6. Earthquakes and Stress Field

Although a few seismological observatories were established in Australia early in the 20th century, the development of an extensive national seismological network came rather late. The current network was substantially enhanced by investment following the Sumatra–Andaman Mw 9.3 earthquake on 2004 December 26, and resultant destructive tsunami. A major goal in the improved network was early identification of tsunamigenic potential, particularly in the Indian Ocean and events in the subduction zones to the north and east of Australia.

Data from all the stations in the national network are transmitted to Geoscience Australia in Canberra, where continuous monitoring and analysis is undertaken for event location and character. The national facilities include three medium aperture arrays: WRA and ASAR in the Northern Territory, and PSAR in the Pilbara region of northwestern Australia. WRA and ASAR are primary seismological stations in the monitoring network established under the 1996 Comprehensive Nuclear-Test-Ban Treaty. The broadband array PSAR, was established as a major component of the tsunami warning system.

As a result of investment through the AuScope infrastructure program since 2012, a secondary national network has been established exploiting research-grade seismometer systems deployed in schools across the country. Data from this AuSIS network is made available to Geoscience Australia and the international community. Noise levels at these stations tend to be rather higher than in the vault instruments in the national network, but still provide useful additional geographic coverage and have often been used in improving the locations of recent events.

![Figure 6.1: Seismological stations in the Australian network and international networks hosted in Australia (shown in black). Stations in the Australian Seismometers in Schools network (AuSIS) have the prefix AU and are displayed in green.](image)
6.1 Earthquake Activity

With the latest improvements in the national seismological networks, all magnitude 3 events across the continent should be reliably located. However, the coverage is much patchier in the past. From 1920, events above magnitude 6 should be captured, and from 1959 events above magnitude 5. However, the threshold of completeness would have been higher than magnitude 4 well into the 1990s. As a result, the distribution of known events is skewed towards larger magnitude.

Earthquake activity in Australia is widespread (Figure 6.2), though the largest events onshore in the last century have not exceeded magnitude 7. The largest energy release was the group of three events (Mw 6.2, 6.5 and 6.7) in just 12 hours near Tennant Creek in the Northern Territory (20°S, 135°E) in January 1988. The largest of these events was felt from coast to coast as a consequence of the very low attenuation of seismic waves in the cratonic regions.

The pattern of seismicity across the continent indicates concentrations of events in fairly well-defined zones, with some regions having little obvious activity. However, absence of events does not necessarily imply that future earthquakes are not possible. Prior to 1987, the region around Tennant Creek had no known seismicity, but then activity started with two magnitude 5 events culminating in the group of Mw 6 events followed by a long sequence of aftershocks. The return period for intracontinental earthquakes can be very long, e.g. over 10,000 years from trenching evidence at Tennant Creek, and so the historical record needs to be supplemented with information from neotectonic studies.

Figure 6.2: Distribution of earthquakes across Australia from historical and instrumental catalogues. The size of the symbols is scaled with magnitude and colour coding indicates depth. The strong subduction zone activity to the north of Australia is largely suppressed to aid clarity.
Earthquakes in Australia are generally quite shallow. Even the largest events rarely appear to initiate deeper than 12 km and generally faulting propagates upward towards the surface. Depth control for older events is rather poor because of the sparse national network of the time.

**Geographic Distribution of Earthquakes**

The Phanerozoic domains of eastern Australia show a generally diffuse zone of seismicity with some concentration around the Sydney Basin and southern Victoria. Although seismicity in the instrumental period has generally been quite weak in Queensland, a number of larger events have occurred in recent years, with a Mw 5.8 event offshore from Gladstone in August 2016. In the late 19th century there were many events to the east of Flinders Island, north of Tasmania, but little recent activity.

A small cluster of events occurs in the southern Tasman Sea near 40°S, 155°E, which is close to the location where the projection of the Tasmanid seamount chain would occur, as a consequence of the northward movement of the Australian plate over a fixed hotspot.

A relatively tight band of seismicity occurs through the Adelaide Fold Belt and the Flinders Ranges, with many events at greater depth than is common elsewhere across the continent. This belt of earthquakes may well link to the Simpson Desert, where a number of larger events occurred in the 1940s.

Through central Australia, most events reflect a compressive regime associated with the ongoing collision of Australia with the Pacific Plate to the north. In recent years there have been a number of sizeable events aligned roughly east–west from the Musgrave towards Yulara. The detailed study of Bowman (1992) for the Tennant Creek events to the north indicates the complexity of faulting and differences between nearby faults. Such features are not readily captured in the summary centroid moment tensors that show an equivalent point source. Although most of the faulting at Tennant Creek was associated with south over north thrusting, a segment of the second fault to fail had the reverse behaviour. Surface faulting has also been found associated with the 1986 Marryat Creek event in northern South Australia and the 2016 Petermann Ranges event in the south of the Northern Territory.

A range of different styles of earthquake activity occurs in Western Australia. A concentrated zone of activity to the west of Perth has produced a number of events above magnitude 6 with distinct surface fault traces. This zone has a nearly north–south trend parallel near the eastern edge of the Yilgarn Craton. To the west, a zone of modest size events with a southwest to northeast orientation follows the edge of the Yilgarn Craton, linking into the Musgrave Province and the central Australian earthquake belt. A number of events have occurred in the fold belts surrounding the Kimberley Block in northwestern Australia, with a Mw 6.3 event near Derby WA in 1997. The trend of the King Leopold Belt towards the southeast leads into a distinct group of events that appears to be associated with continuing deformation at the northeastern margin of the Canning Basin. The western edge of this basin, where it meets the Pilbara Craton, is also marked by a modest number of events.

The western and northwestern margins of the Australian continent show a moderate amount of long-term activity. The events mostly lie close to the transition between thinned continental and oceanic crust. To the south the earthquakes lie much further offshore with ongoing activity along a belt close to 37°S.

The seismicity of the region is dominated by the earthquake activity associated with subduction along the Indonesian arc and in New Guinea. Strong and continuing activity occurs both in the subduction zone itself, and leading into the trench. Limited location accuracy for older events means that some of this activity on the seaward side of the subduction trench may be placed closer to Australia than their true locations.

### 6.2 Earthquake Source Mechanisms

For well-recorded seismic events, waveform information can be employed to help characterise the nature of the seismic source represented as a point in time and space. The simplest approach to source characterisation employs the polarity of arrivals linked to a double-couple model for the earthquake mechanism. This approach can work well with a good azimuthal distribution of stations covering a range of distances. More sophisticated methods match seismic waveforms for a postulated source to observed waveforms, and use a moment tensor representation for the source without any explosive or implosive component. Frequently, attention is concentrated on the large amplitude surface waves that are least affected by seismic noise. Such methods for source determination can be quite sensitive to the choice of Earth model, particularly at regional ranges (Young et al., 2012; Sippl et al., 2015), but have been successfully used with combinations of permanent and temporary stations for sources in Western Australia.
The Global Centroid Moment Tensor Project (www.globalcmt.org) undertakes source mechanism inversions for events larger than Mw 5.5, using the long-period surface wave records at stations across the globe. Only the largest Australian events are big enough to be included in this database. The frequency limits used (highest frequency 0.0125 Hz) mean that there is indeterminacy for some moment tensor components for very shallow events. The shallow depth limit in the inversions is therefore set at 15 km. In consequence, there can be some bias in the results for events that are actually shallower than 15 km. Nevertheless, the catalogue provides an invaluable record for events going back to 1977 with a common style of moment tensor evaluation.

Figure 6.3 shows the available moment tensor solutions from the global centroid moment tensor database, supplemented by recent results for events in the Kalgoorlie region of Western Australia from Sippl et al. (2015). The compressive domains for each event are shown in dark brown. In addition, the highest quality focal mechanisms for smaller events within the continent, mostly determined from polarity studies, are shown in lighter brown.

The various clusters of events across the continent show locally consistent source mechanisms, but we see a significant change in regime in different parts of the continent.

The source character of the smaller events is generally comparable to the moment tensor inversions for the larger events. Some early studies were based on aftershocks to avoid saturation of analogue signals. Such results have to be used with care, since aftershock sequences can show a wide variety of mechanisms, reflecting the rebalancing of the stress state around the location of the main shock.
6.3 Neotectonic Features

As previously noted, the long return period for intracontinental earthquakes means that the historic record needs to be supplemented with information from neotectonic features to provide a more complete picture of the state of the continent. During the last few decades, a number of earthquakes in Australia have been sufficiently large to rupture the Earth’s surface. The largest fault traces are little more than 30 km long, but relatively young features in the Australian landscape show much longer scarps. For example, the Cadell Scarp over 70 km long and 15 m high lies across the former path of the Murray River that has been deflected around the end of the feature. The field evidence suggests that 3–4 events of magnitude 7.2–7.3 would be needed to create the observed topography, with the last event at about 20 ka (Clark et al., 2011). No events of this magnitude have occurred since European settlement.

A major effort has been made by Geoscience Australia to assemble a database of neotectonic features across the continent (Figure 6.4) and a significant number are of definite association (Class A) or probable association (Class B) with seismic events.

Since the Miocene, the Australian continent appears to have tilted downwards to the northwest (Sandiford, 2007), as also seen in the deviation of the Australian Height Datum from the geoid (Figure 5.2). The geological evidence comes from systematic variations in the extent of Neogene marine inundation. Thus, on the southern Australian margin, Miocene limestones of the Nullarbor Plain have been uplifted and subjected to marine erosion to form impressive cliffs along the Great Australian Bight.

Figure 6.4: Neotectonic features across Australia. Class A have definite association with earthquake events. Class B are probable and Class C are possible (Clark et al., 2011). Faults longer than 60 km associated with Class A and B features are shown.
In the last few million years it appears that the lithosphere has buckled slightly, giving rise to undulations of the order of 100 m on wavelengths of a few hundred kilometres. This has changed the drainage patterns of a number of basins, such as those containing Lake Torrens and Lake Frome.

The most distinct neotectonic features in the landscape come from fault motions. Locally uplift rates can be large, as in the Flinders Ranges where up to 50 per cent of the current topography appears to have developed in the last 5 million years. One of the strongest lines of evidence for generation of neotectonic features by faults is that the majority have comparable geomorphological effects to those associated with the scarps generated in recent events that have broken the surface. Thus the neotectonic features rated in Classes A and B are accompanied by localised modifications of drainage including ponding, diversion or incision of channels or terrace formation.

Because the rates of erosion across Australia are generally low outside the wet tropics, it is possible for neotectonic features to be preserved for long periods of time. In eastern Australia and the Flinders Ranges, features may be recognisable for up to 50,000 years, but in central and western Australia where erosion rates are lower, features could survive for 100,000 years or more. For the lowest erosion rates, as on the Nullarbor Plain, many scarps can be preserved even longer, possibly for several million years.

The neotectonic database illustrated in Figure 7.4 has been compiled from a combination of remote sensing information particularly digital elevation models, and field based mapping. The coverage across the continent is somewhat heterogeneous and biased towards the south, but still provides a better measure of the long-term deformation of the Australian continent than is provided by the historic record of seismicity.

Many of the Class A and Class B neotectonic features are associated with long scarps that are much bigger than those produced by any historic events. Only fault traces longer than 60 km are shown in Figure 6.4, since only these large features are visible when mapped at the continental scale. In most cases, several large seismic events would seem to be the likely cause.

The many features designated as Class C have a possible association with seismogenesis but the evidence is not as compelling as for Class B. Several of these features are very long with displacements too large for any single seismic event.

When allowance is made for the likely preservation of the neotectonic features, we see a good general correspondence with the current-day pattern of seismicity, though with events in some regions that have not had any historical activity. The results suggest that the general stress pattern across the continent has remained reasonably stable in the last 100,000 years or so.

6.4 Continental Deformation

The dominant motion of continental Australia is rigid body motion as a part of the Australian Plate with a direction of absolute plate motion slightly to the east of north and a velocity of about 6.7 cm/yr. The size of the continent means that the simple rigid rotation on the sphere is reflected in a systematic variation in direction across the continent with a stronger easterly component in the west.

Direct measurements of continental deformation using space geodetic techniques indicate that there are no significant changes in the dimensions of the Australian continent as part of the Australian Plate (Tregoning, 2003). Since 2000 there have been five recent earthquakes in the region which have produced considerable coseismic displacement at thousands of kilometres from the epicentre:

- 2004 December 24, Mw 8.2 Macquarie Ridge,
- 2004 December 26, Mw 9.3 Sumatra-Andaman,
- 2005 March 28, Mw 8.7 Northern Sumatra,
- 2007 April 1, Mw 8.1 Solomon Islands,
- 2007 September 12, Mw 8.4, Southern Sumatra (Nias).

The size of these coseismic displacements is consistent with the predictions from source models. In addition, in the GPS time series at sites along the eastern side of Australia there has been a small, nonlinear deformation due to post-seismic relaxation from the 2004 Macquarie Ridge event decreasing with distance from the epicentre. The size of the signal on the north component is comparable to the coseismic effects.

Once allowances are made for these effects by excluding GPS stations in the southeast regions of New South Wales and Victoria as well as Tasmania, the deformation across the rest of the continent is less than 0.2 mm/yr on top of the rigid motion of the Australian Plate (Tregoning et al., 2013). This makes much of continental Australia one of the most stable regions of crust across the globe.
6.5 Current Stress Field

The orientation of horizontal stress in the crust can be estimated from many different types of information. A major source is earthquake focal mechanisms, although there is the possibility that fault-planes may align with zones of pre-existing weakness rather than lie in the expected relation to the stress axis. Measurements in boreholes such as the orientation of breakout, drilling failures and the results of hydraulic fracturing are important indicators of the shallow stress state. As a result of the Australian Stress Map project (Hillis and Reynolds, 2003), and the ongoing efforts of the World Stress Map (Heidbach et al., 2016), a wide range of stress indicators have been collected for the Australian region. Figure 6.5 displays the indicators with the highest level of confidence, together with an indication of their stress regimes.

Stress orientations across Australia continent are more variable than is common on other continents, and do not parallel the absolute plate motion of the Australian Plate (north–north-northeast: DeMets et al., 2010). However, stress orientations are broadly consistent within individual areas, at the scale of hundreds of kilometres.

This makes it possible to define regional stress averages, with an indication of their reliability (Hillis and Reynolds, 2003). In Figure 6.5 these regional stress averages are marked with grey open symbols superimposed on the stress data. The regional symbols are scaled to indicate the level of reliability.

The regional stress directions rotate across the continent. In western Australia the maximum horizontal stress lies west–east. This direction rotates to northwest–southeast along the northern continental margin and eastwards into central Australia.

Figure 6.5: Stress directions for the Australian continent from the World Stress Map (Heidbach et al., 2016), with indication of domains: NF—normal faulting, TF—thrust faulting, SS—strike-slip, U—undetermined. The markers increase in size with confidence. The regional stress indicators from Hillis and Reynolds (2003) are shown in grey; symbol size increases with confidence.
There are stronger variations in direction in the eastern half of Australia. The stress regime in Queensland mirrors the trend in central Australia. Further south, there is a rotation towards west-southwest–east-northeast in the Sydney Basin. In both the Gippsland and Otway basins, the maximum horizontal stress orientation is northwest–southeast. In central eastern Australia there is a zone where there is a rapid change in stress orientation and stresses tend to be east–west or poorly defined.

The patterns of stress orientation across the whole Australian continent are consistent with the primary controls arising from plate-boundary forces along the complex boundary of the Australian Plate, with differing senses of subduction in Indonesia, Tonga and New Zealand. Stress focusing due to the continental collision in New Guinea has a particularly strong influence (Reynolds et al., 2003).