Passive seismic studies of the Capricorn Orogen, Western Australia

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SUMMARY

The study of incoming seismic waves from teleseismic earthquakes can be used to investigate the deep structure of the Earth's crust and upper mantle. Resolving the deep crustal structure and locating potential mantle-tapping structures is critical for understanding the metallogeny of mineral deposits at the surface. From 2014 to 2018, a network of 83 seismic monitoring stations was moved across the Capricorn Orogen in Western Australia. This survey was intended to complement the previous deep crustal seismic reflection lines, and although the resolution was lower, the survey covered the majority of the orogen in 3D and provided different geophysical information from the reflection surveys.

Results from studies of receiver functions provide the depth to Moho and average composition of the crust for the orogen. The distribution of more felsic crust and a deeper Moho outline the extent of the Archean Glenburgh Terrane in the central part of the orogen. Common conversion point (CCP) studies provide a view of compositional layering in the crust, and have led to a revised interpretation of the 10GA-CP2 seismic reflection line. Intriguing features within the upper mantle obtained by bodywave tomography have yet to be interpreted within the context of the tectonic evolution of the orogen.

Key words: Capricorn Orogen, receiver function, ambient noise, tomography

INTRODUCTION

This project focussed on the crustal and lithospheric structure of the Capricorn Orogen including the Gascoyne Province and the flanking Archean cratons of the Yilgarn and Pilbara. This is an area with complex geological evolution which is largely covered by regolith resulting in paucity of outcrop. The area has received little attention in spite of several large economic deposits of gold (Plutonic, DeGrussa, Abra Paulsens) and mineral systems of other commodities such as Fe, Cu, Zn, U and Pb.

According to the mineral systems theory, (McCuaig et al., 2010; Hronsky et al., 2012; McCuaig and Hronsky, 2014) hydrothermal mineral deposits form by enriched fluids which travel from deep within the crust or mantle to shallower levels where, they drop the minerals in concentrations economic for mining,. Hence, an important part of defining a mineral system is to understand potential pathways for the fluids to flow between the source and deposition area. These pathways are crustal-scale structures and their subsidiary faults.

Extensive field mapping by the Geological Survey of Western Australia within the western Capricorn Orogen and recent deep seismic reflection surveys (Johnson et al., 2011a; Johnson et al., 2011b) have provided a framework for the Orogen in its western half. However, to the east, where there is less exposure, it has been difficult to translate the structure across and in particular, define the eastern boundaries.

Particular objectives of this project were:

1) Define the margins of the Pilbara and Yilgarn Cratons as the extent of the cratons underneath the Proterozoic basins is not known.

2) Image deep penetrating faults which extend to the mantle hence providing fluid pathways.

3) Determine the depth and nature of the Moho which can be indicative of the age of the crust

4) Estimate crustal composition as older Archean crust has been observed to be more felsic than younger Proterozoic crust (Christensen, 1996; Griffin et al., 2009).

5) Image other layering or faulting with in the crust which can help in building a tectonic history.

6) Investigate structure of the upper mantle. This is not observable using reflection methods so any information on structures within the mantle may hint at an early Archean history.

Few geological or geophysical methods are capable of imaging deep crustal levels or can cover a large area with sufficient resolution quickly and cost-effectively. Hence we used passive seismic techniques to attempt to address these objectives.

FIELDWORK

The initial network of seismic monitoring stations was established in March 2014 and the final seismometers were taken out in September 2018. Over that four years, 3 TB of data were recorded over a total of 83 temporary stations with an overall 70% recovery of data.

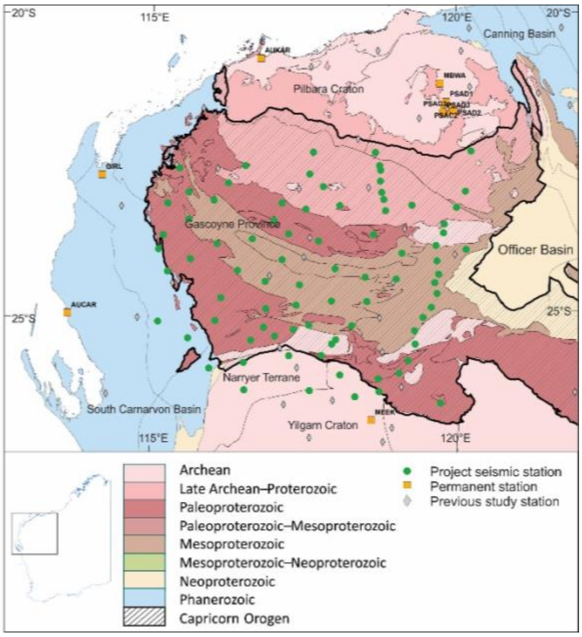

Figure 1. Location of the Capricorn Passive Seismic Array and other stations used in this study. Background shows the tectonic units of the Gascoyne Province of Western Australia.

The initial network was composed of two parts: a framework of nine stations and a mobile network of up to 24 stations (Figure 1). Mobile stations were moved across the array west to east after gathering data for 12 to 18 months. All stations were three-component broadband seismometers which recorded continuously at 100 samples per second. Data was stored locally and downloaded every four months.

Data was also downloaded from the surrounding permanent stations run by Geoscience Australia and also from previous temporary arrays (Figure 1) run by Reading et al. (2003; 2012).

DATA PROCESSING

Receiver functions - *H-k* stacking

Receiver functions use the arrivals of different phases from teleseismic earthquakes ($M_s > 5$ at distances > 20°), in particular the direct Moho converted phase (P_moho_s) and two free surface reflections (2p1s and 2s1p).

The *H-k* method of Zhu and Kanamori (2000) was used to determine the bulk crustal thickness (*H*) and the Vp/Vs ratio (*k*) at each station. For each station, the waveforms were stacked according to the method of Yuan (2015). From *H* calculations across all stations, a map of the depth of the Moho is obtained. From the Vp/Vs ratio, the distribution the bulk crustal composition is obtained with lower values indicating a more felsic crust and higher values indicating a more mafic crust.

Receiver functions - Common Conversion Point Stacking (CCP)

As the waveform passed through the crust, all changes in velocity have the potential to cause a mode conversion. All receiver functions at all stations are back projected along their incident pathway (Dueker and Sheehan, 1997) was followed. The crustal volume is divided into bins of 1 km thick by 2 km by 2 km wide at the surface and a period of 2 s is used. At each depth the horizontal region affected by each receiver function is approximated at the first Fresnel zone $\sqrt{(0{,}5\lambda z_i)}$ where λ is the wavelength and z_i is the depth of the bin. Bootstrapping was used to average the energy within the 3D bin. A continuous velocity map in 3 dimensions is obtained with the Moho and other intracrustal discontinuities showing as velocity gradients.

Ambient noise tomogrpahy

Ambient noise cross correlation was used to image large-scale crustal velocity variations. This exploits the dispersive nature of the Raleigh surface wave to extract the Greens function between two stations (Shapiro and Campillo, 2004; Bensen et al., 2007; Saygin and Kennett, 2010). Data from the vertical component at two stations from the same time period are cross correlated using a 600 s window. Over 10,000 traces were used per station pair to enhance the signal to noise ratio and remove the effect of earthquakes and other temporal noise sources.

The final correlated trace is filtered at different band widths from 2 s to 30 s which correlate to different depths of investigation. Since surface waves are dispersive, the group and phase velocity can be measured at each frequency. 2D maps for a particular frequency were generated (Rawlinson and Sambridge, 2005). For a grid across the study area, 1D shear wave profile was extracted using a modified transdimensional inversion approach (Yuan and Bodin, 2018) that incorporated a smooth background velocity from AUSREM and the Moho topography from our receiver function analysis. These 1D profiles are interpolated to give a volume of surface wave variation.

Bodywave tomography

Bodywave tomography uses the direct P-wave arrivals including the PP and PcP reflection from the core-mantle boundary. It looks at the travel-time delay in earthquakes 28-90° away across a volume. Travel time delays are frequency dependent and are a product of wavefront healing, scattering and other diffraction phenomenon (Hung et al., 2004; Zhao et al., 2016). Sensitivity kernels for the same phase arrival in different frequency bandwidths sample different regions along the travel path (Hung et al., 2004). P-phase arrivals are measured at low (0.1-0.4 Hz), intermediate (0.4-0.8 Hz) and high frequencies (0.8-2.0 Hz). Traveltime residuals are calculated relative to the AK135 1D Earth model of Kennett et al. (1995).

A finite-frequency body-wave tomographic inversion (Dahlen F.A., Hung, S.-H., Nolet, G, 2000; Hung et al., 2000) was used across the array to invert for slowness. The area is discretised into cells 0.25° by 0.23° by 23 km depth from 50 to 700 km deep. The depth of investigation is dependent upon the aperture of the array, which in this case was 500 km. We show results down to about 250 km.

RESULTS

Receiver functions - *H-k* stacking

The depth to the Moho shows a variation of over 20 km across the study area. The Pilbara shows as an area of shallow Moho with depths 30-35 km. Likewise the Yilgarn Craton shows depths of less than 35 km. There is a large “L” shape across the Gascoyne Province, northern Narryer and south eastern

Gascoyne of deeper (>36 km) Moho. The thinner crust is typical of Archean Crust (Abbott et al., 2013) with the crust getting progressively thicker as the Archean progressed, although neither craton is comprehensively sampled. The Narryer Terrane would be expected to show a thin crust, but due to a dearth of good quality stations the interpretation is not straight forward and includes a confusing possible double signal (Yuan, 2015).

The crust under the Carnarvon Basin is a passive margin which generally shows a shallower Moho.

The Gascoyne Province shows a deeper Moho as would be expected of Proterozoic crust.

The Vp/Vs ratio map shows low values in the Yilgarn including the Narryer Terrane and Pilbara Cratons. Low ratios are typical for Archean terranes indicating felsic composition and hypothesised delamination of a refractory lower crust (Rudnick, 1995; Abbott et al., 2013).

There is a third low ratio area in the centre of the Gascoyne which appears to be delimited by the Lyons River Fault and the Cardylia fault. It is proposed that this area is indicating the presence of an accreted arc sandwiched between the Glenburgh Terrane and the Pilbara. However there are issue with volume of material required to produce such a signature.

Receiver functions – CCP

The major feature visible in the CCP stacks is the Moho. Several profiles have been extracted from the volume along orientations which have denser data coverage. Five north-south lines are chosen and the dip and strength of the Moho are used as an indication of possible tectonic features. In the western lines, the asymmetry of the Moho signal could indicate that there is a feature which dips to the north and underthrusts a more northerly segment of Moho. If viewed in 3D, these segments do not line up, but may be consistent with an interpretation of tears in a slab.

The eastern profiles show a Moho asymmetry which may indicate a Moho which dips to the south. The dips in these profiles do line up to form a potential dipping slab which if continued across to 11GA-CP2 line correlated to the MacAdam Seismic Province (Johnson et al, 2011a).

In the west, we see the Cardylia Fault bring the Glenburgh Terrane under the Narryer Terrane with the associated depression in the Moho. This is along strike from the depression caused by the MacAdam Seismic Province.

In the western half of the study area, the Moho shows two areas of depressed Moho. One lies along the line of 11GA-CP2. The interpretation of this line has been revised by Dentith et al. (2018) to include a wedge which has been back thrust and depresses the Moho with a northerly dip. This area correlates well with the area of low Vp/Vs ratio. However, the volume of this first backthrust in not big enough to cause the Vp/Vs ratio (and we would also expect it to have a more mafic signal). A second backthrust is also inferred, but although this intersects the Moho at the deepest point of the depression, there is no associated low Vp/Vs ratio.

Another section from the CCP block further to the northwest shows the Carlathunda Seismic Province (the seismic province that underlies the Pilbara) as a strong negative gradient. This appears to dip to the south and form a depression in the Moho. The seismic provinces under the other components, i.e. Bandee – northern Gascoyne, MacAdam – Southern Gascoyne and Yarraquin – Yilgarn, all seem to be well delineated in the CCP stacks.

The features in the gradients shallower in each section can be correlated with boundaries associated with the base of the Edmund, Collier, Fortescue, although the resolution of the CCP stacks does not allow for detail.

Ambient noise

The ambient noise model is currently being run across the whole volume, but initial results show variations in shear velocity across the different cratonic/orogenic blocks.

Bodywave tomography

The bodywave tomography shows high and low velocity areas. The Archean Craton of the Pilbara and Yilgarn show high velocity roots. The Gascoyne area shows a low velocity root down to 250 km. Under this in the eastern Gascoyne, a high velocity regions exists whereas the northwest Gascoyne the low velocity root continues to greater depths. The Glenburgh Terrane does not feature.

Interestingly the Narryer Terrane lacks an Archean high velocity root. This supports the theory that the Narryer is an exhumed piece of crust which has been thrust up initially onto the Glenburgh terrane during the Glenburgh Orogeny and then backthrust on to the Yilgarn Craton during the post-collisional phase of the orogeny. Hence it has lost its root (Korsch et al., 2011) and has suffered substantial reworking throughout the Proterozoic .

Throughout the volume, there appears to be a fabric in both the fast and slow velocities which dips towards the east. This is interesting as it is perpendicular to crustal fabrics.

Seismic tomographic anomalies are often explained by thermal variations (e.g. Fishwick and Reading, 2008). However, since the Pilbara and Yilgarn cratons have been stable for over a billion years, a compositional explanation is more likely. Considering the high P-wave speeds in the upper mantle, a typical Archean heat flow of 40 mW/m^2 (Morgan, 1984; McLaren et al., 2003; Goes et al., 2005), and low electrical conductivities suggest that the keels of these Archean Cratons are still intact.

The sharp transition in P-wave speed to the slow speeds seen in the Proterozoic Capricorn Orogen can be correlated with the Godfrey or Lyons River faults at the surface which agrees with previous studies (Cawood and Tyler, 2004; Selway et al., 2009; Johnson et al., 2013).

CONCLUSIONS

Seismological studies of the Capricorn Orogen and the bordering Archean Cratons has provided a 3D picture of the crustal and lithospheric structure. This dataset has given information much deeper than we have been able to investigate with traditional geophysical methods. The interpretation of the deep structures provide critical input to understanding the Archean and Proterozoic mineral systems.

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