Fleet's real-time ambient noise tomography service trialled at Northern Star's Kalgoorlie Operations

Gerrit Olivier — *Fleet Space Technologies* — Gerrit.Olivier@fleet.space
Karen Pittard — *Northern Star* — KPittard@nsrltd.com
Louis Gauthier — *Northern Star* — lgauthier@nsrltd.com
Philippe Dales — *Fleet Space Technologies* — Phil.Dales@fleet.space
Jacinta Ireland — *Northern Star* — jireland@nsrltd.com
Philip Brown — *Northern Star* — pbrown@nsrltd.com
Tim Jones — *Fleet Space Technologies* — timothy.jones@fleet.space

SUMMARY

As mineral exploration extends deeper below surface, innovative geophysical techniques are necessary. In this paper we report on one of the first real-time field trials of Fleet Space Technologies' real-time ambient seismic noise tomography service, called ExoSphere, at Northern Star's Kalgoorlie Operations. During 45 days of acquisition, 40 Geode seismic sensors were deployed to survey roughly 80 km^2 to the north and south of the Fimiston gold mine, over eleven consecutive individual surveys. Acquisition was in near real-time, to a depth of 1km below surface. Due to the abundance of geological, geophysical and geotechnical data available in the study area, the trial uniquely showcases the applicability of the method to mineral exploration. The results of the trial indicate that the method is well suited to image the sub-vertical stratigraphy in Kalgoorlie in three dimensions, especially when acquired at an appropriate resolution. The challenges of applying the method are interpreting seismic velocities, which can vary significantly for the same rock type, and the non-unique nature of the inverse problem which requires robust parametrisation. The real-time application of ambient seismic noise tomography is a new geophysical tool available to mineral exploration companies to expedite the discovery of new deposits under cover, where traditional exploration methods struggle. The Kalgoorlie case study demonstrates the tremendous potential of the method, as an alternative to the more expensive and logistically challenging active seismic equivalent.

Key words: Seismic imaging, tomography, mineral exploration, geophysics

INTRODUCTION

It is estimated that 80% of the Australian continent is covered by post-mineralisation sedimentary basins. The majority of the known mineral deposits are located within outcrop and under very shallow basin. Undercover discoveries are crucial, given demand for minerals is rising, at a time when mineral discovery worldwide is in decline. This will require innovative geophysical techniques.

Traditional geophysics, remote sensing and geochemistry have allowed explorers to rapidly scan large swaths of land at low cost. These methods are most successful in identifying deposits that are shallow or which otherwise lie beneath thin and simple cover (Okada, 2020). But inherent properties of each method limit their application below deep, or complex, cover. For example, remote sensing cannot penetrate below the Earth's surface, and geochemical signatures may be dispersed, depleted by weathering effects, or completely masked by transported cover (Kyser, 2015). Potential field methods, such as gravity and magnetics, have limited depth sensitivity (Tarantola, 2005). Accurate modelling of potential field datasets requires strong constraints, especially with respect to cover thickness. Given the consistent application of these methods through a period of discovery decline, many industry experts agree that new approaches and techniques are the best strategy for increasing exploration success (Koch et al., 2015).

For decades, active seismic reflection imaging has been the cornerstone of oil & gas exploration, for its high resolving power and depth sensitivity, compared to other geophysical techniques (e.g. Waters et al., 1981). The method has found some success in mineral exploration however high cost, considerable environmental impact and complex logistics impede its routine application in mineral exploration (Salisburyet al., 2007; Malehmir et al., 2012; Schijns, 2019).

In recent years two advances in the seismology community have addressed these challenges and led to a so-called "boom in boomless seismology" (Hand, 2014):

The first major advance is the maturation of a new method of passive seismic imaging, called ambient seismic noise tomography. Compared to conventional active seismic imaging, ambient noise tomography (ANT) refers to the use of environmental (wind, ocean, lakes) and anthropogenic sources to image the subsurface. The method relies on reconstructing estimates of the seismic Green's function between pairs of stations, by cross-correlating long time series seismic records (Bensen, 2008). This effectively turns each receiver into a virtual seismic source (Curtis, 2007). From these pair-wise seismic Green's functions, velocity measurements made from the Rayleigh surface wave arrivals are used in an inversion which outputs a 3D shear-wave velocity model. To date, most applications of this technique have been at regional and crustal scales (Shapiro, 2005; Bensen, 2008; Yang 2008). Permanent broadband seismic stations, used for earthquake monitoring, have provided public seismic data fit for this purpose.

DIRECT-TO-SATELLITE NODES AND REAL-TIME IMAGING

The application of the ANT technique at project and prospect scales has been made feasible by a major advancement in seismic instrumentation. Cheap, durable, and wireless seismic stations are now readily available and allow for large scale seismic surveys at low cost. These "nodal" seismic stations are as light as 650 g and have batteries that can last over 50 days (Dean and Sweeney, 2019). Surveys consisting of hundreds or even thousands of these temporarily deployed recording devices can now be performed at low cost and with low environmental impact (Hand, 2014). This has allowed for an impressive range of applications of ambient noise tomography at smaller scales, including mineral deposits, hydrocarbons, geothermal resources, fault zones, volcanoes, and geotechnical structures, amongst others (Hollis, 2018; Dales, 2020; Ryberg, 2022; Boué, 2019; Zhou, 2021; Mordret, 2019; Brenguier, 2016; Olivier, 2018; Wang, 2021).

Although modern nodal seismic stations have enabled the use of ambient noise tomography for a range of different applications, the sensitivity, frequency response, and sampling rates of these devices have been engineered for active seismic reflection imaging. This type of reflection survey utilises relatively strong and high frequency body waves sourced from active sources, in contrast to ambient noise tomography which uses faint, low frequency surface waves. Another drawback of blind nodal technology is the requirement to manually harvest data from sensors, meaning data cannot be viewed until survey completion. Processing time further slows the production of the final 3D model.

Fleet Space Technologies recently developed the Geode to address these limitations (Olivier et. al, 2022). The Geode is a real-time, satellite-enabled seismic node specifically designed for mineral exploration in remote settings. The three key improvements of the Geode compared to other commercially available nodes are: (1) lower frequency and higher sensitivity geophone (see Figure 1), (2) pre-processing conducted in the Geodes (edge processing) and (3) transmission of pre-processed data to the cloud in real-time, using a built-in DtS-IoT modem.

In this paper we show one of the first real-time ambient noise tomography surveys conducted using Geodes at Northern Star's KCGM operations, part of the Kalgoorlie production centre.

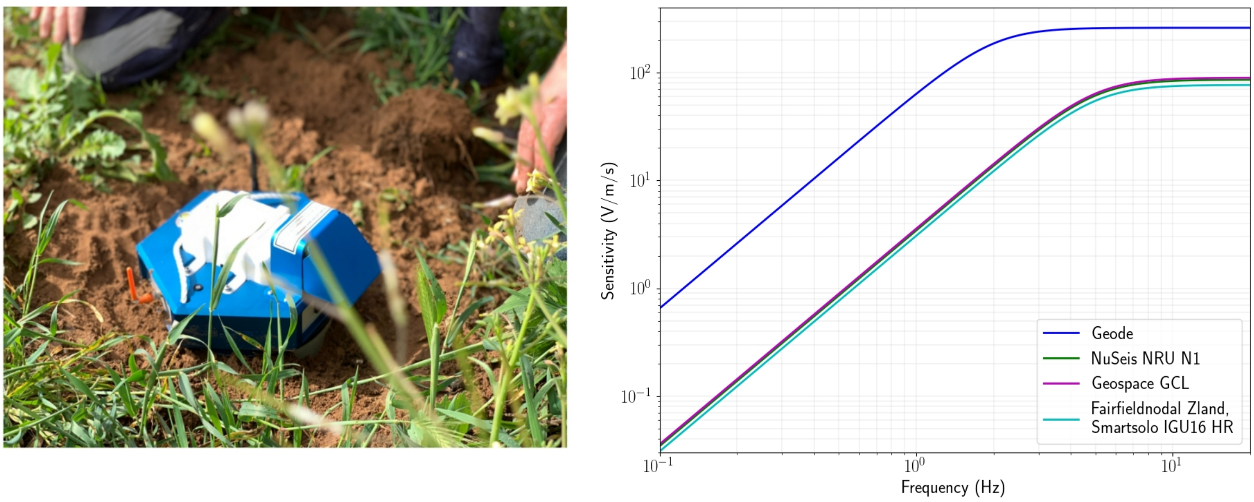

Figure 1. Picture of an installed Geode, along with the sensitivity of the Geode compared to commercially popular seismic nodes. Modified from Olivier et. al, 2022.

KALGOORLIE ANT CASE STUDY

Geology and Logistics

Kalgoorlie is one of the best endowed Archean orogenic gold camps in the world. The Boulder Lefroy fault is a first order controlling structure along the western margin of an uplifted mafic block, surrounded by volcaniclastic sediments. Along this structure, a string of orogenic gold deposits, the Golden Mile and Mt Charlotte being the largest ones, are hosted dominantly within the Golden Mile Dolerite and spatially associated with the Golden Mile Fault (Robert et al, 2005, Tripp et al., 2020). The ANT survey was completed to better document the 3D structural architecture of this major gold camp, south and north of the main gold deposits.

Between 24 October and 11 December 2022, Northern Star deployed 40 Geodes to investigate whether real-time ambient noise tomography could assist in mapping the structural architecture of the Kalgoorlie region (Figure 2). In particular, the survey aimed to map large scale structures at depth, utilising density and velocity contrasts between mafic and volcaniclastic stratigraphies.

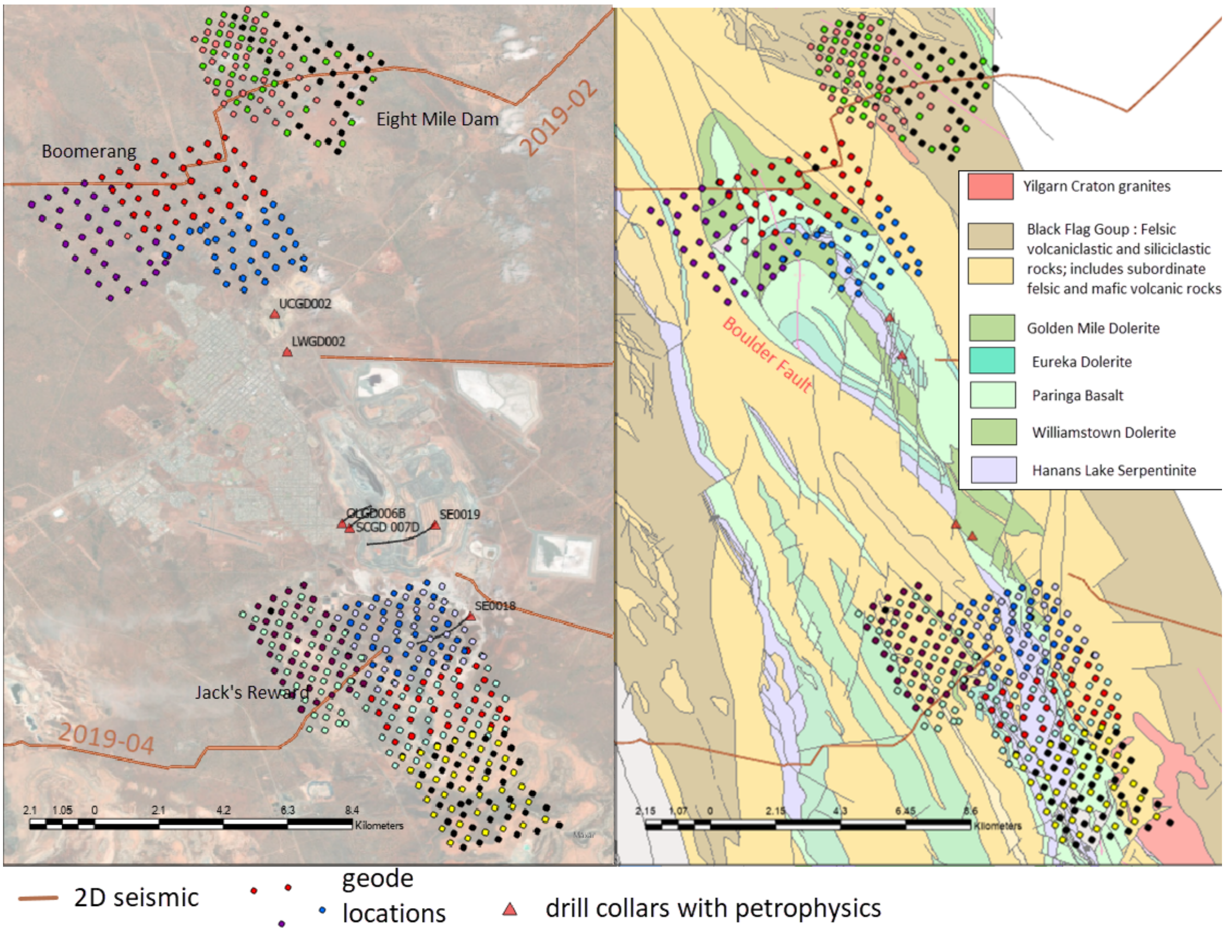

Figure 2. Geodes deployed against satellite imagery (left) and GSWA 100K solid geology interpretation (right). Geode colours map phases of deployment. The location of GSWA 2D seismic lines, and drill collars relating to petrophysical samples, are displayed for reference

The survey was planned at 500m station spacing. Early in the survey, one area was infilled to 250m spacing to assess the benefit of tighter spacing at the cost of less area surveyed. Infill and original survey data were jointly inverted and reviewed soon after acquisition, highlighting the benefits of the near real-time nature of the data acquisition. It was possible to quickly assess that the 250m infill considerably improved the lateral resolution and interpretability of the 3D model, especially at depth. The infill data increased the number of low frequency measurements significantly and reduced the model uncertainty at depth. As a result, high priority regions were infilled, including the western part of the Eight Mile Dam survey, and the Jack's Reward survey.

In total, eleven individual surveys were conducted to cover approximately 80 km^2, with an average acquisition time of roughly 3 days per survey phase. The signal-to-noise ratios of the cross-correlation functions, along with the inversion residuals, were closely monitored to determine each individual survey duration.

Petrophysics

In 2016, HiSeis acquired core measurements of specific gravity and seismic velocity from deep diamond holes SE0018 and SE0019, collar and trace locations displayed in Figure 2. Figures 3 and 4 display results from SE0018 against grouped stratigraphy, gold assays and sulphide estimates.

On average, mafic stratigraphies exhibit higher densities than the Black Flag sequences, however there is variability within stratigraphies. This variance is also seen in the p-wave velocity data. Lows (in density and/or p-wave velocity) may surround faults or areas of alteration, however Figures 3 and 4 don't contain this information.

In 2020, an EIS funded collaboration between the Geological Survey of Western Australia (GSWA) and Terra Petrophysics (Terra) involved the collection of 1976 petrophysics measurements from the Kalgoorlie Terrane across seven drillholes (Markoski et al, 2021). Five of these lie between the ANT survey blocks and their locations are displayed in Figure 2 (LWGD002, OLGD006B, SCGD007D, SE0019 and UCGD002). Out of the figure's field of view are CD16056 and PGDD15001.

Summary statistics for GSWA/Terra density, p-wave velocity and acoustic impedance are displayed in Figure 5. Data suggest that lithologies comprised of mafic and ultramafic minerals exhibit higher densities than felsic and sedimentary lithologies. P-wave velocity (Vp) data are less clear: overlapping ranges are seen across most lithologies. This overlap carries across to the acoustic impedance data, where variations are seen within stratigraphic groups rather than between them.

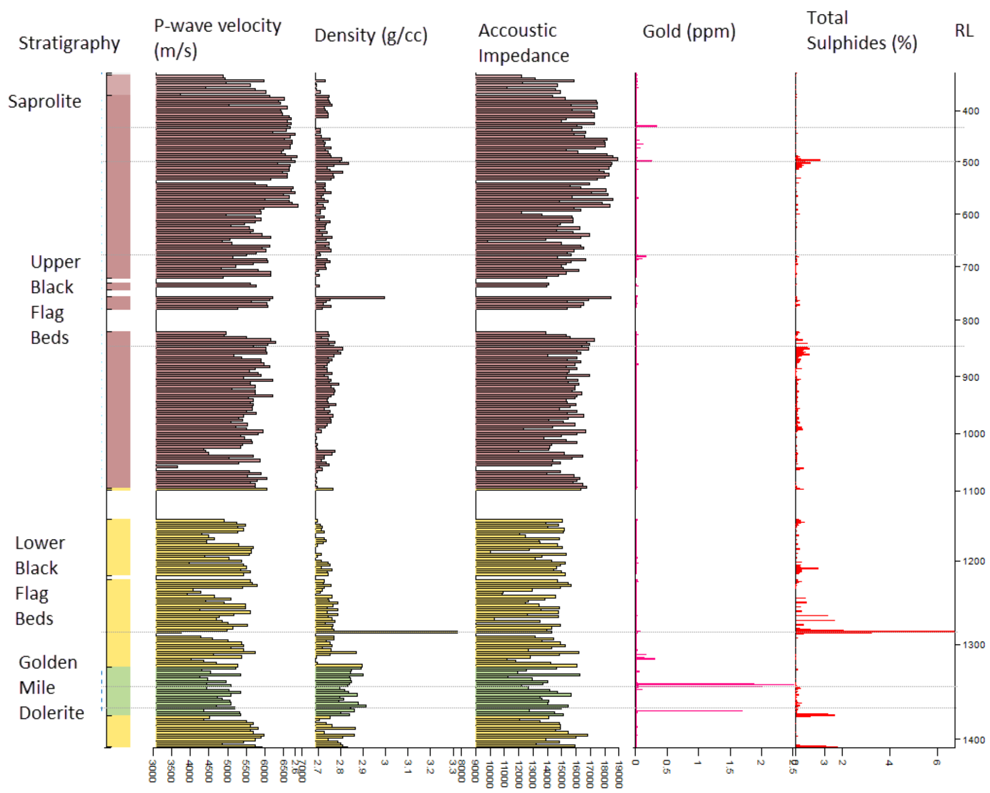

Figure 3: Petrophysical measurements made on core plotted against grouped stratigraphy, gold and sulphides, for diamond drill hole SE0018

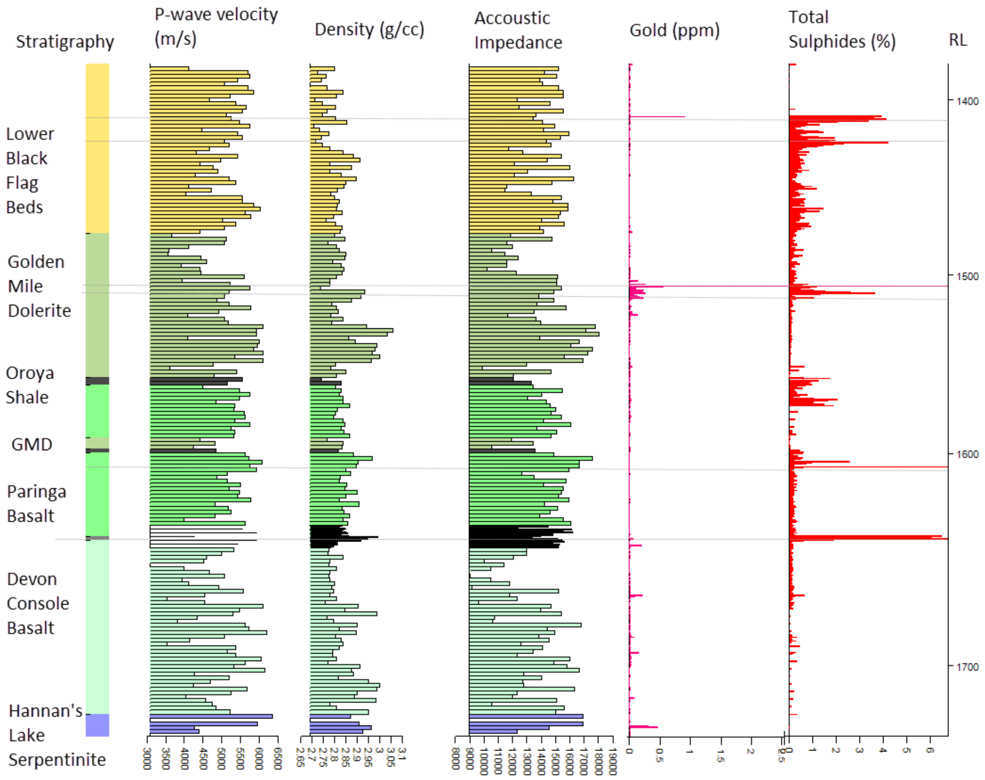

Figure 4: Petrophysical measurements made on core plotted against grouped stratigraphy, gold and sulphides, for diamond drill hole SE0018W1

The results of petrophysical analysis indicate one of the biggest challenges we face when using seismic methods: the same rock types can have vastly different seismic velocities. Although there is some overlap in measured density for different lithologies, the distributions of densities are much tighter than for seismic velocities. Seismic velocities are dependent on density and elastic moduli (Poisson's ratio and rigidity). Since there is a range of various elastic moduli for the same density (e.g. Brocher, 2005), the broader distribution of seismic velocity compared to lithology is expected.

Although there are several established empirical relationships between seismic velocity and density (e.g. the Nafe-Drake curve), some rock types fit these trends poorly due to the influence of elastic moduli. A notable example is serpentinite, which has a high Poisson's ratio, resulting in a significantly lower S-wave velocity than one would expect from its density (Brocher, 2005). Mafic and calcium-rich rocks also display this behaviour, although to a lesser extent.

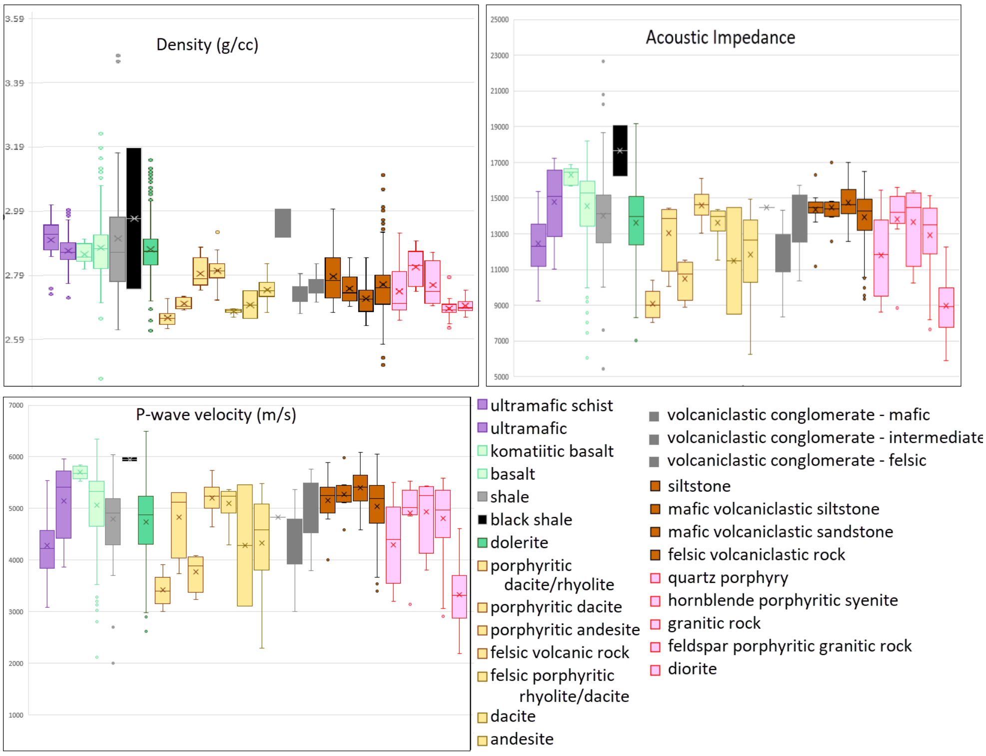

Figure 5: Density, p-wave velocity and impedance statistics of different rock types in the Kalgoorlie region, arranged roughly in chronological order (left being oldest). Colours correlate with the map displayed in Figure 2. Impedance is density (g/cc) multiplied by velocity (m/s)

Comparison with Geological model and other Geophysical Data

An advantage of the ANT trial in this region is the wealth of geological and geophysical data present. Figure 6 displays plan gravity and aeromagnetic data compared with a -400mRL depth slice of the ANT results (approximately 800 m below surface). Figure 8 displays a comparison of active 2D and passive ANT seismic data.

The depth slice indicates several structures highlighted by velocity gradients which are consistent with the potential field geophysics. A prominent feature in the north-west (Boomerang) survey area is the north-south trending low velocity feature that is consistent with the interpreted location of the Boulder fault. Within the north-east (Eight Mile Dam) survey, velocity anomalies may delineate intrusions.

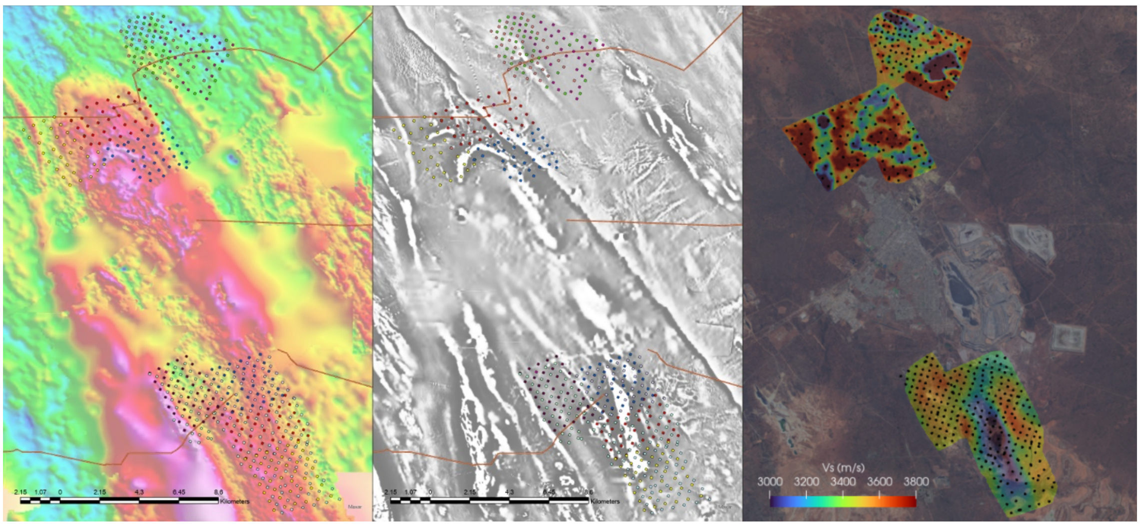

Figure 6: ANT results (right) against gravity (left: 0.5VD SCBA267 shaded from 045) and aeromagnetic (middle: RTP 1VD no sun angle) data

In Figure 7 we show a comparison between the geological model and a cross section through the Jack's Reward survey area. The most prominent feature we observe is the Hannans Lake Serpentinite, which is not surprising given the expected low velocity of serpentinite as discussed previously. We also note the Boulder and Mt Hunt faults appear consistent with horizontal gradients within the ANT model, along with the serpentinite wedge to the west of the Mt Hunt fault. The Golden Mile Dolerite and Williams Town Dolerite appear to be coincident with high velocity anomalies. The model does not appear to delineate the Devon Console Basalt well, likely due to a lack of lateral resolution.

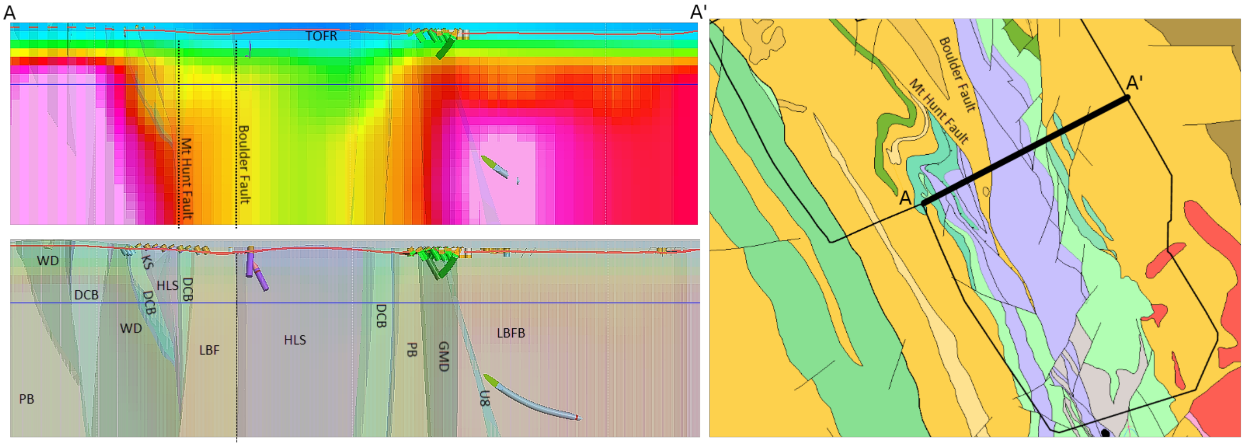

Figure 7: Cross Section through Jack's Reward survey area. Top left image shows the ANT velocity model. Bottom left shows the geological model. Right figure shows the plan view location of the slice. PB = Paringa Basalt, WD = Williams Town Dolerite, DCB = Devon Console Basalt, HLS = Hanans Lake Serpentinite, GMD = Golden Mile Dolerite, LBFB = Lower Black Flag Beds, U8 = Unit 8 within the GMD

Comparison with 2D active seismic data

The survey location also provides the opportunity to compare the results of the ANT survey with 2D active seismic lines that were commissioned by GSWA (Zibra, 2020). In Figure 8 we show the comparison for the seismic line in the southern survey area (Jack's Reward).

We see that there is relatively a good agreement in the depth of cover between the two methods, with the ANT potentially providing more information on the nature of the cover. While many reflection responses correlate between surveys, the sub-vertical stratigraphy is better imaged with ANT. The subvertical high velocity region near the middle of the section likely corresponds to the Golden Mile dolerite. We see a transition from high to low velocity either side of the Mt Hunt fault. The Mt Hunt fault is seen in the active seismic data near surface, but hard to identify and delineate at depth.

Several of the deeper reflections in the active seismic data appear to be associated with high velocity anomalies in the ANT model, most notably the east-dipping sub-horizontal reflector at 800 m depth. The geological cause for this response is not clear at this stage.

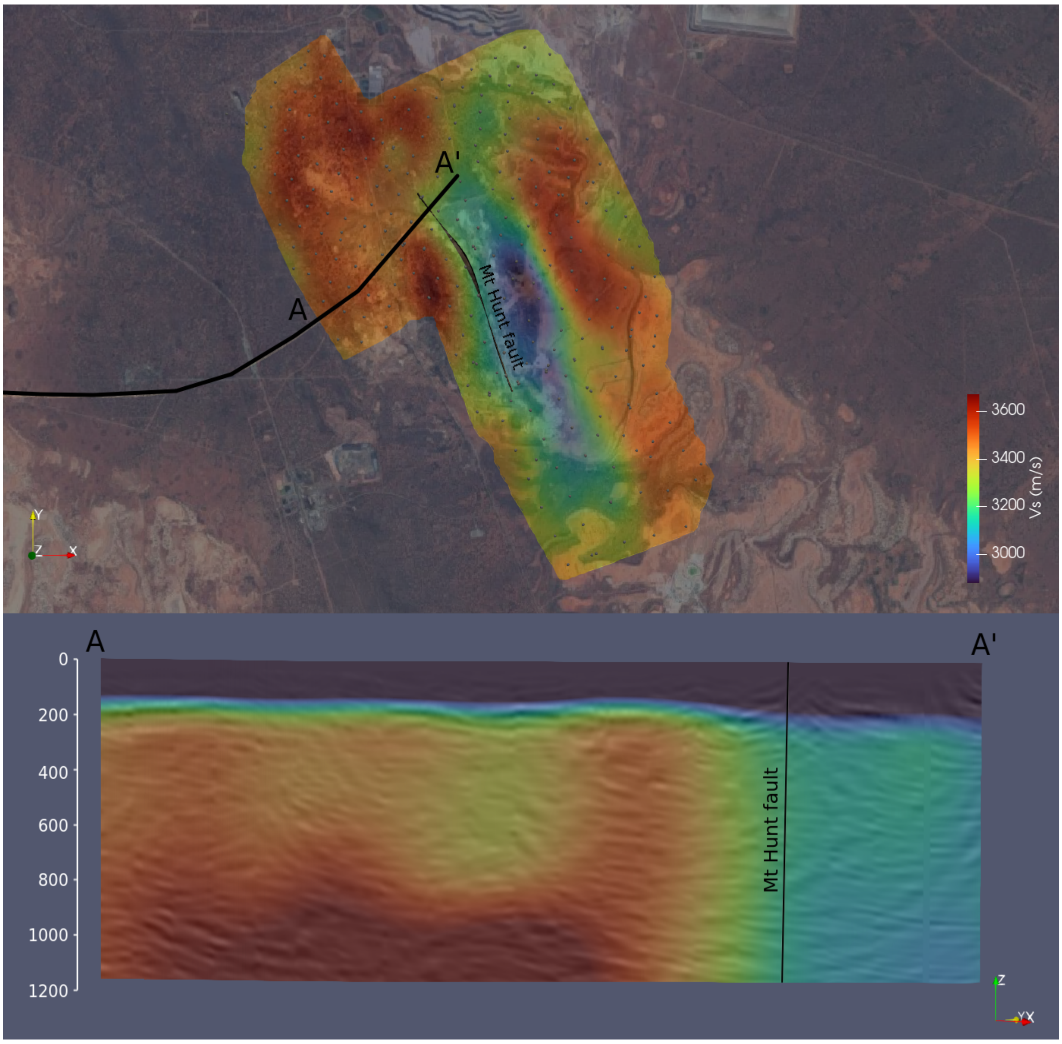

Figure 8: Comparison of the results of the ANT survey in Jack's Reward area and the 2019-04 GSWA 2D active seismic line. Top: 800m depth slice. Bottom: East-west section with the comparison of the active and ANT results.

CONCLUSIONS

In this paper we presented preliminary results of one of the first trials of Fleet Space Technologies' real-time ambient seismic noise tomography method, called ExoSphere, for Northern Star in Kalgoorlie. The real-time nature of the method enabled the quick adjustment of the station spacing to achieve the resolution required to image sub-vertical structures and stratigraphy in 3D. Short, active seismic lines find such geometry challenging, as illustrated by the direct comparison of ANT and 2D active seismic data. The main challenges of the method are the wide range of velocities for the same rock types, making interpretation non-trivial, and the non-unique nature of Rayleigh wave dispersion inversion which requires robust parametrisation for reliable results. Interpretation and refinement of the ANT data is still ongoing.

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