Benchmarking passive seismic cover depth assessments

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SUMMARY

Passive seismic techniques utilise the properties of ambient seismic waves to infer information about the structure of the subsurface, namely the depth(s) at which significant impedance contrasts occur. Geoscience Australia has recently conducted three passive seismic surveys to assess the suitability of two passive seismic methods, the horizontal over vertical spectral ratio (HVSR) and spatial autocorrelation (SPAC) techniques, for estimating cover depth over crystalline basement. Both techniques rely on ambient seismic noise in the form of surface waves. The HVSR technique involves measurement of the horizontal and vertical components of ambient seismic noise at an individual site. Where an impedance contrast exists, a maximum is observed in the HVSR value at a frequency directly dependent on the interface depth. The SPAC technique utilises dispersion observed in surface waves, which is also dependent on interface depth. Shear wave subsurface velocity profiles are constructed through inversion of the HVSR and/or SPAC curves.

The logistically simpler HVSR method, requiring only one seismometer, was found to produce estimates with significantly lower error than estimates from SPAC for depths up to 300 m in the Murray Basin, where unconsolidated to semi-consolidated Cenozoic sediments overly Paleozoic crystalline basement. Both HVSR and SPAC methods failed to resolve the target interface with the exception of one site in the Gawler Craton, located at a depth of 900m. Further work is planned for these data with different processing techniques. The HVSR technique produced estimates consistent with other geophysical techniques (airborne electromagnetic, refraction seismic, and magnetotelluric methods) for the majority of sites in the Thomson Orogen, where the Mesozoic Eromanga Basin, Cenozoic cover, and regolith associated with both these stratigraphic groups overly crystalline basement to a depth of up to 550 m. The accuracy of these profiles will be verified with stratigraphic drilling.

Results from these three surveys provide strong support for the passive seismic technique, in particular the single station HVSR method, as a highly effective and logistically low-cost and simple tool suitable for mapping cover depth in many regions of interest across Australia.

Key words: Passive seismic, cover thickness, benchmarking, depth to basement, UNCOVER.

INTRODUCTION

Mineral exploration in Australia has moved into an era where exploration under cover is vital to the continued discovery of economic deposits. This has been recognised by the Australian Government and is being spearheaded by the Australian Academy of Science's UNCOVER initiative which draws together Australian earth scientists across government, industry, and research institutions to develop innovative techniques in undercover mineral exploration (Cairns et al., 2010; UNCOVER Group, 2012). Non-invasive geophysical techniques provide a powerful tool for initial investigation into buried geological structures including defining the cover-basement interface, a crucial parameter in greenfields exploration for defining the economics of potential deposits.

A range of geophysical techniques are well established in this initial broad-scale geological mapping phase such as gravity, magnetics, AEM, radiometrics, active source seismic, and more recently magnetotelluric methods. These have been widely applied in Australia, as illustrated by the broad coverage of these datasets. Each geophysical technique, however, has its limitations in cover thickness mapping and if there is no physical property contrast relating to the cover-basement interface, then no expression can ever be detected by geophysical techniques. To assist in developing an exploration toolkit for understanding the best approaches for cover thickness assessments, benchmarking of available techniques is required. In this paper, we will address the benchmarking of passive seismic for cover thickness assessment.

Passive seismic techniques are a recent addition to the greenfields exploration toolkit. Work by Geoscience Australia and other researchers indicates that passive seismic shows great potential for cover thicknesses up to 500–700 m in Australian terrains. Passive seismic is also an economical geophysical technique to employ, with arguably the cheapest and logistically easiest data collection of any of the non-airbourne geophysical methods (Czarnota & Gorbatov, 2015; Scheib, 2014; Smith et al., 2013). Scheib (2014) trialled HVSR in the Gunbarrel and Eucla Basins, and Yilgarn Craton of Western Australia, producing estimates consistent with drilling data for sedimentary successions down to 700 m (after drill hole calibration). Smith et al. (2013) applied the HVSR and MMSPAC (a variant of SPAC) methods to consolidated sedimentary cover in central Australia and discovered augmenting the ambient seismic field with vehicle induced seismic energy optimised results, allowing a theoretical investigation depth of 600 m with their array specifications. Czarnota & Gorboatov (2015) found the inversion of HVSR data produced the most robust estimates for interface depths from 27 to ~300 m between Murray Basin sediments and crystalline basement. The HVSR depth predictions are within 20% error for 80% of sites including successful profiling of one site with an inverted velocity profile.

This abstract summarises the results of the Stavely Project deployment (Czarnota and Gorbatov, 2015) and presents the results of two further passive seismic surveys conducted by Geoscience Australia. Both HVSR and SPAC methods were employed in the Gawler and Stavely surveys, while only the HVSR method was utilised in the Southern Thomson region. Combined, the results of these benchmarking studies provide strong support for the HVSR passive seismic technique in particular as a robust, highly efficient, and cost-effective method of estimating cover thickness in terrains of unconsolidated to consolidated sedimentary cover over crystalline basement.

DEPLOYMENT

Broadband Nanometrics Trillium compact three component seismometers from the AuScope ANSIR fleet were used for all data collection. In the Stavely Project, seismometers were deployed at ground level on a metal baseplate with spikes and protected with a weighted bucket. In the Gawler survey, experimental deployment with both methods showed burial resulted in less noise in the data so this method was employed for the Gawler and Thomson surveys where recording time was longer. Seismometers were buried at a depth of ~50cm (to allow for a protecting bucket), levelled on a square concrete paver base. The duration of deployment was predominantly a minimum of overnight, and generally several nights in the Gawler survey to account for the increased depth of investigation and low expected impedance contrast. Where possible, sites were selected to provide a solid base reducing the risk of instability and also to provide good ground coupling. Proximity to trees or objects likely to vibrate beneath the surface in windy conditions was avoided.

HVSR technique

Where HVSR was the soul technique employed, two seismometers were deployed a maximum of 20 m distance from each other to provide data redundancy. Seismometers were left to record at least overnight, except at a couple of sights due to logistical constraints.

SPAC technique

A spiral arm array configuration shown to provide comparable azimuthal coverage to a series of full circles, but with minimal stations was adopted for SPAC arrays (Kennett et al., 2015). A thirteen station array with three spiral arms was used in both the Stavely and Gawler Craton surveys. An array radius of 250 m was adopted in the Stavely survey, and due to the greater depth of investigation and low impedance contrast at the target interface in the Gawler Craton, a wider radius of 650 m was adopted to increase the dispersion between stations. Stations were positioned with a differential GPS in the Gawler and Stavely surveys and a handheld GPS in the Thomson survey.

PROCESSING AND INVERSION

Field QA/QC was performed using SeisGram2K Seismogram Viewer developed by Anthony Lomax (Lomax, 1991). Subsurface shear wave velocity profiles were constructed through both joint and separate non-linear inversion of HVSR and SPAC data. Geopsy version 2.5.0, an open-source tool for the application of a range of processing techniques for ambient noise seismic surveys, was used to invert the data (see Wathelet (2005), Wathelet et al. (2005), and Wathelet (2008) for theory and development). In this study, we used the neighbourhood algorithm (Sambridge, 1999), as implemented in Geospy by Wathelet (2005) and refined subsequently by Wathelet (2008).

Processing of the three component data for HVSR was performed according to recommendations in the SESAME HVSR User Guidelines (SESAME European research project, 2004). Processing of the data involved pre-processing through subtraction of mean amplitude, tapering, and application of a 0.1–30 Hz Butterworth bandpass filter, followed by frequency dependent windowing with anti-triggering to remove transient noise. It should be noted, however, that generating the optimum HVSR curve with minimum uncertainty is an iterative process, with features of the curve informing adjustment of parameters. Only the vertical component is normally used for SPAC processing. For a detailed review of the theory and processing workflow for SPAC, interested readers are directed to Bettig et al. (2001). For the SPAC method, all possible station pair combinations are generated and binned by inter-station distance ranges. Ranges were set to include at least 8 station pairs in order to ensure good azimuthal coverage.

Model parameters set before inversion are the number of layers and the range within which the properties of that layer can vary. The relevant properties are shear wave velocity, compressional wave velocity, density, and Poisson's ratio. In addition, the dependency relationships between parameters are set. Shear wave velocity was allowed to vary between 100–3500 m/s, compressional wave velocity between 200–6000 m/s, Poisson's ratio between 0.2–0.5, and density was kept constant at 2000 kg/m^3. We used constant density as we discovered that the inversion algorithm did not converge on an adequate solution when density was allowed to vary. All parameters were linked to shear wave velocity as the independent variable. The number of initial layers was guided by the number of peaks in the HVSR spectra, but generally more layers were required to achieve best fit.

RESULTS

Stavely Project

HVSR inversion produced estimates within 20% error of actual depths, as defined by drilling, for eight out of ten sites. Of the two remaining sites, site 04 exhibited a highly weathered basement profile, with HVSR correctly identifying the depth to unweathered basement where the increase in density occurs (from ~1.8 g/cm^3 to ~2.5 g/cm^3). Site 07 (the shallowest, 27 m) displayed highly variable HVSR profiles, which could be attributed to a variable basement depth, or simply unreliable data due to factors such as high levels of transient noise resulting in poor estimates. SPAC estimates were less accurate, with 8/10 sites being within 30% of drilled depths. However, some sites show clear overtones, indicating multimodal inversion would be more suitable and this may yield more accurate results in the future. Joint inversion produced the most reliable results where inversion was successful, with 4/7 sites being within 15% and 6/7 being within 30% of drilled depths, however for three sites the solutions were non-convergent. As an example results from site 6 are shown in Figures 1 and 2.

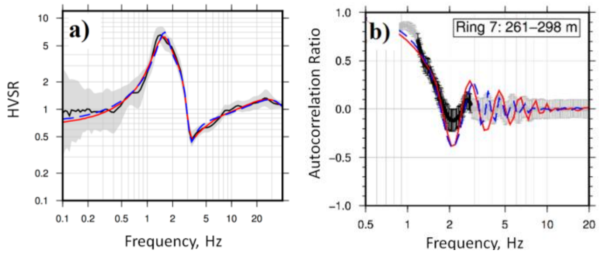

Figure 1: HVSR and SPAC data for site 6. (a) HVSR as a function of frequency where black line = mean HVSR; grey band = one standard deviation; solid red and dashed blue lines = fit to HVSR for minimum misfit HVSR and joint HVSR/SPAC inversions, following Wathelet (2008).
(b) Example of a spatial autocorrelation curve, constructed from station pairs located within a ring with minimum and maximum radius shown, black line = selected fundamental mode autocorrelation ratios, grey band = excluded autocorrelation ratios, solid red and dashed blue lines as for (a).

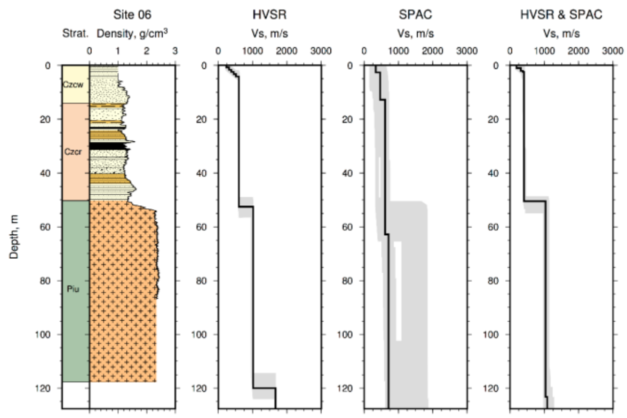

Figure 2: Shear wave velocity profiles constructed from inversion of HVSR, SPAC, and joint HVSR and SPAC data for Site 6. Columns, left to right: abbreviations of stratigraphic groups colored by age, lithology and wire line density log; Vs-depth profiles resulting from inversion of HVSR, SPAC, and combined HVSR/SPAC respectively. Black line = best fit χ2 solution; grey band = solutions within 10% of the minimum χ2 solution.

Gawler Craton

SPAC and HVSR data was collected for five sites. Evidence of the target interface has so far been observed in only one HVSR profile, site SAR8, where a low amplitude peak occurs at ~0.2 Hz. SAR8 was located directly above an old exploration hole, allowing validation of the modelling results. The model produced with inversion predicts an interface at 1094m, 21% deeper than the drilled depth; a remarkable result for this depth. Shear wave velocity from drill core is not available, but the drilling report provides a density log, sampled every 10 m. A small jump in density occurs at the target interface, between the Gawler Range Volcanics and Torrens Uplift Zone basement comprised of a sedimentary breccia. The 200 m above the interface has an average density of 2.67 g/cm^3, while the 200 m below has an average density of 2.88 g/cm^3. The ratio over the interface is hence 1.07, considerably lower than values encountered in the Stavely. For example Stavely site 01 has a density ratio of 1.4 over the target interface. Most perplexing is the absence of the 0.2 Hz peak in a repeat deployment at site SAR8. This could potentially be attributed to differences in the ambient seismic noise field, but further investigation is required to resolve this discrepancy. The SPAC analysis was not deemed reliable as the expected bezel shape of the SPAC curve was not observed. Further work is currently being conducted on the SPAC data, as techniques utilising group velocity have not yet been exploited. Figures 3 and 4 illustrate the difference between the two result sets obtained at site SAR8. Test 2 is typical of the other sites in the Gawler survey.

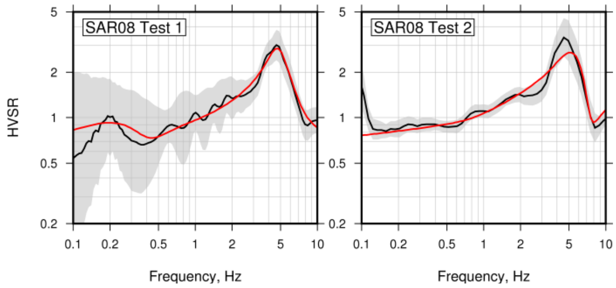

Figure 3: HVSR as a function of frequency for tests 1 and 2 at site SAR8. Black line = mean HVSR; grey band = one standard deviation; solid red = fit to HVSR for minimum misfit HVSR inversion, following Wathelet (2008).

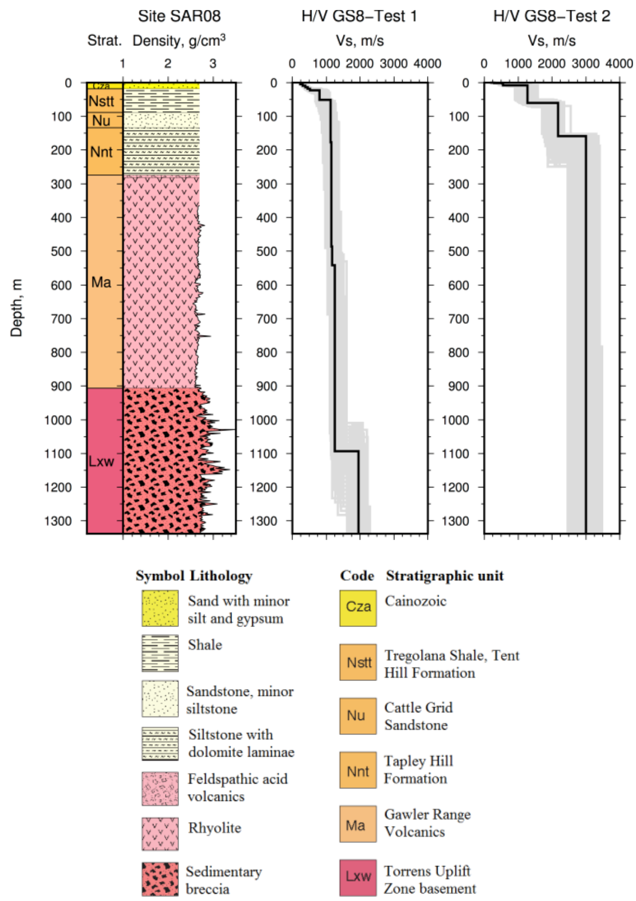

Figure 4: Comparison of shear wave velocity profiles constructed from inversion of HVSR test 1 and test 2 data at site SAR8 with stratigraphic drill log data. Left column, left to right: abbreviations of stratigraphic groups colored by age, lithology and wire line density log. Central and right columns

show Vs with depth resulting from inversion of HVSR test 1 and test 2 data respectively; black line = best fit χ2 solution; grey band = solutions within 10% of the minimum χ2 solution.

Southern Thomson

In the Thomson Project HVSR spectra show highest amplitude peaks at approximately the expected frequency given priory estimates of cover-thickness at 14/16 sites. Failure at the remaining two sites was caused by instrument failure. Refraction seismic, magnetotelluric, and aerial magnetic data were also acquired at each site in the Thomson Project. The predicted depth to the interface with highest impedance contrast (assumed to be depth to basement) from passive seismic data is in reasonable agreement with at least one of these other geophysical methods for eleven of fourteen sites (values predicted by each method are within 25% of each other, and for four sites within 10%). Planned stratigraphic drilling will reveal which techniques were most suitable at each site. Figure 5 shows an example of results from a site near the NSW-Queensland border. This site has the deepest predicted basement with good agreement between passive seismic, audio magnetotellurics, and magnetic modelling (517 m, 480 m, and 497 m respectively). The only site with any existing stratigraphic drill core constraint is site 10, 4 km from an old stratigraphic hole. The hole intersected the Hooray Sandstone, a Great Artesian Basin aquifer at 123 m, 12% deeper than the predicted passive seismic depth of 110 m.

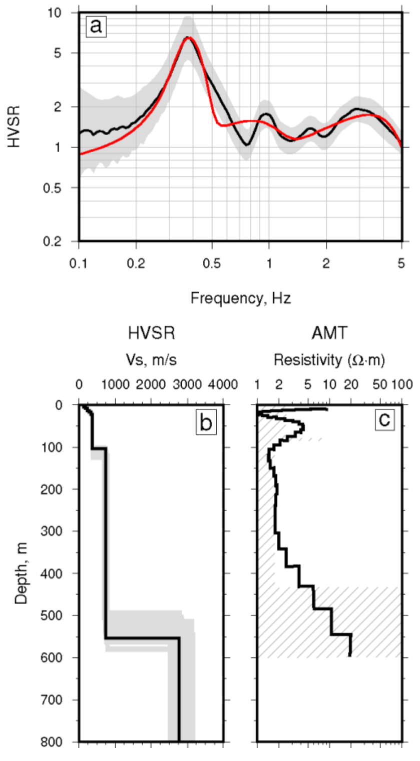

Figure 5: (a) Thomson site HVSR as a function of frequency. Black line = mean HVSR; grey band = one standard deviation; solid red = fit to HVSR for minimum misfit HVSR inversion, following Wathelet (2008).(b) Shear wave velocity-depth profile constructed from inversion of HVSR. Black line = best fit χ2 solution; grey band = solutions within 10% of the minimum χ2 solution. (c) Resistivity-depth profile from coincident modelling of audio magnetotelluric data (pers. comm. Jingming Duan). The predicted depths of interfaces from audio magnetotellurics are ~80 m and ~490 m, in good agreement with passive seismic modelling. Black line = resistivity profile, grey hashed = stratigraphic model approximation.

Synthesis

The HVSR passive seismic technique successfully predicted depth to basement, or depth to shear wave velocity contrast, in the Stavely Project for 90% of sites. The method also shows great promise for the Southern Thomson-Eromanga Basin region where results are generally in good agreement with predictions from other geophysical methods. Particularly encouraging is the performance and agreement of passive seismic and audio magnetotelluric methods at the two deepest sites. HVSR was only successful at one of five sites in the Gawler Craton, and this result was not replicated on a second trial using a larger array. This could be due to ambient seismic noise conditions, but based on the results of this survey the impedance contrast would appear to be insufficient for reliable passive seismic estimates. The SPAC method produced results with greater error in the Stavely project but there are clearly overtones in the SPAC curves and a multi-modal approach to inversion may prove the SPAC approach to be equally capable. Similarly, SPAC data from the Gawler survey has not been fully exploited and conclusions about the performance of SPAC relative to HVSR cannot be drawn. Figure 6 illustrates the performance of HVSR, SPAC, and joint HVSR/SPAC inversions relative to drilled depths in the Stavely project, clearly showing the superior performance of HVSR with the current extent of processing and modelling. Further comparison in this vein, with further processing of the SPAC data, is necessary to properly compare the two methods.

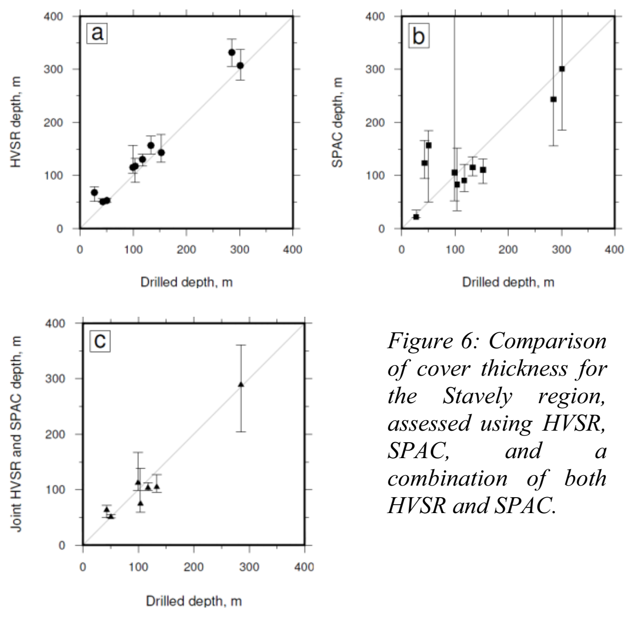

Figure 6: Comparison of cover thickness for the Stavely region, assessed using HVSR, SPAC, and a combination of both HVSR and SPAC.

CONCLUSIONS

The results of the Stavely, Gawler Craton, and Thomson Orogen passive seismic surveys indicate that the HVSR method is potentially the superior method for cover thickness assessments when compared with SPAC. The lesser performance of the SPAC method in the Stavely project is surprising, but could be attributed to highly favourable conditions for the HVSR method and the need for a multi-modal approach to inversion of SPAC data. Considering the similarity of vast areas of the Australian continent to the geological settings of the Stavely and Thomson surveys, this is a very encouraging result and provides confidence in the technique for future undercover exploration. The use of non-linear inversion as opposed to forward modelling is unique to the majority of passive seismic work conducted in Australia to date. The ability of this method to extensively sample the model space and produce estimates of uncertainty on our depth of cover assessments place it as arguably a superior method of modelling.

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