Developments in passive seismic techniques through the ANSIR National Research Facility

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ABSTRACT

Since 1997 the ANSIR Major National Research Facility has significantly enhanced Australia’s national capacity for recording regional and distant earthquakes using seismic recorders distributed across the continent. Both broad-band and short-period recorders have been deployed in innovative experimental designs that have made major contributions to the understanding of the 3D structure in the Earth’s crust and upper mantle beneath the Australian region. The Facility continues its national role with investment in equipment suitable for both seismic and electromagnetic sounding.

Deployments of recorders with broad-band seismometers have made a substantial contribution to surface wave tomography, particularly with the gathering of extensive data sets from Western Australia and a deployment bracketing the Tasman Line. The significant increase in the number of portable stations provides constraints on the character of the crust and the crust-mantle interface across the continent, via the analysis of receiver functions from distant earthquakes. Anisotropy beneath the continent is now better characterised but remains enigmatic. New analysis methods are likely to make more extensive use of continuous seismic data.

Short-period instrument deployments have been mostly directed towards delay-time tomography studies in south-eastern Australia, and have employed new methods for event picking and tomographic inversion. Enhancements to the instruments mean that servicing of experiments will be simpler in future and allow new applications with three-component recording at higher sampling rates.

Passive seismic recording offers a cost-effective way of obtaining structural information across substantial areas of the continent. The results are valuable in their own right, but can also provide important constraints on seismological structure that are valuable in planning more expensive deep crustal reflection profiles.

INTRODUCTION

The Australian National Seismic Imaging Resource (ANSIR) Major National Research Facility was established by ANSIR National Research Facility

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The portable facility at the time of establishment comprised 50 solid-state recorders and 12 systems for broad-band seismic recording. The solid-state recorders, which record on flash cards, were designed at the Research School of Earth Sciences of The Australian National University. These low power consumption units were designed for use with 1 Hz or 4.5 Hz geophones. The broad-band systems provided high-fidelity recording of ground motion, with 24-bit analogue to digital conversion and feedback sensors with broad dynamic range and frequency bandwidth. The relatively high power consumption needed for high-fidelity recording requires large batteries and solar panels. Subsequently the equipment owned by the Australian National University was also made available for use through the same ANSIR access mechanism. A successful Australian Research Council infrastructure grant led by Flinders University also provided 40 solid-state instruments of ANU design in 1997. These instruments are now administered by ANSIR. As a result Australia has in recent years had a truly national pool of instrumentation that has been accessible through a simple competition based on the merit of submitted proposals.

The ANSIR National Research Facility has continued operations after the end of the MNRF contract, in June 2005, by agreement between The Australian National University and Geoscience Australia, and will continue in its current form until at least July 2007.

ANSIR EXPERIMENTS

The impact of the infusion of equipment provided by ANSIR can be seen in the detailed coverage of the Australian continent achieved in the eight-year period of the MNRF contract (1997–2005), illustrated in Figure 1. A reconnaissance survey of much of the continent with widely spaced broad-band instruments had been achieved in 1993–1996 in the SKIPPY experiment undertaken by the Research School of Earth Sciences of The Australian National University (van der Hilst et al., 1994; Kennett, 2003). The limited number of instruments available in 1993 had forced an experimental style that involved recording for a period at a group of stations spanning a region, subsequently moving the entire array to a contiguous region. The continent was covered in six deployments of about 5–6 months each that exploited the frequent earthquakes at regional distances in the subduction zones surrounding Australia. The SKIPPY operational concept has since been adopted in other parts of the world, and has inspired the USArray project in the USA which represents a SUS60M investment, many orders of magnitude larger than the cost of the original SKIPPY project.

The ANSIR facility has enabled a sequence of deployments designed to improve earthquake recordings in important regions, or to address structural issues that have been recognised from earlier analysis. The ANSIR experiments mostly build on the information obtained from SKIPPY. In Western Australia, instrumental problems had resulted in low data yields for the later phases of the SKIPPY work, and this region became one of the areas of attention. With the additional ANSIR equipment it became possible to provide resolution at finer scales than in the
SKIPPY project. New styles of experiments using broad-band equipment were designed to provide information on a range of scales exploiting as many different aspects of the recorded seismic data as possible.

Thus, in the QUOLL experiment in south-eastern Australia in 1999 and subsequently in Western Australia, a broadly distributed set of instruments with a long duration of recording was supplemented with more closely spaced recorders with shorter deployment times. Approximately linear arrays of closer spaced stations were placed to span major features such as, for example, the different terranes of the Yilgarn craton.

The broadly spaced stations provide valuable information for surface wave tomography (e.g., Fishwick et al., 2005) and the more closely spaced recorders have proved valuable for the insights they have provided into crustal structure, using receiver function information derived from the reflected and converted energy following the onset of the seismograms from distant events (e.g., Reading and Kennett, 2003; Reading et al., 2003, Reading, 2005).

Although ANSIR can still field far fewer broad-band instruments than other national groups, Australian seismologists have been able to stay at the forefront of international developments in the use of portable instrumentation. This has been made possible by close interaction between the user base to keep the instruments fully occupied and dedicated to work in Australia, and also by continuous improvements in interpretation based on innovative theoretical techniques.

More than 150 recording sites have been occupied across the continent with broad-band systems. The data from medium to large earthquakes (Ms 5.5 up) has been extracted, for time windows of up to an hour, to aid ready analysis of the seismograms. Recently, new methods based on the correlation of seismic data segments at...
different stations have been employed (e.g., Saygin et al., 2005) which have exploited the continuous data collected in the field.

The work on the Australian continent has been supplemented by an ambitious program of deployments in Antarctica. The initial work was undertaken in cooperation with IGNS New Zealand with a deployment into the Transantarctic Mountains supported out of Scott Base; this revealed important constraints on variations in crustal structure (Bannister and Kennett, 2002; Bannister et al., 2003). Subsequently deployments have been made in the vicinity of the Lambert Graben working out of Davis Station. Six seismic recording stations have been deployed deep into the ice (as far south as 75°S), but logistic complications have limited data return. Fortunately, data quality from the stations which have been serviced is high and has been suitable for receiver function analysis (Reading, 2006).

The ANSIR facility supports more than 100 recorders that use flash card memory; these low-power systems were originally designed for use with short-period seismometers or geophones. The instruments were initially used successfully in field work in Rabaul, Papua New Guinea, and have subsequently seen service in many parts of Australia and on the Amery Ice Shelf in Antarctica. These recorders have been also been used in wide-angle seismic profiling studies associated with land reflection profiles and off-shore/on-shore recording. Their main role in passive seismic studies has been in applications of delay-time tomography in south-eastern Australia.

**Styles of structural analysis**

The configuration of earthquake belts around Australia provides a wealth of events at suitable distances that may be used as probes into the seismic structure of the upper mantle. The extensive deployments of portable broadband stations throughout Australia in recent years have been used in a variety of studies of 3D structure (Kennett, 2003).

The various ANSIR experiments have been designed to exploit as broad a range of analysis techniques as possible. Because the

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![Figure 2](image.png)

**Fig 2. Configuration of stations deployed in Western Australia in (a) 2000–2001, WR, WS, WT, WV, (b) 2003–2004 WP, (c) 2005–2007, LP and CP, RP (open symbols) deployed in June 2006.**

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The initial data from the SKIPPY experiment in Western Australia suffered from hardware problems, and as a result this region became a target of several ANSIR-supported experiments. Seismic stations were deployed in and around the Kimberley region in 1997 and 1998 (Figure 1), including the first use of the then new ANSIR broad-band recorder systems. Later work has concentrated on the Archaean cratons, with three separate phases of instrument deployment (Figure 2).

The experiments were planned to provide a broad control on structure, through a network of stations at 200–400 km spacing left in place for a long period. These stations provide a major source for information for surface wave tomography. The broad network is then supplemented by more local deployments with closer spacing particularly directed toward understanding the transitions in structure in the crust and uppermost mantle. The more closely spaced instruments are deployed for a few months, which is normally sufficient to provide enough suitable earthquake recordings for receiver function analysis.

In 2000–2001 a large-scale network of broad-band recorder stations was deployed by the Australian National University across the cratonic regions of Western Australia (stations WR..), supplemented by two lines of instruments: WS.., extending from the Pilbara into the Yilgarn; and WT.., a nearly east-west transect across the Yilgarn craton. A shorter-term deployment of stations (WV..) was made to provide additional information in the neighbourhood of a major seismic reflection profile in the Leonora-Laverton region.

In 2002–2003 a new deployment of broad-band stations (WP..) was made with support from the Predictive Minerals Discovery CRC, to link the previous lines and provide closer instrument spacing in the neighbourhood of the Eastern Goldfields.

In 2005 an ARC Linkage Project Grant to the University of Western Australia in association with the Australian National University and Geoscience Australia enabled the deployed of eight stations (L.P.) in northwest Australia, designed to improve local earthquake location and hence understanding of neotectonics. These stations, together with the permanent station at Marble Bar (MBWA) provide a useful framework to improve coverage of the Pilbara craton and the Capricorn orogen. A further set of 20 stations (CP.., RP..), deployed in May 2006, link all the prior experiments together in the north (Figure 2).

There is thus a complex network of stations in Western Australia (Figure 2) providing a dataset with unprecedented coverage of a cratonic region at multiple scales. The full set of data is useful for a wide range of applications as described below that provide constraints on crustal and mantle structure.

The Tasman Line Project, supported by an ARC Discovery grant to the Australian National University, deployed 20 broad-band stations across central-eastern Australia in a network surrounding this enigmatic structure. The Tasman Line marks the eastern edge of Pre-Cambrian outcrop, but limited exposure means that considerable extrapolation is required with very different results from different authors (Direen and Crawford, 2003). The broad-band stations were deployed to bracket the region of high wave-speed gradients revealed in earlier tomographic studies (Kennett, 2003), in a pattern that in the north was largely dictated by convenience of access to station sites. Most stations were in place from May 2003 through to June 2005, with a few stations in the south present until November 2005. The benefits of the long-term deployment have been that a wide range of earthquakes can be exploited and that there are many paths available for each event.

Key results from broadband studies

The addition of extensive observations in Western Australia over the period 2000–2006 has provided much denser path...
coverage from regional earthquakes across the whole of continental Australia, and in consequence the 3D models derived from surface wave tomography were much improved. Figure 3 shows the impact of adding the Western Australian data to that collected in the earlier SKIPPY experiments. Good resolution of structure is achieved across most of the continent. It is unfortunately difficult to get strong coverage from the west because there are few suitable earthquakes in the Indian Ocean.

The Western Australian stations and those in the Tasman Line array have also been valuable in extending the coverage of refracted body waves beneath northern Australia.

There is a complex pattern of 3D structure beneath the Australian region, which has been progressively revealed as more data have become available. The cratonic region in the centre and west is underlain by a thick mantle lithosphere extending to around 200 km depth with fast wavespeeds, especially for S waves (see e.g., Fishwick et al., 2005). However, the mobile belt in Central Australia has comparatively low wavespeeds to at least 75 km depth with fast lithospheric material beneath. In the asthenosphere, below the lithosphere, the S wavespeeds diminish, and there is significant attenuation and also some level of seismic anisotropy. Beneath the eastern zone with Phanerozoic outcrop the lithosphere is generally thinner (less than 140 km), and the asthenosphere has a pronounced low-velocity zone for S again with high attenuation.

The major features of the 3D structure beneath Australia are now well revealed (Kennett, 2003). However, the major transition from Pre-Cambrian in the centre and west to Phanerozoic structures in the east is obscured by poor outcrop. There is a major change in mantle structure (Kennett et al., 2004) that has a limited correlation with crustal properties. The extra paths crossing the transition region extracted from analysis of seismograms recorded in the Tasman Line project provide significantly improved resolution in Eastern Australia, with the result that the structure at depth has been revealed much more clearly (Figure 4). These new results suggest that the transition from the craton to the eastern seaboard is accomplished with three distinct steps in lithospheric thickness (S. Fishwick, personal communication, 2006). There is no simple relation between the structure in the mantle and common interpretations of the surface contrasts.

Seismic anisotropy provides an insight into the deformation processes in the lithosphere. Events at suitable distances for analysis of the shear-wave splitting associated with SKS and similar core phases are infrequent, and so long durations of recording are needed to get satisfactory results. The patterns of anisotropy in Australia for body waves seem rather complex and difficult to interpret (e.g., Clitheroe and van der Hilst, 1998; Heintz and Kennett, 2005). The two-year duration of the Tasman Line project was designed to improve the number of events available for analysis at each station. The results, from the analysis of time differences in the arrival of shear waves of different polarisation, show that the lithosphere along raypaths to a number of stations is clearly isotropic in behaviour. The analysis of only a few data acquired in a short-time period can be potentially misleading (M. Heintz, personal communication, 2006).

Analysis of azimuthal anisotropy of Rayleigh waves using surface wave tomography indicates that there is a transition from nearly E-W fast wavespeeds at shallower depths to close to N-S below 150 km. This apparent two-layer anisotropy is unique to Australia (Debayle et al., 2005), and may well arise from strains on the lithosphere imposed by Australia’s rapid progress northwards. Such a two-layer anisotropic structure would act to reduce the splitting of S wave phases and may help to explain why Australia has less pronounced anisotropy than other continents.

The information on crustal structure supplements the results from active seismology. The extensive deployments of stations across the continent mean that much of our control on the depth and nature of the crust-mantle boundary comes from receiver function studies. It would appear that major crustal blocks carry a
distinct signature so that the major terranes of the Yilgarn craton can be recognised through their behaviour at depth (e.g., Reading and Kennett, 2003; Reading et al., 2003; Reading, 2005).

Results from short-period deployments

The application of the short-period instruments for passive seismic experiments has so far been somewhat different. They have been mostly massed in relatively dense arrays with spacings from 15–40 km, designed to provide an effective configuration for delay-time tomography (e.g., Graeber et al., 2002). Relatively dense coverage has been achieved for much of southeast Australia, and the current experiment in eastern Victoria (EVA) will complete the southern coverage on the mainland.

The largest deployment took 60 instruments to northern Tasmania with stations deployed for up to 6 months, a period that is long enough to get a reasonable azimuthal distribution of distant earthquakes recorded at the sites. The Tasmanian experiment has revealed intriguing patterns in wavespeed anomalies that do not favour thin-skinned tectonics (Rawlinson et al., 2006b). In this area as well, innovations in event picking using adaptive stacking (Rawlinson and Kennett, 2004), and in tomographic inversion (Rawlinson et al., 2006a,b) have enabled effective and rapid interpretation.

As demonstrated in Figure 5, even a limited deployment of stations in a critical region can provide useful information. A set of 20 stations across the Murray Basin designed to link to previous deployments has provided new insights into the structure beneath this deep sedimentary basin, indicating the presence of P wavespeed anomalies with a north-south orientation in the uppermost mantle. These features may well represent the signatures of the different terranes associated with the accretion of eastern Australia to the cratonic nucleus.

FUTURE OF PASSIVE SEISMIC EXPERIMENTS

Although the ANSIR contract with the Commonwealth is now complete, the owners have decided to continue the National Facility and it has been possible to exploit a variety of sources of funding to sustain and renew the equipment base. Australian Research Council Infrastructure funding granted for 2006 to ANU in partnership with the University of Adelaide and Macquarie University will see 15 high-fidelity recorders equipped with both seismic and electromagnetic sensors, which will allow new synergies in Earth sounding.

In addition, a partial redesign of the solid-state recorders has allowed the use of new generation flash cards with much higher capacity, which opens the possibilities for a range of new styles of work including extended three-component recording at high frequencies. ANSIR intends to upgrade to a total of 100 higher capacity systems with 40 of these having three-component capability.

The increasing numbers of recorders involved in experiments means that considerable care needs to be taken to avoid data indigestion and make the relevant portions of the seismic records available in useful form. The field procedures have moved from tape archiving to DVD, and cheaper mass-storage means that it has begun to be possible to keep the full continuous data available.
to users. New techniques, using waveform correlation between different stations to extract structural information, can therefore be exploited.

The last few years have demonstrated that the ANSIR Facility, with a flexible equipment base and adequate (if not generous) numbers of portable seismic recorders, can be a major national asset. The synergies that can be achieved if active and passive seismological techniques can be combined have been recognised. Passive methods can provide information on, for example, crustal velocities and depth to Moho, for a fraction of the cost of full refraction surveys, but at lower resolution. Nevertheless such information is of great value for the design of a full-scale reflection survey, which might also include wide-angle and refraction components using higher frequency geophones with portable recorders. A lead time of at least a year is needed for passive seismic work to have an adequate recording interval to capture enough data from sizeable distant earthquakes and to undertake the data extraction and processing. Unfortunately timing and funding constraints have not so far enabled such a passive component prior to any major active experiment, but it is to be hoped that this can be achieved before too long.

A further class of experiment that is likely to be of value in detailed studies of 3D structure is to use three-component recording for a dense array of short-period recorders, supplemented with a smaller number of broad-band systems so that maximum information can be extracted from recording shear body waves. Such a configuration should allow improved definition of structure at depth beneath the region of interest using dual wave-speed tomography. The adaptive stacking procedure that has been employed for time picking of the onsets of seismic phases from distant earthquakes (Rawlinson and Kennett, 2004) can also be applied to use array analysis methods on later arrivals and provide additional information on deep Earth structure.

Although there has been extensive development of seismic processing techniques for reflection seismology, exploitation of the full content of seismograms from local and distant seismic activity requires a diverse range of skills. So far it has not been possible to achieve the data densities where statistical methods can prevail. Australia has been fortunate to have had a group of users who have been actively involved in data acquisition and interpretation. The result is innovation in both experiment design and data analysis to achieve maximum resolution within the constraints of available instruments and funding.

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