Seismic reflection imaging of the mafic-ultramafic Windimurra Igneous Complex, Yilgarn Craton, Western Australia

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SUMMARY

A deep seismic reflection survey was carried out over the Meso-Neoarchean Youanmi Terrane, Yilgarn Craton in Western Australia, including 3 seismic lines across the Windimurra Igneous Complex. This gabbroic intrusion is the largest exposed single mafic-ultramafic intrusion in Australia, currently mined for magnetite-hosted vanadium in its upper zone. Acquisition was carried out with 3 Hemi 60 vibrators, 80 or 40 m VP interval, 40 m group interval, and a 300 channel symmetric split spread, resulting in 75 to 150 fold high quality data. Key processing steps included refraction and residual automatic statics, spectral equalisation, detailed stacking velocity analysis, dip moveout (DMO) correction and post stack Kirchhoff migration. The Windimurra Igneous Complex exhibits high seismic velocity (approximately 6.5 km/s), both in interval velocity from stacking velocity and bedrock velocity from refraction statics analysis. Seismic attenuation is low, resulting in high frequency and good resolution to the base of the complex, seen at a maximum two way time of around 2.5 seconds. Gross structure on the seismic sections is also consistent with the gravity and magnetic data. An inward dipping conical structure is evident and consistent with surface geological observations. The base of the complex is marked by distinctive high amplitude multi-layered reflectors, which may represent significant thicknesses of ultramafic zone material unexposed at the surface. This zone has been a long sought after target for Cr-PGE exploration. The complex internal structure of the intrusion, possibly including discordant igneous layering features, has been well imaged up to the base of regolith.

Key words: Seismic acquisition, seismic processing, igneous intrusion, mineral exploration

INTRODUCTION

The Youanmi Seismic Reflection Survey (L196) was conducted across the northern Yilgarn Craton in Western Australia in May and June 2010 by Geoscience Australia and ANSIR, under a National Geoscience Agreement with the Geological Survey of Western Australia. Funding was through the Western Australian Government's Exploration Incentive Scheme (EIS). A total of 695 line km of 2D deep seismic reflection data was acquired along three separate regional lines (Table 1), along with gravity and magnetotelluric (MT) data.

Line	10GA-YU1	10GA-YU2	10GA-YU3
Length (km)	302	283	110
Direction	N to S	W to E	W to E
Shots	1 - 4878	1 - 4803	1 - 2240
Stations	1000 - 8554	2000 - 9070	3000 - 5746
CDP	2000 - 16499	4000 - 17778	6000 - 11293

Table 1. Summary of Youanmi Seismic Survey lines.

The main objectives of the Younami Seismic Survey were to image deep structures in the Narryer and Youanmi Terranes, investigate the structure of greenstone belts and the nature of granite-greenstone contacts, identify crustal structure controls on mineralised zones, and develop a 3D image of the mafic-ultramafic Windimurra Igneous Complex. This paper focuses on the seismic imaging of the Windimurra Igneous Complex, using a subset of the data where the three lines intersect.

The Windimurra Igneous Complex is the largest exposed single mafic-ultramafic intrusion in Australia, currently mined for magnetite-hosted vanadium in its upper zone. This predominantly gabbroic, layered intrusion extends for 85 km north-south and 37 km east-west. Prior to deformation, the main body would have resembled one of the main lobes of the Bushveld Igneous Complex, according to Ivanic *et al.* (2010). They observe that the cumulative thickness of gabbroic and ultramafic rocks is 13 km, noting that a true thickness of ~6 km is indicated from the gravity modelling of Ahmat (1986). The exposed part of the complex has an extremely felsic overall composition, suggesting that a significant thickness of ultramafic material exists at depth (Ivanic *et al.*, 2010).

The potential field signature of the complex is very distinctive and is clearly visible on continental scale gravity and magnetic anomaly images. A gravity high occurs over the complex, with more subtle features revealed in the high resolution image in Figure 1, which also shows the seismic lines. The magnetic image in Figure 2 clearly shows the extent of the complex, and corresponds well with the outline of the gravity anomaly in Figure 1.

In this paper, we present the results of the first seismic survey in Australia over a large mafic-ultramafic intrusion, including details of seismic reflection acquisition and processing, and a preliminary interpretation. Of particular interest are the thickness and internal structure of the Windimurra Igneous Complex, and the location of unexposed ultramafic material of economic interest.

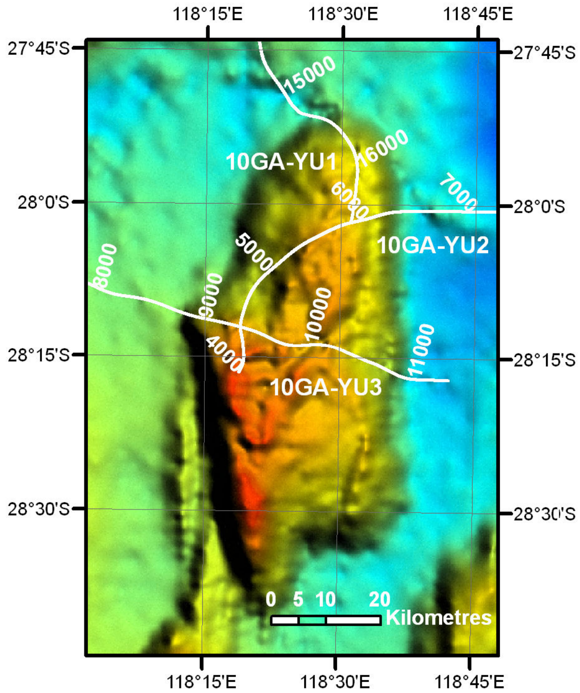

Figure 1. High resolution gravity image over the Windimurra Igneous Complex, combining regional and company infill gravity data (1.5 km grid) with that acquired every 400 m along the seismic lines, gridded at 200 m (Ray Tracey, pers. comm.). Seismic lines are annotated every 1000 CDP.

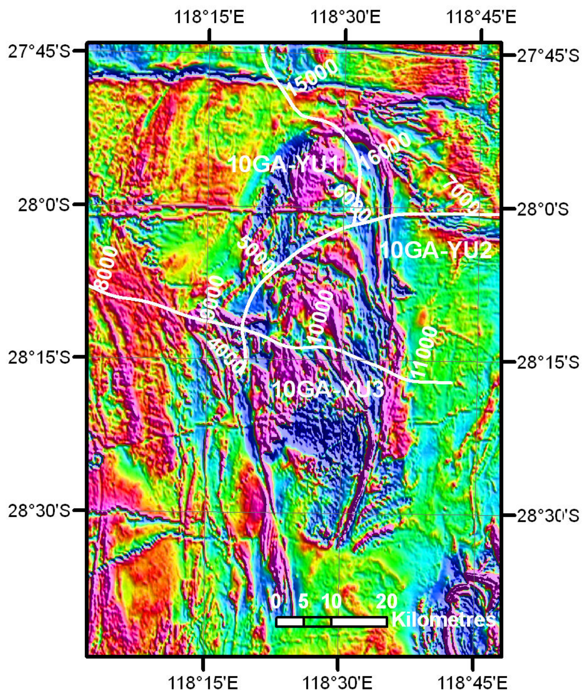

Figure 2. Enhanced colour image of the TMI anomaly across the Windimurra Igneous Complex produced from the 80 m cell resolution grid used to make the Magnetic Anomaly Map of Australia (Milligan *et al.*, 2010). Seismic lines are annotated every 1000 CDP.

SEISMIC ACQUISITION

Seismic reflection data were acquired along the verges of existing roads by Terrex Seismic, using a slightly modified version of Geoscience Australia's regional acquisition parameters (Table 2). A Sercel 428XL acquisition system was used for recording the data, with output in SEG-D demultiplexed format.

Group interval	40 m
Group pattern	12 in-line over 40 m
VP interval	80 or 40 m
Source type	3 x IVI Hemi-60
Sweep type	3 or 2 x 12 s varisweep
Sweep frequencies	6-64, 8-84 & 10-72 Hz 6-64 & 8-84 Hz
Source pattern	15 m pad-pad, 15 m moveup
No.active channels	300, symmetrical split spread
Fold (nominal)	75 or 150
Record length	20 s @ 2 ms

Table 2: Acquisition parameters for the Youanmi Seismic Survey

In a successful attempt to improve the signal to noise ratio in the shallow section over the greenstone belts and the Windimurra Igneous Complex, the vibration point (VP) interval was decreased from 80 to 40 m, thus increasing the nominal fold from 75 to 150. However, to maintain production rates, only two sweeps per VP were then used, which still resulted in an increased source effort per km. Note that this approach did not improve spatial resolution, since the group interval remained at 40 m. The sweep frequencies were chosen so that the sweep with the narrowest bandwidth (octaves) could be dropped, while the remaining two would allow both high resolution at shallow depths and deep crustal penetration (Terrex Seismic, pers. comm.). In hindsight, the upper frequency should have been at least 90 Hz, since frequencies up to 84 Hz are contained in the shot records to at least 2 s two way time, indicating low seismic attenuation in the Windimurra Igneous Complex.

SEISMIC PROCESSING

Seismic processing was carried out within Geoscience Australia's Seismic Acquisition and Processing Section, using Paradigm Geophysical's Focus software. The processing stream is given in Table 3. Note that the same processing stream was used for Windimurra as for the whole of crust imaging, except for more closely spaced velocity analysis.

One of the key processing steps was zero phase spectral equalisation to suppress low frequency traffic and source generated noise, and to boost the high frequency component of the signal, thus improving vertical and horizontal resolution. Refraction statics, calculated from first break picking on all shots, were applied using an intermediate (floating) datum, so that only residual refraction statics were applied during processing, with the full static applied just prior to display. As a by–product of the refraction statics analysis, refractor (bedrock) velocity could be mapped along the lines (see Figure 3 and 4). The statics were fine tuned with residual automatic statics, calculated over a deep gate from 2 to 8 s, to take advantage of the strong reflectivity in this region with less sensitivity to the normal moveout (NMO) correction

- Crooked line geometry definition (20 m CDP interval)
- SEG-D to Disco internal format, resampled at 4 ms
- Trace edits and 50 Hz notch filter
- Spherical divergence gain recovery
- Spectral equalisation with time variant AGC
- Common mid-point sort
- Application residual CDP refraction statics
- Velocity analysis (3 pass, after refraction statics, auto statics and DMO)
- NMO correction, 25 % stretch mute
- Application automatic residual statics
- Band pass filter
- Offset regularisation and DMO correction
- Common mid point stack
- Amplitude balance
- Kirchhoff migration, using 95% of DMO corrected stacking velocity
- Band pass filter
- Coherency and S/N enhancement
- Application mean CDP refraction static, datum 450 m (AHD), replacement velocity 6000 m/s
- Resample to 4 s, trace amplitude scaling

Table 3: Seismic processing sequence for the Windimurra Igneous Complex

Three pass interactive stacking velocity analysis was done every 2 km, after residual refraction statics, again after automatic residual statics and finally after dip moveout (DMO) correction. Even with the high stacking velocities (generally over 6 km/s within the complex), the stack response was sensitive to +/- 50 m/s changes in velocity down to 2 s two way time (TWT). Post-stack Kirchhoff time migration used 95% of the smoothed DMO corrected stacking velocity. The final migrated sections are displayed in Figures 3 and 4.

PRELIMINARY INTERPRETATION

The gross structure of the Windimurra Igneous Complex is readily apparent on the seismic sections (Figures 3 and 4), with the base indicated by distinctive high amplitude multi-layered reflectors, down to a depth of approximately 7 km. This is consistent with the ~6 km interpreted by Ahmat (1986) from gravity modelling. The Bouguer gravity anomaly profile highs match the thickest parts of the complex on the seismic sections, which show an inward dipping conical structure consistent with surface geological observations. The distinctive high-amplitude reflectors are interpreted to be a basal ultramafic zone which is not exposed in the main part of the complex but inferred from the gravity response and from sheared lenses exposed to the south (Ivanic *et al*., 2010). The seismic data show that these basal reflectors approach the surface in the vicinity of the shear zones marking the boundary of the complex. This ultramafic zone has been a long sought after target for Cr-PGE exploration.

Bedrock P wave velocity generally exhibits a high over the complex, except where the greenstone supracrustal rocks occur on line 10GA-YU2 (Figure 3). There is also a good correspondence between areas of large amplitude magnetic anomalies and the extent of the complex on the seismic sections, particularly on line 01GA-YU3 (Figure 4).

Seismic imaging shows the internal structure of the intrusion is very complicated, which may explain why there is not always a good match with the previously interpreted geology. A significant magmatic discordant zone (the Shephard's Discordant Zone) is characterised by ~3 km stratigraphic offset (Ivanic *et al*., 2010). On line 10GA-YU3 (Figure 4), this location corresponds with a prominent dipping reflector. However, farther west (beneath CDP 10000), there appears to be a major disruption of reflectors with at least 2 km offset. This may correspond to a later episode of high angle reverse faulting.

Clearly more interpretation of the Windimurra Igneous Complex is needed in light of the seismic results. Further work will also include integration with other geophysical data, for example the coincident magnetotelluric data, as well as gravity inversion, and modelling the seismic response of the ultramafic stratigraphy.

CONCLUSIONS

A deep seismic reflection survey carried out in the Meso-Neoarchean Youanmi Terrane of the Yilgarn Craton has revealed the internal structure and depth extent of the Windimurra Igneous Complex, the largest exposed mafic-ultramafic intrusion in Australia. Gross structure on the seismic sections is consistent with gravity and magnetic data. An inward dipping conical structure is consistent with surface geological observations, but the seismic may prompt a re-evaluation of some of the previously interpreted geology. The base of the complex at depths of up to 7 km is characterised by distinctive high amplitude multi-layered reflectors, which may represent a significant thickness of Cr-PGE prospective ultra-mafic rocks unexposed at the surface.

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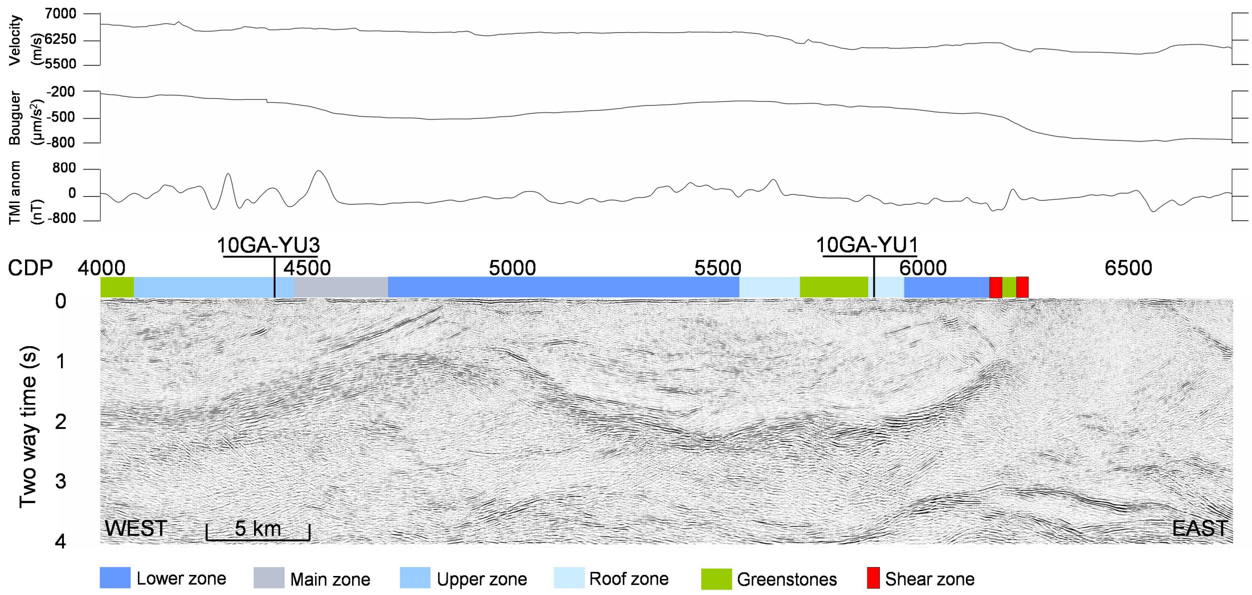

Figure 3. Migrated seismic section for the part of line 10GA-YU2 over the Windimurra Igneous Complex. V/H ~ 1 for a velocity of 6000 m/s. Profiles across the top are Total Magnetic Intensity (TMI) Anomaly taken from the grid used to make the Magnetic Anomaly Map of Australia (Milligan *et al*., 2010), spherical cap Bouguer Anomaly from measurements every 400 m along the line (cubic spline interpolation), and P wave refractor velocity corresponding to bedrock. Interpreted geology simplified after Ivanic *et al*. (2010). Note that viewing at 500% in the electronic version of this abstract will show much greater detail.

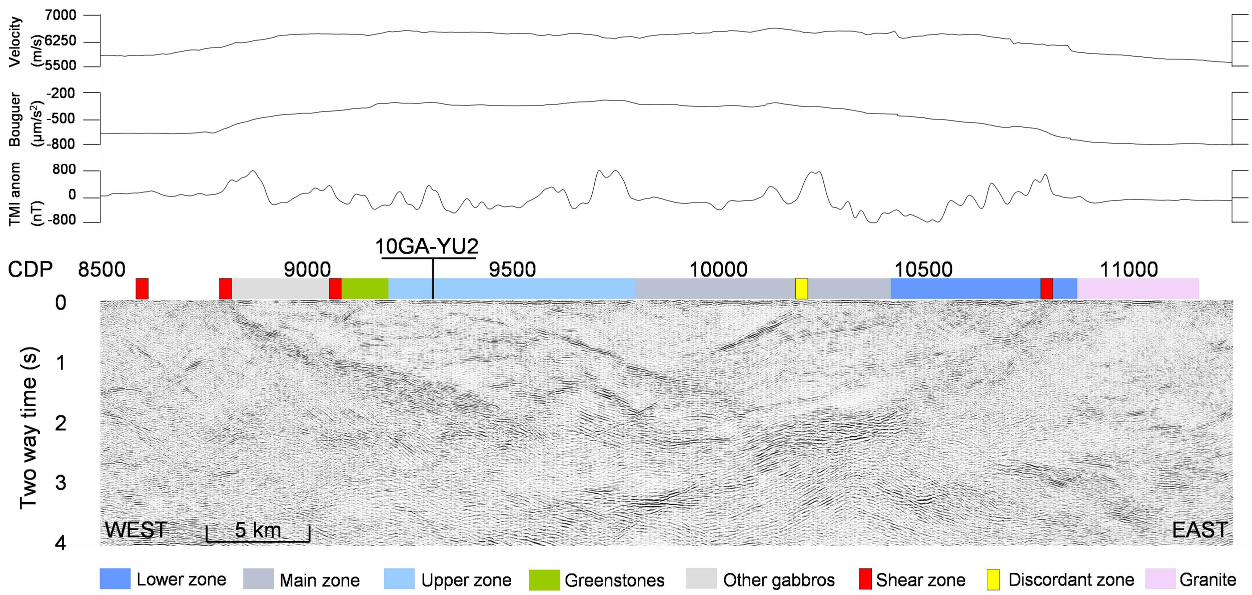

Figure 4. Migrated seismic section for the part of line 10GA-YU3 over the Windimurra Igneous Complex. V/H ~ 1 for a velocity of 6000 m/s. Profiles across the top are Total Magnetic Intensity (TMI) Anomaly taken from the grid used to make the Magnetic Anomaly Map of Australia (Milligan *et al*., 2010), spherical cap Bouguer Anomaly from measurements every 400 m along the line (cubic spline interpolation), and P wave refractor velocity corresponding to bedrock. Interpreted geology simplified after Ivanic *et al*. (2010). Note that viewing at 500% in the electronic version of this abstract will show much greater detail.