CHAPTER 1

An Australian perspective

Australia – a continent of great age, stability, aridity and flatness.

Radiometric dating is one of the keys to reading the story in the stones.

How has deep sea and space exploration changed our perspective on the Earth and Australia?

AUSTRALIA: AGE, STABILITY, CLIMATE, MAIN FEATURES

Some call Australia the world's largest island, others the smallest continent. I want to describe Australia as a continent, one of the primary building blocks of planet Earth, and one which spans almost the entire record of Earth history.

Traditional stories of the Aboriginal people tell of the creation of this continent, and of many of its landscape features. These stories are a parallel to this book because they emphasise the close spiritual relationship between all of us and the land that supports us.

This book tells how the rocks formed, and how the present climate developed over millions of years. As the Reverend J. Milne Curran wrote in one of the earliest explanations of Australian geology, in 1898:

Australia has a history far more ancient than any written by men – to read this history is one of the objects of geology – records preserved in the great stone-book of nature.

There is evidence that the Chinese knew of a land in the south from perhaps as early as the Sui dynasty (589–618 AD) and that Chinese ships had mapped part of Australia in 1422, even landing to search for metalliferous ores.

The first documented European discovery of this continent was by the Dutch commander Willem Jansz, who sighted the 'Great South Land' in 1606. He had sailed the *Duyfken* around the southern coast of New Guinea early in 1606, and veered southward to 13 degrees 45 minutes (13° 45′) latitude. Here a party landed, on the eastern side of the Gulf of Carpentaria, before heading back to Java. He named the point *Cabo Keerweer* (Cape Keerweer), which means: 'Cape Turnabout' in Dutch. It lies at the mouth of the Kirke River, about 70 km south of Aurukun. Thus a small, remote sandspit on a flat coastline was the first part of this continent to be given a European name.

Later that year the Spanish captain Luis Vaez de Torres sailed from the New Hebrides (Vanuatu) through the gap south of New Guinea, now called Torres Strait, on his way to the Philippines. Torres did not realise what lay to the south of his vessel. Some 40 years later, Abel Tasman mapped most of Australia's southern, western and northern coastlines, as well as discovering New Zealand and Tasmania, in his voyages of 1642–1643 and 1644. Finally, 125 years later when James Cook charted the eastern coast in 1770, the extent of Australia became known to Europeans. Later the French explored much of the western coast in greater detail.

The early Dutch explorers named this continent 'New Holland', but they decided there was not much of value in spices or precious metals to warrant further exploration. When Cook left on his journey, authorised by the British Admiralty to search further for a southern land, he referred to it as New Holland. It was Matthew Flinders, the man who first circumnavigated and mapped the coastline, who gave real impetus to the present name of Australia, based on the Latin term for 'southern land', *terra australis*. He published an account of his discoveries in the great work *A Voyage to Terra Australis*, a printed copy of which was placed in his unconscious hands on 18 July 1814, the day before he died.

Geological investigation of Australia really began in the mid 1800s. So we have about 150 years of information to draw upon. Perhaps the earliest geological map of Australia was the one published about 1850, prepared by J. Beete Jukes, who had been the naturalist on the survey vessel HMS *Fly*. This map of the whole continent shows old rocks around the edge, and the centre completely blank.

For many people in those days Australia was so different to Europe that extraordinary theories were proposed to explain the differences. The Reverend W. B. Clarke, in an address to the Philosophical Society of New South Wales on 20 November 1861, took time to refute the following notions:

It was once maintained by a philosopher of some eminence that New Holland, being so singular and anomalous a region, must have

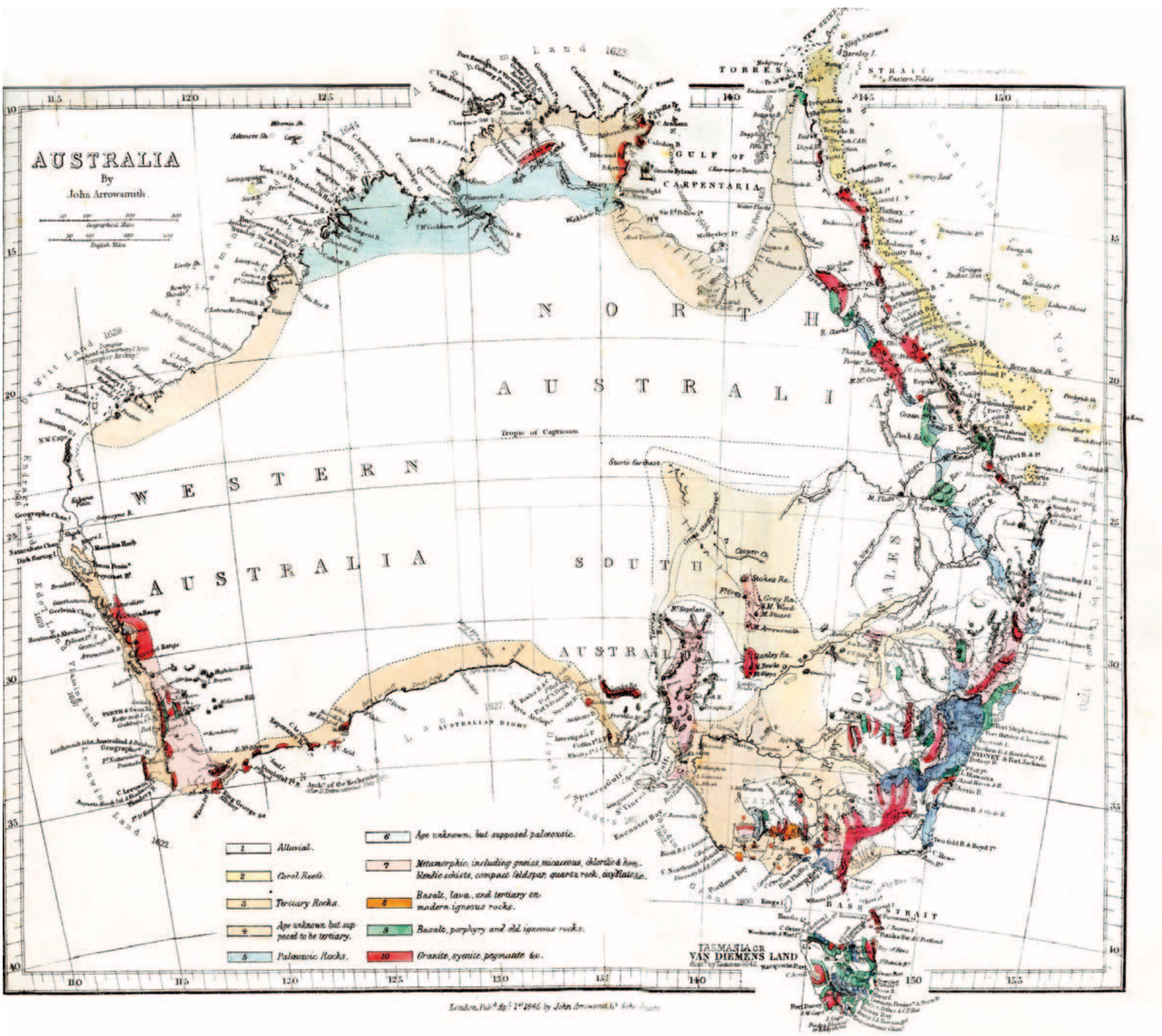

Figure 1.1 Early map of the geology of Australia by J. Beete Jukes, drawn in 1846 and published about 1850, showing the geology mapped along the coast but a dearth of information on the inland. Note the track of data in northeastern Australia based on reports by Ludwig Leichhardt of his journey in 1844–1845. Tasmania is labelled as Van Diemen's Land. There is detail on the Great Barrier Reef, since this was also investigated by Jukes during his time in Australia.
Source: David Johnson

> *originated in a corner of the sun knocked off by a comet, and that, tumbling into the Pacific Ocean, it soon became the suitable abode of those bizarre marsupials … which are only an imperfect development of life upon the more recently raised lands, such as Galapagos and Australia.*

All these early explorers, and the naturalists who sailed with them, had noted the strange animals and plants. Australia did not fall out of the Sun, but it is still a very individual place with unusual animals and plants inhabiting an extraordinarily diverse landscape.

Age

To early theorists, Australia was not only very young but also populated by totally different life to that known from the natural worlds of Europe, America and Africa. They thought they had discovered a completely new existence, something which must have formed *after* their established order. However this theoretical stance was not supported by the rocks. In the 1800s many geologists spent time confirming that there were fossils and rocks in Australia that were demonstrably of the same age as those in Europe. Prominent early geologists in New South Wales were the Reverend W. B. Clarke, the Reverend J. Tenison-Woods, the Reverend J. Milne Curran and C. S. Wilkinson, in Queensland Robert Logan Jack, in Victoria Alfred Selwyn, and in Western Australia Dr W. G. Woolnough.

We know now that Australia is very old. Continental crust in Western Australia has been dated at older than 3500 million years, and metamorphosed sedimentary rocks in the Yilgarn region contain zircons that are even older, dated at 4404 million years. This implies that a crust of rocks was formed before 4400 million years ago and then eroded, with the zircons subsequently deposited in sediments. It is the oldest material known on Earth, and is only about 200 million years younger than our present estimates for the age of the planet. The youngest materials are still forming in the river systems, beaches and reefs around our coastline.

It is also clear that much of the fossil life has links to the other continents. In particular, the similarity of rocks around 250–300 million years old in such distant places as India, Africa and South America suggested these continents were once joined with Australia, and this observation led to the theory of continental drift. Scientists in the late 1800s and early 1900s proposed that a huge continent, which they called Gondwana, broke up, and that the fragments then drifted apart. But at that time there was no known mechanism to effect such massive changes, and the theory was not strongly supported.

In the 1960s new evidence showed how the break-up might have happened, and the theory of plate tectonics was developed. We now know Gondwana was not the only supercontinent: there was an earlier one, which we call Rodinia. The rocks in Australia have an extraordinary story to tell, starting before the formation of any other rocks still preserved on the planet.

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BOX 1.1 RADIOMETRIC DATING OF ROCKS

In the 1800s geologists could only interpret the *relative* ages of rocks. Guesses of the actual ages were made, but there was no way to do absolute dating. It was the discovery of radioactive decay in 1896 by the French physicist Henri Becquerel, and later work by the Curies, which provided the means. The key fact is that radioactive elements decay to daughter products in a special way. The daughter products can also be radioactive and lead to another decay cycle, though most commonly they are stable and not radioactive. For each radioactive pair (parent and daughter) there is a period of time – the half-life – after which exactly half the original number of radioactive parent atoms remain, half having been transformed into daughter atoms.

For instance, radioactive uranium atoms decay to stable lead atoms. In 1907 Boltwood had found that the ratio of the decay product (lead) to the parent radioactive uranium increased with geological age. This discovery confirmed the potential of radiometric dating to provide accurate measurements of the absolute age of rocks.

The radioactive decay process is random, and it is not possible to predict when an individual atom will disintegrate. However, given a large number of atoms, it is possible to predict when half will have decayed. It is like watching a heated pan of popcorn. You cannot tell which kernel will pop next, but you can predict how long it will take to finish the batch.

For the decay of uranium-235 (U-235) to lead-207 (Pb-207) the half-life is 704 million years. That is, over 704 million years, or one half-life:

1000 atoms of U-235 $\rightarrow$ 500 atoms of U-235 + 500 atoms of Pb-207

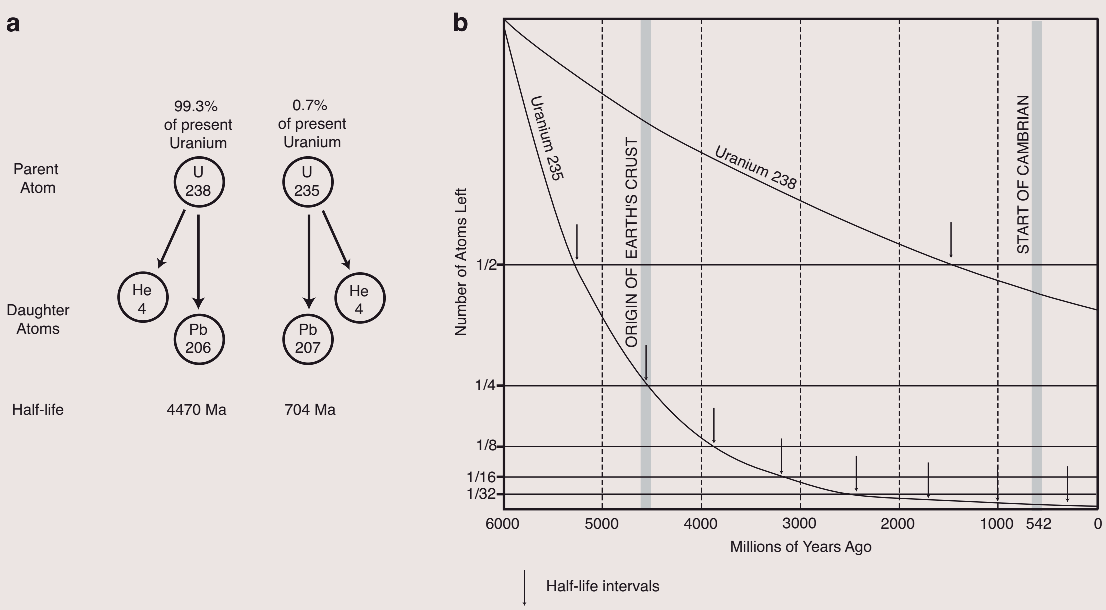

Figure 1.2 Radioactive decay of uranium-238 and uranium-235. a. Parent and daughter atoms and half-lives. b. Decay curves over 6000 million years, showing the more rapid decay of U-235, which has a shorter half-life (704 million years) than that of U-238 (4470 million years). Note that when the Earth formed there would have been about twice as much U-238 and 32 times as much U-235 as at present. The diagram also emphasises the enormous time span of the Precambrian era, which spans most of the history of the planet.

Source: Arthur Holmes

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After a further half-life, or a total of 1408 million years, the remaining 500 atoms of U-235 → 250 U-235 + 250 Pb-207 which, with the 500 Pb-207 already formed, will mean there would be 250 U-235 plus 750 Pb-207. Note that this implies that the Earth was far more radioactive earlier than it is now.

We can determine very accurately both the amounts and the decay rates of radioactive elements, so we can then calculate the age of the specimen. Samples for dating are selected very carefully to avoid rocks that are altered, contaminated, or disturbed by later heating or chemical changes. Multiple samples are taken to provide cross-checking.

Different radioactive isotopes are used for different age ranges, depending on the half-life of the decay process. The following pairs have the stated half-lives:

rubidium-87 to strontium-87	48800 million years
uranium-238 to lead-206	4470 million years
potassium-40 to argon-40	1250 million years
uranium-235 to lead-207	704 million years

A common method for measuring the amounts of each isotope is thermal ionisation mass spectrometry (TIMS). The isotopes are extracted from the rocks and vaporised over a hot filament, and the gas is then analysed in a mass spectrometer. Laser ablation of grains under a microscope evaporates a minute sample, and the gas can be analysed by Inductively Coupled Plasma Spectrometry (ICP).

Another technique involves using a high-power electron microscope – the superprobe – to analyse minute amounts of radioactive materials in mineral grains such as monazite.

These elements are useful for dating rocks up to hundreds of millions of years old. But what about younger materials? In 1951 Walter Libby discovered that minute amounts of a radioactive isotope of carbon – carbon-14 (C-14) – exist in air, natural waters, plants and organisms. Radioactive C-14 is produced continually by cosmic ray bombardment of nitrogen atoms in the atmosphere. The C-14 decays to nitrogen-14, with a half-life of 5568 years. Radiocarbon dates are normally reported as 'before present' (BP), with reference to the year 1950. So if carbon from prehistoric wood is found to have only half the amount of C-14 present when compared to 1950 wood, the estimated age for the prehistoric wood is 5568 years. The age would normally be expressed as 5570 ± 150 years.

The natural production of C-14 has not been constant over time. Ages must therefore be calibrated, for instance by reference to C-14 dating of trees whose true ages have been measured by counting the tree rings.

SHRIMP

Australian geologists have made a speciality of dating ancient rocks, and some of the technology was developed at the Australian National University (ANU). The sensitive high-resolution ion microprobe (SHRIMP) uses oxygen ions, positively charged particles, for very detailed uranium–lead age dating of individual grains, typically zircon, within a rock. The very fine microbeam can also probe and date individual growth zones within a single grain.

Previous radiometric dating was limited to analyses of whole rocks or of groups of grains extracted from the rock, and almost always for igneous rocks. The SHRIMP capability enables absolute dating of individual grains.

The SHRIMP date records the age of the magmatism (or rarely, metamorphism in high-grade rocks) which formed the zircons, and hence the age of the original rock. If the rocks are uplifted and eroded the zircons retain their age signature, even when recycled from igneous or metamorphic rocks into sedimentary rocks, and weathered again into loose sand. Thus even the age of grains in modern beach sands can be determined.

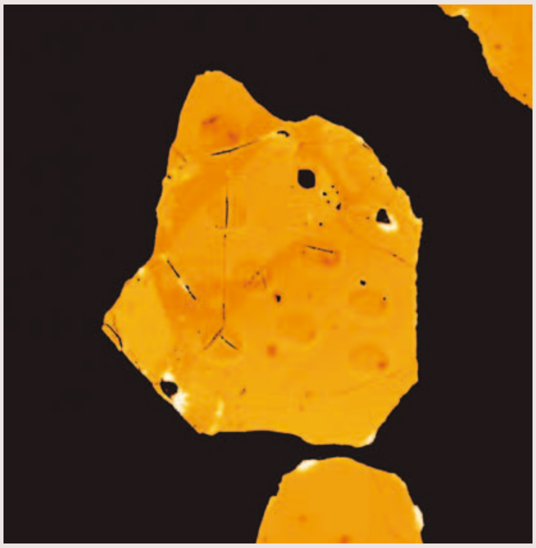

Figure 1.3 Electron microscope image, taken in back-scatter mode, of microcraters formed in a cut and polished zircon grain during SHRIMP analysis. The grain is 150 μm (micrometres) wide and the microcraters are the eight, slightly darker, rounded blotches in the grain. This is the oldest grain dated on Earth – 4404 million years old.

Source: John Valley and Simon Wilde

Stability

Australia is tectonically stable and has no active mountain building or major fault systems. We have no mountains as young as those in New Zealand or the Himalaya, nor faults like the San Andreas Fault in California. We have no active chains of volcanoes like those in New Zealand, Japan or Indonesia. Active tectonism, involving earthquakes and volcanism, occurs mainly at the boundaries of the large plates that make up the outer part of the Earth. Australia is situated well within a very large plate. Over the last 50 million years there has been minor downward tilting (c.300 m) of Australia to the north due to subduction under Indonesia and New Guinea, and also minor buckling on the order of 100 m, due to fault movements and lateral stress from the plate boundaries.

Most earthquakes occur in the outer crust of the Earth, where rocks are cold enough to be brittle. At greater depths, where the temperature is high enough for the rocks to deform by plastic flow, there is rarely sudden fracturing to trigger an earthquake. In eastern Australia earthquakes occur at depths of up to about 20 km. In very active seismic zones, like Indonesia or Fiji, earthquakes occur from close to the surface to depths of 700 km. Shallow earthquakes can cause much damage, but deep earthquakes rarely do.

Australia is just one landmass sticking above the waves, riding on a much larger plate on the surface of the Earth. This plate is the Indo-Australian plate, which contains parts of New Zealand and Fiji in the east, and India in the northwest. We are all travelling northeastwards towards Asia at about 70 mm/yr.

To put this in perspective, consider that in 220 years of European settlement the Australian landmass has moved about 15 m closer to Asia. It is hard to notice this when there is no permanent marker by which to

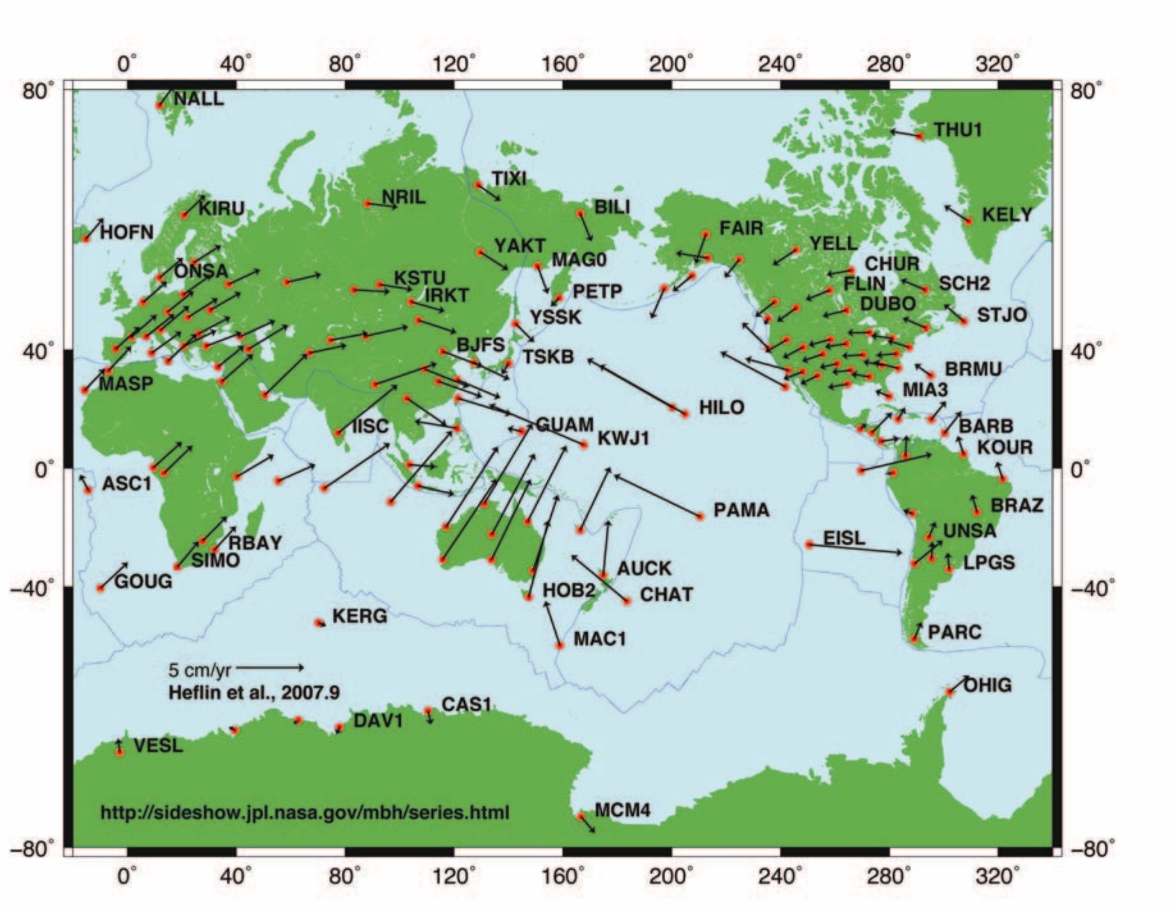

Figure 1.4 The Earth's surface consists of interlocking plates, shown as blue lines on this diagram. Most plates comprise both continents and ocean floors. Australia sits on the Indo-Australian plate, and to the east is the Pacific plate. The original concept of continental drift emphasised continents because that was where the rocks were mapped and the connections drawn. However, we now use the term 'plate tectonics' because it is the plates that are moving, and the continents are being carried upon them.

The Indo-Australian plate carries two continental masses (Australia and India) and three smaller masses (Papua New Guinea and the north island and the western side of the south island of New Zealand). To the south of Australia the ocean floor is spreading as the Indo-Australian plate moves away from Antarctica. To the north, the plate is converging with Asia.

The red spots indicate survey locations that are being tracked by GPS. The arrows indicate the direction of movement averaged over 5 years, and the length of the arrow indicates the speed of movement. Note that the 8 survey stations in Australia are all moving at the same speed in the same direction, on average 67 mm/yr in the direction 35° east of north.

Antarctica is hardly moving. Africa, Europe and Asia are together moving eastwards in a broad curve, and the Americas are moving in a broad curve westwards. The plates are converging towards the north Pacific region.

Source: Michael Heflin, JPL, NASA

judge the movement. However, imagine if this movement was occurring in the street outside your front door, so that one side of the street was stable and the other was moving sideways at 70 mm/yr. A house built directly across the street by members of the First Fleet would now be down the road, and the block next to it would be opposite you. In 50 000 years – a minimal estimate for the time Aboriginal people have been here – the same block of land would have moved 3.5 km.

Despite the stability of the plate there are small earthquakes within Australia (intra-plate tectonism). The reasons for these earthquakes are not obvious in comparison to those along major plate boundaries. Some earthquakes are caused by new movements on old faults, and some may be caused by heating effects in the deep sedimentary basins.

Analyses within drillholes and mines do show that most of the continent is being gently compressed towards a northeast–southwest axis, which lies parallel to the plate movement. Some compression is to be expected because the plate is starting to be forced against the edge of the Eurasian and Pacific plates to the north. The southeastern corner shows more east–west compression, perhaps reflecting the nearby boundary at New Zealand, which is transmitting some pressure inwards towards Australia. More details on plate tectonics are given in Chapter 2.

Low-intensity earthquakes occur in Australia almost daily. Early European settlers noted slight earthquake shocks; the first was felt by Governor Phillip on 22 June 1788. However, most tremors are never felt by people even though they are detected by sensitive instruments. Fortunately Australia is sparsely populated so that most significant earthquakes cause little damage.

The most common method of describing the size of an earthquake is the Richter magnitude scale. The ground displacement is measured with a seismograph, and a correction for the distance from the earthquake epicentre to the seismograph is applied. Each unit increase in magnitude represents a tenfold increase in ground displacement and about a thirtyfold increase in the seismic energy released.

Another measure of earthquake size is the moment magnitude, which is derived from mathematical modelling of the surface wave generated by the earthquake. Moment magnitudes are better measures of the energy released, especially for earthquakes above Richter magnitude 7. The 1960 Chile earthquake, which measured 8.5 on the Richter scale, had a moment magnitude of 9.5.

A significant earthquake is followed by smaller events, called aftershocks, and is sometimes preceded by foreshocks. Worldwide, for every magnitude 5 earthquake, 10 magnitude 4 earthquakes are expected, 100 magnitude 3, 1000 magnitude 2, and so on.

A magnitude 1.0 earthquake (commonly written as M1) releases a similar amount of seismic energy as a typical quarry blast. An M5 earthquake releases about the same seismic energy as the explosion of 10 000 tonnes of TNT – about the energy released by the atomic bomb dropped on Hiroshima. M9 earthquakes, such as those in Chile in 1960 or Alaska in 1964, are extremely damaging.

Australia has had large earthquakes, but they occur very infrequently; on average an earthquake exceeding M7 occurs somewhere in Australia every 100 years or so. Such an earthquake would affect only a small area. Any particular place in Australia would only expect to be within 50 km of an M7 earthquake about once every 100 000 years. Seismically active areas such as Japan, New Guinea, the Philippines and California experience M7 earthquakes every few years.

Significant earthquakes in Australia

There have been several major earthquakes recorded in Australia over the past 160 years. The largest was magnitude 7.1 at Meeberrie, west of Meekatharra in Western Australia, on 29 April 1941. Damage was limited because of the isolated location, but included cracked walls in farm houses and burst water tanks.

The largest earthquake measured in South Australia was the Beachport earthquake on 10 May 1897. At M6.5 it caused serious damage at Kingston, Robe and Beachport, and caused minor damage even in Adelaide. It was felt as far away as Port Augusta and Melbourne. It is thought that the epicentre was offshore.

In New South Wales the Newcastle earthquake on 28 December 1989 resulted in 13 deaths, over 120 injuries, and building damage exceeding A$1.5 billion (1990 values). Although only magnitude 5.6 its location in a major city meant there was serious damage to life and property.

The Tennant Creek series in the Northern Territory involved three tremors between magnitudes 6.3 and 6.7 on 22 January 1988. They were felt in Darwin, and the largest was felt as far away as Cairns in northern Queensland and in high-rise buildings in Perth and Adelaide. In Tennant Creek, walls were cracked in well-constructed buildings, objects fell from shelves, and furniture was shifted. There were no serious injuries, but the strong shaking from the main events and the prolonged aftershocks badly frightened many residents. The epicentres were in the desert about 40 km southwest of the town, so total damage was limited to about A$1.2 million (1990 values) – mainly damage to a high-pressure gas pipeline between Alice Springs and Darwin.

Some earthquakes produce small fault scarps where they displace the ground surface. The Tennant Creek earthquakes produced a surface rupture about 35 km long trending east–west, with the southern block thrust over the northern block by up to 1 m vertically and about 2 m horizontally. The Meckering earthquake in Western Australia on 14 October 1968 also produced a surface fault rupture, 32 km long and trending north–south. The land east of the fault was lifted vertically by up to 1.5 m, and moved westward by up to 2 m. Thus the eastern block was thrust over the western block, indicating strong compression of the crust.

Western Australia has experienced several earthquakes: Meckering (1968), Cadoux (1979) and the Burakin series, which started in July 2000 but had its most significant events on 28 September 2000 (M5.0), 5 March 2001 (M5.1), 23 March 2002 (M5.1) and 30 March 2002 (M5.2). The Meckering quake (M6.7) destroyed a bank, hotel, shire hall, three churches and 60 of about 75 houses, with total damage about A$29 million (1990 values). There were no fatalities and only