia were themselves joined by extensive and long-lived processes of accretion and orogenesis. Around 1.8 Ga, the West and North Australian Cratons were linked by a wide mobile belt, including the Rudall Terrane adjacent to the northern Capricorn. The South Australian Craton joined the West and North Australian Cratons through further extensive accretion and orogenesis from *ca* 1.45 Ma. This included the formation of the Albany-Fraser mobile belt which ran through what is now East Antarctica and between the West and South Australian Cratons. The Musgrave Block, in central Australia, is 1.3 Ma in age and offers further exposure of this extensive orogen between the North and South Australian Cratons (Betts et al., 2002). The pre-assembly configurations of the West, North and South Australian Cratons are far from certain and may include links between the Curnamona and Mt. Isa Blocks (Giles et al., 2004). Towards the end of the Proterozoic, central Australia experienced episodes of extension and compression with the large central basin being broken into a number of other fault-bounded basins at 750 Ma (Myers et al., 1996). Deformation continued in central Australia during the Palaeozoic including metamorphism in the Arunta Inlier at 450 Ma (Hand et al., 1999) and the long-lasting Alice Springs Orogeny (400-300 Ma) which lifted deep rocks to the surface and then focused deformation on the Redbank Shear Zone producing a very large, long-lived gravity anomaly (Sandiford, 2002). The geodynamics of the Alice Springs Orogeny, which appears to have occurred without a significant collisional event at an appropriate plate boundary is also the subject of further investigation (Roberts & Housemann, 2001).

2.3 Palaeozoic Provinces

2.3.1 Tasman Line

The Tasman Line shown in figure 2.1 is a conceptual boundary between the older, Proterozoic and Archaean, continent in west and central Australia and the younger rocks of east Australia. Direen & Crawford (2003) review geological and geophysical potential field evidence suggesting that the lineaments associated with the Tasman Line result from a number of events of different ages and there is no simple line defining a single (albeit extended) tectonic event. However, there is evidence for a contrast in the deep crust from electrical conductivity surveys (Lilley et al., 2003). The contrast between older and younger crust is certainly very evident in the deeper mantle and is clearly shown in seismic data (Kennett et al., 2004).

The TASMAL project stations were distributed, as far as logistic constraints allowed, in order to improve the resolution of crust and upper mantle structure in the vicinity of this important boundary.

2.3.2 East Australia

The history of the lithosphere of eastern Australia is made up of a succession of orogenic events along the Pacific margin of Gondwana as summarised by Betts et al. (2002) and extensively reviewed by Glen (2005). Locations of the Palaeozoic orogens discussed below are shown in figure 2.1 with the oldest, the Delamarian, occuring in south Australia adjacent to the Adelaide successions. The extensive Lachlan Orogen occupies most of present-day southeast Australia and is the subject of much ongoing research and controversy. The Thomson Orogen underlies the inland regions of northeast Australia while the New England Orogen covers extensive regions of coastal east Australia.

The Delamarian Orogen (which corresponds to the Ross Orogen of the Pacific margin of East Antarctica) is of Cambrian age and formed by subduction-related accretion along this margin of Gondwana. The rocks have undergone multi-stage deformation through to the early Ordovician. The Delamarian is subdivided into west and east parts, the west being a fold-thrust belt that developed from inversion of the Adelaide Rift Complex and overlying shallow-water, Cambrian-age, sediments. The eastern part comprises deformed and metamorphosed sediments which are intruded by granites and developed from inversion of a deep-water Cambrian Trough (Glen, 2005).

The Lachlan Orogen is of Late Cambrian and Ordovician age. At this time, the continental margin of east Australia stretched some 20,000 km through East Antarctica to the Andes (Foster & Gray, 2000). Its formation and evolution are subject to ongoing debate, however, it clearly comprises thick accumulations of turbidite successions deposited in a back-arc setting to the east of the eroding Delamarian Orogen (Betts et al., 2002). Structurally, the Lachlan Orogen may be divided into three (Foster & Gray, 2000) or four (Glen, 2005) subprovinces which are separated by major faults or sutures. It is probable that all provinces formed at the same margin, but at different distances and positions relative to the margin, sediment sources and volcanic arc.

The Thompson Orogen is poorly exposed and age constraints are derived from drill hole data. They range from Precambrian to Late Devonian and include rocks with Delamarian-aged deformation in the north of the province. The concealed southern part of the Orogen is characterized by major aeromagnetic and gravity anomalies and are possibly associated with the accretion of an intra-oceanic arc. It remains questionable whether the Delamarian deformation extended up the continental margin or, alternatively, if parts of the Thomson are made up of rifted pieces of Delmarian Gondwana (Glen, 2005).

The New England Orogen is Late Devonian to Carboniferous in age and and is made up of a series of north-northwest trending belts, varied in formation from volcanic arc, fore-arc, back-arc and subduction assemblages (Betts et al., 2002). It is divided into two subprovinces, like the Delamarian, the western part is a fold-thrust belt and the eastern part is a deformed and metamorphosed accretionary complex. This implies a classical convergent margin system. Subsequent history shows Permian rifting and further subduction into the Triassic.

The lithosphere that underlies east Australia may be older than the surface orogenic rocks. Handler & Bennett (2001) use isotopic data from mantle xenoliths to infer the age of the lithospheric mantle in southeast Australia. They suggest that Proterozoic lithosphere extends further east than the surface Tasman Line with a lithospheric boundary corresponding to the boundary between the Delamarian and the Lachlan Orogens. The deep crust beneath the Lachlan Orogen may be oceanic or continental in nature (Glen, 2005) and many such fundamental questions remain concerning the Orogens of eastern Australia.

Present day Australia is characterized by a belt of elevated land that runs the length of the eastern margin of the continent. The mechanism for, and timing of, the uplift of the Eastern Highlands is investigated by Lambeck & Stephenson (1986) who suggested that the present elevation was not due to recent crustal motion but was the remnant of a higher Palaeozoic mountain belt. Lister & Etheridge (1989) suggested that initial uplift in the mid-Cretaceous could have been caused by the removal of lithosphere and consequent igneous underplating caused by the rifting of the Tasman Sea. Most of the present day drainage and denudation history can be explained without invoking mid-Cretaceous uplift (van der Beek et al., 1999) with the exception of the regions of present highest elevation (southeast Australia). The presence of Mesozoic marine sediments in the highlands of northeast Australia implies that uplift may have taken place after the mid-Cretaceous in this area (Wellman, 1987).

2.4 Previous Seismic Studies

Early seismic investigations of the structure of the Australian continent used either explosion data (Cleary, 1967) or earthquake data from short-period instruments (e.g., Thomas (1969)). These early studies provided some of the earliest evidence for the strong contrast in structure beneath Proterozoic west and central Australia and the younger provinces of east Australia. The deployment of portable short period seismometers allowed more detailed body wave studies to be undertaken focused on regions within Australia (e.g., a study in the north of Australia by Hales et al. (1980)).

With the advent of broadband seismic recording, and the availability of quality, high-fidelity portable seismic instruments, a great diversity of seismic techniques could be applied to the increasing volume of broadband data. From 1992, an ongoing series of seismic field deployments began starting with the SKIPPY campaign (van der Hilst et al., 1994). The results of many studies using data from these campaigns have been summarised by Kennett (2003). The account given below focuses on previous receiver-based and other complementary methods of determining crustal structure, and on recent surface wave studies that may be usefully compared with the work described in this thesis.

The first comprehensive receiver function study of the Australian continent was carried out by Clitheroe et al. (2000) who modelled receiver structure beneath stations of the SKIPPY project and plotted variations in crustal depth beneath Australia. This work also included a characterization of the Moho discontinuity as either thin, broad or intermediate. Collins et al. (2003) summarised crustal depth measurements, including those derived from active source experiments, across Australia. In general, both classes of study find a thin (or sharp) Moho discontinuity beneath the oldest Archaean regions and thicker crust and a less distinct, or broader, Moho beneath younger regions such as southeast Australia. More detailed studies in the west (Reading & Kennett, 2003; Reading et al., 2003a) have enabled S wave velocity structure variations within the Archaean cratons of Western Australia to be examined at the scale of the major terrane groups. In the most recent work (Reading et al., 2007) this has led to insights into the formation of ancient lithosphere.

There have been numerous studies of mantle structure beneath Australia including one of the first studies making use of the extended SKIPPY dataset (Simons et al., 1999). In that work, a partitioned waveform inversion method was used and compared to a regionalised geological model. This work revealed that the edge of the Proterozoic shield does not have a simple relationship with the surface expression of the Tasman Line. Further work continued to improve upon the resolution and methods employed in previous studies and is summarised by Kennett (2003). Debayle & Kennett (2003) include a consideration of anisotropy on the surface wave observations.

Recent studies have included a larger dataset and a three stage approach to inversion that takes account of off-great circle wave propagation and allow clearer definition of regions containing high velocity gradients (Yoshizawa & Kennett, 2004). New techniques (Fishwick et al., 2005) have also improved the reliability of images derived from surface wave tomography using multiple starting models and a damping scheme with a multi-scale component where the final model is damped to large scale features of the data rather than a global reference model. This last study also incorporates recent data from Tasmania and New Zealand, improving image resolution in eastern Australia and the Tasman Sea.

The work described in this thesis improves the quality and coverage of receiver-based structure determination in eastern Australia and is the first major study to be undertaken on the Australian continent using noise-correlation techniques.