10. Electrical Conductivity

The electrical conductivity of rocks has strong sensitivity to rock composition, temperature and the influence of fluids. To a greater extent than for seismic wavespeed, minor chemical constituents can have a substantial effect on conductivity. Thus, the presence of a thin zone of a highly conducting phase such as graphite can have a major impact on apparent conductivity.

At the continental scale, studies of electrical conductivity are reliant on variations in natural source of the electromagnetic field. Fortunately, Australia has a favourable location for studies of electromagnetic induction exploiting variations in the external magnetic field of the Earth due to solar and ionospheric activity. Such fluctuations induce electrical field variations and currents.

As an island continent, at a large scale Australia appears as a resistive block embedded in a highly conductive ocean. The contrasts at the edge of the continent produce strong localised effects on the electromagnetic field at the margins. A variety of localised deployments of magnetometers across the continent have exploited electromagnetic induction effects to identify a number of crustal-scale conductivity anomalies. These major features are shown in Figure 10.1 as a set of red lines.

Over the period 1989–1990, the variation of the magnetic field on three orthogonal components was observed simultaneously at 57 sites across the continent in the AWAGS experiment (Australia-Wide Array of Geomagnetic Stations). The four continental geomagnetic observatories operating at that time were supplemented with 53 portable magnetometer systems (Figure 10.1). This achieved a relatively uniform distribution across the continent with a typical station spacing of 275 km.

This continent array of magnetometers has been exploited by Wang et al. (2014) to produce a broad-scale model of the heterogeneous electrical conductivity structure across the Australian continent, making use of the spatial variations in the observed magnetic fields at the stations.

The penetration of an electromagnetic disturbance into the Earth is greater for lower frequencies ($f$), and depends on the electrical conductivity $\sigma$ as $1/(f\sigma)^{1/2}$. Hence the need for long duration recordings at multiple sites so that low frequencies are well recorded, along with their spatial variations.

Fluctuations in the external magnetic field due in large part to solar effects induce electric fields that depend on the local electrical conductivity structure, and these electric fields in turn modify the local magnetic field. This leads to correlation between the vertical component of the magnetic field that has a strong component from external influences and the horizontal components that are most sensitive to induced effects.
The correlations in the multiple magnetic time series across the AWAGS stations are captured by working with the complex transfer functions between the vertical and horizontal magnetic fields, as a function of frequency. The inversion for electrical conductivity structure across Australia by Wang et al. (2014) used the dataset of such vertical transfer functions at the suite of AWAGS stations for seven frequencies (periods: 338, 660, 1097, 1807, 3072, 5120 and 9480 s). These periods were selected to give around two samples per octave, and to stay within the domain for which a plane-wave approximation for the magnetic field variation at each site was appropriate.

The electrical conductivity model comprises a grid of 86 x 71 cells, each 55 km x 55 km (approximately 0.5°), spanning from 46.5°S to 7°S and 110°E to 157°E. In depth, 21 layers are used down to a depth of 648 km. The layer thicknesses increase progressively with depth, reflecting the approximately logarithmic sensitivity of the frequency data to depth. The entire model is surrounded by a buffer zone about 2° wide to avoid edge effects in the forward modelling. The resulting 3-D model of electrical conductivity from the inversion of the AWAGS data captures the broad-scale variations. However, there is inevitably some smearing in depth without the additional constraints that come from recordings of the electric field.

We show four slices through the 3-D model in Figures 10.2–10.5 at depths of 17 km, 52 km, 92 km and 172 km. Because the variations in electrical conductivity are very large, we use a logarithmic scale. The shallow portion of the model is sensitive to the assumptions made about the initial structure, e.g. the inclusion of sediments as well as the continent–ocean contrast. But from 17 km depth, the solutions stabilise and show very similar character. The illustrated model does not include sediments in the initial structure, and provides a good fit to the vertical transfer function in both magnitude and direction at nearly all stations, except for the two on the southern coast of Western Australia where the induction effect is underestimated. This effect may be associated with persistence of low conductivity to great depth beneath the Yilgarn Craton because of low temperature gradients with depth.

The conductivity image at 17 km depth (Figure 10.2) shows two strong zones of high conductivity along the Halls Creek Belt and in the Rudall component of the Paterson Province to the east of Telfer (station TEL). Both features persist to 25 km depth. The southwestern margin of the Halls Creek anomaly coincides with the previously identified ‘C’ conductivity anomaly (Figure 10.1).

The low conductivity of the Yilgarn Craton is truncated at its margins with higher conductivity in the Albany–Fraser Orogen and the Capricorn Orogen. The Eucla Basin appears with a distinct contrast to its neighbours.

Reduced conductivity at the east of the Gawler Craton reflects the presence of the ‘E’ and ‘F’ anomalies (Figure 10.1). The expression of the ‘C’, ‘G’ and ‘S’ anomalies become more apparent as the base of the crust is reached, and they are still distinct in the image at 52 km depth (Figure 10.3).
In the 3-D conductivity model, the zone of high conductivity surrounds the Kimberley Block, in both the King Leopold and Halls Creek orogens. The Halls Creek anomaly fades by 92 km depth (Figure 10.4), but high conductivity in the King Leopold Orogen persists to great depth linking into a north–south trend of increased conductivity that traverses the continent down to at least 200 km (Figure 10.5).

By 52 km depth, the Rudall anomaly has subsided and now we see a zone of higher conductivity roughly parallel to the King Leopold Orogen to the southwest of the Canning Basin. At this depth a very prominent feature is the high conductivity extending from the Mt Isa Province to the south into the Eromanga Basin and then to the west to the north of Lake Eyre. The southern limb is stronger at shallower depths, but the entire feature persists to at least 100 km (Figure 10.4).
A rather localised high-conductivity zone emerges at depth in the neighbourhood of Geraldton (station GER), and can be tracked to 172 km depth (Figure 10.5). The spatial sampling with the AWAGS stations does not place tight constraints on position and it is possible that the feature is actually confined to the Pinjarra Orogen to the west of the Yilgarn Craton.

As the depth increases, the New England region switches from rather resistive at 17 km depth (Figure 10.1) to a noticeable high-conductivity feature at 92 km and 172 km depth (Figures 10.4–10.5). It is likely that this change is an expression of the electrical asthenosphere with much higher conductivity than the rather thin lithosphere above. The depth of transition fits reasonably well with seismic estimates of lithosphere thickness for the eastern seaboard of Australia, and indeed a weaker version of the transition appears all along the eastern continental margin.

A deep-seated east–west oriented higher-conductivity zone also emerges in Victoria. The conductivity anomaly lies slightly further north than comparable seismic wavespeed reductions that have been linked to elevated temperatures associated with the Newer Volcanics Province. Xenolith information suggests the conductivity feature is related to metasomatized mantle.

Within the Yilgarn Craton there is a persistent contrast between the southwestern corner and the rest of the craton. In the crust this area is more resistive, but gradually its conductivity increases whilst the rest of the craton becomes steadily less conductive. Indeed, at 172 km depth (Figure 10.5), the eastern part of the craton has the lowest conductivity anywhere in the continent. There is a distinct contrast between the character of the Archean Yilgarn and Pilbara cratons, with much higher conductivity beneath the Pilbara.

The outlines of the other cratons are less marked in the conductivity images. The northern part of the North Australian Craton is less conductive than the south at all depths. A distinct resistive patch is found beneath the Wiso Basin (around 19°S, 132°E) that persists through the full depth range illustrated. At 172 km depth (Figure 10.5), the lower conductivity links to a similar feature along the Musgrave Province that abruptly terminates against higher conductivity to the west, in the neighbourhood of magnetic and gravity lineations that suggest a continent-wide shear zone (Braun et al., 1991).

The South Australian Craton has a somewhat heterogeneous conductivity structure at all depths, probably related to the complex history where major volcanic events have modified the character of the core of the Gawler Craton.

There is a similar subdued expression of the South Australian Craton in seismic wavespeed (Section 8.1), with lower shear wavespeeds in the mantle lithosphere than in the other cratons.

The use of the continent-wide magnetic data from the AWAGS stations has enabled the construction of a 3-D model for conductivity through the full thickness of the lithosphere, with resolution limited by the spacing between stations. Improved models of the electrical conductivity structure, with better depth control, require the joint use of magnetic and electrical information with magnetotelluric recording exploiting the full vector character of the fields induced by external sources.
Major efforts have been made in recent years to make closely spaced magnetotelluric measurements across the entire continent. Many stations have deployed in association with major seismic reflection lines.

AUSLAMP—the Australian Lithospheric Architecture Magnetotelluric Project—has set the goal of 55 km station spacing, and already significant progress has been achieved. Most of South Australia has been covered, together with Victoria and Tasmania. Substantial progress has also been made in coverage of New South Wales. The distribution of stations to the end of 2016 is shown in Figure 10.6, and subsequent deployments have covered much of New South Wales and have made significant inroads into coverage of northern Australia. Even though stations do not need to be occupied for more than a couple of months, logistical and access issues in remote areas pose considerable problems.

Once the magnetotelluric data has been acquired, substantial effort is needed to extract the appropriate complex frequency responses of the appropriate transfer functions for subsequent inversion. Full 3-D inversion of data at the AUSLAMP spatial sampling is computationally very demanding, and major challenges remain for a fully integrated model at the continental scale.

Figure 10.6: Distribution of magnetotelluric sounding stations to the end of 2016.