ASEG-PESA 2013
'THE EUREKA MOMENT'
11-14 AUGUST 2013 • MELBOURNE, AUSTRALIA

Depth to basement and seismic velocity structure from passive seismic soundings in central Australia

Nicholas R. A. Smith
OZ Minerals Ltd.,
University of Tasmania
Melbourne, Australia
nick.smith@ozminerals.com

Anya M. Reading
University of Tasmania / CODES
Hobart, Australia
anya.reading@utas.edu.au

Michael W. Asten
Monash University
Melbourne, Australia
michael.asten@monash.edu

Charles W. Funk
OZ Minerals Ltd.
Melbourne, Australia
charles.funk@ozminerals.com

SUMMARY

We constrain the depth and seismic structure of stiff sediment cover overlying a prospective basement terrane using a passive seismic technique which uses surface wave energy from microtremor (also known as ambient seismic energy or seismic noise). This may be applied to mineral exploration under cover to decrease the inherent ambiguity in modelling potential field data for exploration targeting.

Data from arrays of portable broadband seismometers are used to produce vertical profiles of seismic velocity structure using Both the Multimode Spatially Averaged Coherency (MMSPAC) method which measures the azimuthal average of the coherency between sensor pairs with a common separation, and the Horizontal to Vertical Spectral Ratio (HVSR) method, to estimate the seismic velocity structure and cover thickness respectively.

We have developed field protocols to ensure consistent acquisition of high quality data in a variety of ground conditions. A wavefield approaching the theoretical ideal for MMSPAC processing is created by combining the energy content of an off-road vehicle, driven around the seismometer array, and ambient sources. We find that this combination results in significantly higher quality MMSPAC waveforms in comparison to that obtained using ambient energy alone. Under ideal conditions a theoretical maximum depth of investigation of 600m can be achieved with a hexagonal sensor array with 50m radius and both MMSPAC and HVSR, although the maximum thickness of sedimentary cover in the study area limits the depth of investigation to approximately 180m. The modelling procedure we employ is sensitive to layer thicknesses of ± 5 %.

Key words: microseismic, arrays, noise, shear wave (S-wave, sediment cover

INTRODUCTION

The Exploration Challenge

Mineral exploration for targets under cover often takes place across prospective terrane covered by vast, shallow sedimentary basins. Local scale internal variation and changes in the total depth of the sediment cover cause ambiguity in models produced from the inversion of magnetic and gravity data. This can lead to exploration targets being missed or the creation of false target anomalies so it is therefore necessary to constrain such structure to optimise subsequent 3D geophysical potential field modelling. A wide range of approaches are currently in use to constrain cover sequence structure and depth include basement surface interpolation between drill holes, conductivity structure mapping using electrical techniques, processing of potential field data for depth to source estimation, and reflection and refraction seismic surveying. Sometimes these methods are successful, but for the inland Australian exploration scenario addressed in this study the properties of the sediment cover, the remoteness of the exploration area, the expense and logistical effort required, and the exploration budget can limit their usefulness.

Depth to Basement using Passive Seismic

Passive seismic approaches are an attractive option, capable of determination of sediment structure and depth to basement at a resolution which produces information appropriate to subsequent 3D potential field modelling. An example is the microtremor technique, which produces 'soundings' of shear wave velocity structure from the energy in ambient signals, also called 'seismic noise' or 'microtremor wavefield'. It is well suited to a mineral exploration context as it is cost-effective, has a relatively low environmental impact and the data collection can be managed by a two-person field team in a single tray-back off-road vehicle. The microtremor technique (in common with other methods using seismic noise, or ambient energy) is based on processing signals from a diffuse field to provide an estimation of the Green's function between a pair of sensors which is often dominated by fundamental-mode Rayleigh waves (Lobkis and Weaver, 2001). We apply the MMSPAC and HVSR methods to determine depth to basement and the seismic velocity structure of sediment cover in a location approximately 20 km north-west of the Prominent Hill Cu-Au mine in central Australia (Figure 1). The use of the MMSPAC method in a mineral exploration context is a novel application which progresses from its established use for engineering studies which commonly investigate relatively low velocity sediment in "high noise" urban and coastal environments. In the mineral exploration context of remote inland Australia the thickness of sediment cover commonly exceeds 500 m and has relatively high seismic velocity. The ambient microtremor wavefield of the sparsely populated central Australia region contains less useful energy than for urban study locations. This is a challenging application of the method both in terms of the available signals and in the difficulty of modelling seismic velocity contrasts within faster sediments than are encountered in engineering studies.

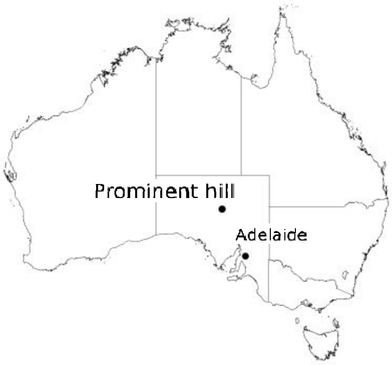
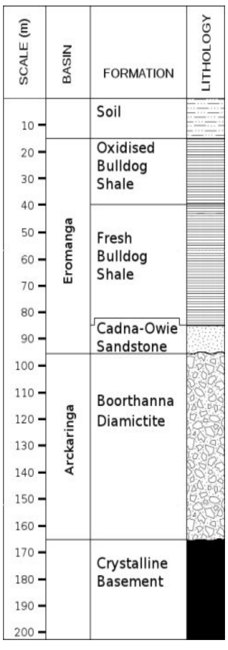


Figure 1. The field area for this study is located close to the Prominent Hill mine in central Australia which is approximately 650 km north west of Adelaide.

Overview of Sediment Cover Geology

The sediment cover in the study area comprises glacial sediment of the permo-carboniferous Arckaringa basin and marine sand and shale of the early cretaceous Eromanga basins (Figure 2). The cross-sectional outcrop view provided by open pit mining activities at Prominent Hill, and drilling results, show that the Arckaringa basin sediments are extremely variable in both lithology and density, therefore for the purpose of this study we consider them to be "basement" in the modelling procedure. Drilling results indicate a total sediment thickness at the Prominent Hill mine of approximately 120 m. To the north and west of the Prominent Hill mine the thickness of cover decreases moving north, with basement outcropping north of the study area. To the south and east of the Prominent Hill mine, sediment thickness increases at a variable rate to a depth exceeding 600 m.



Stratigraphic Unit	Dry V_P (ms^{-1})	V_S Range (ms^{-1})
Oxidised Bulldog Shale	-	**< 517**
Fresh Bulldog Shale	1292.6	**517 – 760**
Cadna-Owie Sandstone	877.3	**350 – 516**
Boorthanna Diamictite	2671	**1068 - 1571**

Figure 2. Generalised geological log of the sediment cover stratigraphy at the Prominent Hill mine and petrophysical properties (Vp and Vs) for each formation.

We use the measured compressional-wave velocities (Vp) for each stratigraphic unit of the sediment cover to infer the shear wave velocities (Vs) using Vp/Vs ratios from preliminary modelling and previous studies to construct a generalised seismic velocity model of the sediment cover in the study area which we then use as an initial model in the modelling procedure.

This area provides an undercover exploration study area with a cover sequence characterised by challenging seismic velocity contrasts and spatial variability. It provides an excellent opportunity to demonstrate the success and limitations of microtremor seismic methods in providing constraints on the internal structure of the sediment cover and depth to basement.

METHOD AND RESULTS

Overview of the MMSPAC and HVSR methods

The MMSPAC method is a development of the Spatial Autocorrelation (SPAC) method pioneered by Aki (1957), and refined by Okada (2003). Data is acquired with a hexagonal array of broadband seismometers consisting of seven seismometers with six placed evenly around the circumference of a circle with 50 m radius and one placed in the centre. Assuming a horizontally stratified cover geology and plane-wave surface wave propagation, the azimuthal average of the coherency between sensor pairs, *C(f)*, sharing a common separation, *r*, can be expressed as

$$C(f) = J_0(rk) = J_0\left(\frac{2\pi f r}{V(f)}\right), \quad (1)$$

where J_0 is the Bessel function of the first kind and zero order, k is the scalar wavenumber, f is the frequency and $V(f)$ is the Rayleigh wave phase velocity dispersion function for a 1D layered earth model.

The observed HVSR is calculated using records of ground motion from a three-component sensor in the centre of the array. The time series records for each component are transformed to the frequency domain using a discreet Fourier transform and the amplitude spectrum for the vertical component is then divided from the magnitude of the horizontal component amplitude spectra horizontal component to yield the observed HVSR:

$$HVSR(f) = \frac{\overline{S_H(f)}}{\overline{S_V(f)}}, \quad (2)$$

where the horizontal bar indicates spectral smoothing, $S(f)$ indicates the magnitude of the Fourier amplitude spectra and the subscripts H and V indicates the horizontal and vertical components respectively.

Field Procedures

The field procedures for array deployment and data acquisition are a major result of this study. The field work requires only a two person field crew and a single tray-backed off-road vehicle. We use the field vehicle for equipment transport, as well as creating azimuthally distributed surface wave energy by driving it around the array. In doing this we are able to efficiently acquire consistently high quality data with a 30 minute recording time.

We find that the seismic energy produced by driving the field vehicle around the array boosts the spectral amplitude of ground motion by about an order of magnitude (Figure 3). The comparison of observed coherency spectra for periods when the field vehicle was not in use with periods when it was clearly shows that the use of a field vehicle to generated enhanced microtremor results in an observed coherency spectrum which more closely resembles the shape of a Bessel function (Figure 4).

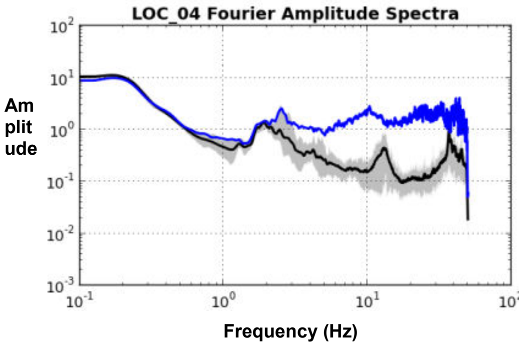


Figure 3. Amplitude spectra plots for location 4 showing the average spectra for time intervals of 30 minutes: black line = ambient-only; blue line = ambient + off-road vehicle; pale grey shading = total variation of ambient-only energy during recording period.

To validate the assumption of plane-wave energy propagation while using the field vehicle the field vehicle an energy source a minimum separation from the closest sensor on the array circumference of 3 times the array radius is maintained. We find that for an array with 50 m radius, several circles around the array by the field vehicle for a total driving time of approximately 30 minutes is sufficient for significantly increase the data quality. We interpret that the improved observed coherency waveform quality is indicative of both a higher proportion of surface wave energy for frequencies above about 5 Hz and an increased azimuthal coverage of microtremor sources.

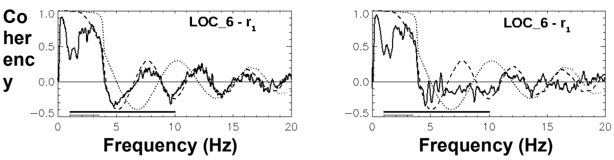


Figure 4: Observed SPAC spectra (black line) for location 6 calculated for an ambient + off-road vehicle wavefield (left) and ambient-only wavefield (right).

Forward Modelling of Seismic Velocity Structure

Estimates of the 1D shear-wave velocity structure below the centre of the array are obtained through an iterative forward modelling procedure (Asten, 2006, and references therein) whereby the modelled SPACand Rayleigh wave ellipticity spectra are fit to the observed coherency and HVSR spectra respectively, which is then iteratively modified to optimise the least squares fit between observed and model curves

A standardised modelling approach is used whereby shallow structure is modelled by fitting modelled and observed SPAC spectra at high frequency and then deeper structure is modelled by fitting modelled and observed SPAC and HVSR spectra at lower frequencies. This procedure accounts for the effect of the shallow velocity structure on the fit of modelled and observed SPAC spectra at lower frequencies. After achieving a close visual fit between modelled and observed SPAC spectra the main peak of the modelled Rayleigh wave ellipticity curve is fit to the observed HVSR spectra by adjusting the overall thickness of the model. Finally, the fit with the observed SPAC spectra is fine-tuned by adjusting layer velocities within the available petrophysical constraints (Figure 5).

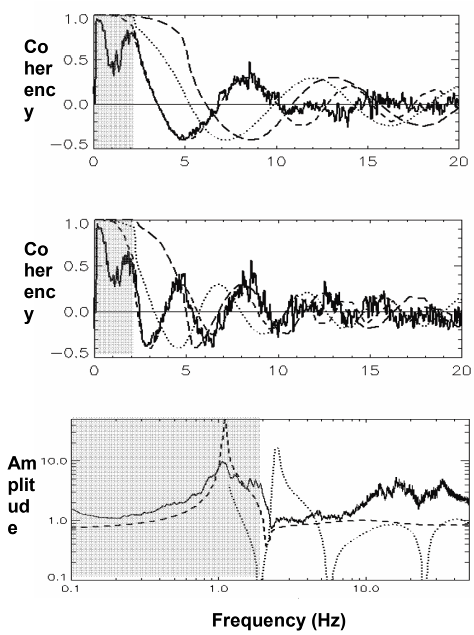


Figure 5: Images showing the fit between observed SPAC (top and middle) and HVSR spectra (bottom), and modelled curves (dashed line) for location 5. Also shown are the modelled curves the first higher mode (dotted line) and second higher mode (long dashed line) Rayleigh waves. The main observed HVSR peak add information on the total thickness of the cover sediment and is modelled at a frequency below which the observed SPAC spectra loses coherency (grey shaded area).

DISCUSSION

Previous analytical and numerical studies (Henstridge, 1979; Okada 2006) have indicated that statistically valid estimates of the SPAC coefficient from observed data can be made up to the first minimum of the SPAC spectrum, which corresponds to measures Rayleigh wave wavelengths, λ, of $2r - 15r$ where r is the sensor separation. The phase velocity of the fundamental mode Rayleigh wave is sensitive to the shear-wave velocity structure at a depth of approximately 0.25 – 0.4 λ therefore we can define the depth of investigation range for the array configuration used in this study of $\lambda_{shortest} \times 0.25 \leq \mathrm{DOI} \leq \lambda_{longest} \times 0.4$, which corresponds to a depth range of 25 – 600 m. We find that the site specific sediment cover thickness to be the limiting factor determining the realised depth penetration, and more specifically the occurrence of a large velocity contrast (a factor of 3 or more). Velocity contrasts of this nature do exist in the study area, and represent the unconformity between the Eromanga and Arckaringa basins, and the cover – basement unconformity. These velocity contrasts produce a major peak in the observed HVSR at a frequency indicative of the depth which we model in terms of the Rayleigh wave ellipticity which is sensitive to both the seismic velocity structure and total thickness of the cover sediment. The HVSR peak represents the degeneration of Rayleigh wave particle motion to the horizontal plane and because we calculate the observed SPAC spectrum using vertical component records only, results in a loss in coherency at and below the frequency on which the HVSR peak is centred. We find that the combined modelling of observed HVSR and SPAC provide velocity and thickness constraints on the cover sediment at different depths, and is extremely useful when multiple major velocity contrasts exist in the sediment cover (e.g. Smith *et al*., submitted).

The modelling procedure and results discussed in this paper represent a greenfields exploration scenario with some additional geological information. The additional geological information in this case are the petrophysical measurements which came from an open-file South Australian government geological database and an OZ Minerals seismic reflection scoping study. The use of some prior information represents the most likely case in a mineral exploration context where the generalised architecture of the sediment is known and some petrophysical data for the cover sequence are available. Using these constraints we have modelled the seismic velocity structure and depth to basement, with a sensitivity to layer thickness of ± 5%, along a transect approximately 12 km in length (Figure 6). Drill holes located along the transect are used to confirm the modelling results and show a close correspondence with the modelled seismic velocity structure. The drilling results also indicate that a velocity inversion, corresponding to the Cadna-Owie sandstone, exists at intermediate depth, which we consistently detect.

CONCLUSIONS

We have applied the MMSPAC and HVSR seismic methods in a challenging and previously untested context: the investigation of stiff, consolidated sedimentary cover, in a remote environment. We find that:

- Data which result in high-quality processed waveforms can be acquired, according to our tested field protocols, in about 30 minutes recording time. Ambient microtremor is enhanced by driving an off-road vehicle around the sensor array at a distance of at least 3 times the array radius from closest point on the array's circumference;
- Using a 7-point hexagonal sensor array with 50 m radius a theoretical depth of investigation of between 25 and 600 m can be achieved with a practical sensitivity to layer thickness approaching ± 5%. We illustrate the success of the method by estimating structure along a demonstration transect with drill-hole results for comparison;
- The presence of a velocity contrast with factor > 3 will limit the maximum depth of investigation to the depth of this interface, if the MMSPAC method is used alone;

This demonstration study illustrates the practical possibility of using a passive seismic approach, with an artificially enhanced microtremor (ambient, seismic noise) wavefield, to constrain sedimentary structure and depth to basement for mineral exploration.

REFERENCES

Aki, K., 1957, Space and time spectra of stationary stochastic waves, with special reference to microtremors: Bulletin of the Earthquake Research Institute, Tokyo University, 35, 415-456.

Asten, M. W., 2006, On bias and noise in passive seismic data from finite circular array data processed using SPAC methods: Geophysics, 71, V153-V162.

Henstridge, J. D., 1979, A signal processing method for circular arrays: Geophysics, 44, 179-184.

Lobkis, O.I. and R.L. Weaver, 2001, On the emergence of the Green's function in the correlations of a diffuse field: Journal of the Acoustic Society of America. 110, 3011-3017.

Okada, H., 2003, The Microtremor Survey Method: Society of Exploration Geophysicists.

Okada, H., 2006, Theory of efficient array observations of microtremors with special reference to the SPAC method: Exploration Geophysics, 37, 73-73.

Smith, N. R. A., Reading, A. M., Asten, M. W. and Funk, C. W., 2013, Constraining depth to basement for mineral exploration using microtremor: A demonstration study from remote inland Australia: submitted to Geophysics

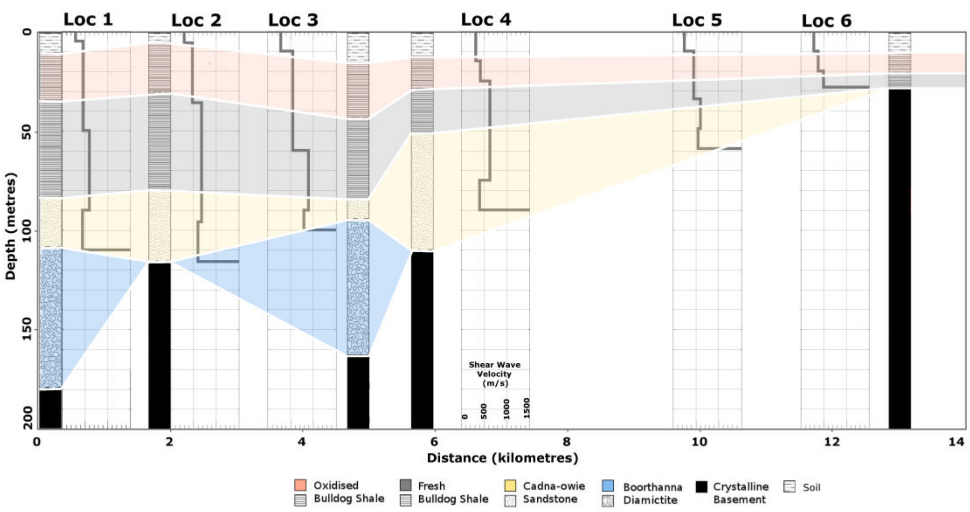


Figure 6: A 2D profile of the cover sequence stratigraphy constructed from drilling information (geological logs and colour-shaded stratigraphy) MMSPAC modelling results for locations 1 – 6 fall within the profile and show a close correspondence with the drilling information, including the imaging of the Canda-Owie sandstone velocity inversion.