BCGS
BC Geophysical Society

BC Geophysical Society
Fall Symposium

November 15, 2024

“Applications in Seismic Methods for Mining Exploration and Engineering”

This event is made possible thanks to the generous support of our sponsors.

FLEET | SMARTSOLO SCIENTIFIC | caur TECHNOLOGIES | CONVOLUTIONS GEOSCIENCE | SJ GEOPHYSICS Science on Target

Passive seismic for mineral exploration

Nicholas Arndt* and Jean-Philippe Mercier

Caur Techologies and Université Grenoble Alpes

Passive seismic methods were developed mainly around the turn of the century and now play an important role in the exploration of the composition and structure of the Earth's crust. Initially employed in fundamental research and later adopted by the petroleum industry, these methods are now gaining prominence in mineral exploration. Unlike the better-known active seismic methods, passive seismic does not require an active source (e.g., explosives); instead it captures signals from ambient seismic noise generated by anthropogenic or natural sources such as traffic, ocean swells or wind in trees, or from earthquakes. When used in mineral exploration, ambient noise tomography (ANT) offers numerous advantages. It generates three-dimensional tomographic images of the subsurface at depths ranging from approximately 100 meters to several kilometres, and is cost-effective, easily deployable, and environmentally friendly.

In this talk, I will focus on how ANT models can be related to the lithology and structure of materials in the subsurface. This will include discussion of the types of targets that can successfully be imaged using the technology and how a combined geological/geophysical approach can guide mineral exploration.

District and Prospect-Scale 3D Models of Ambient Noise Tomography and Gravity Data: A Case Study on Porphyry Copper Exploration in the Macquarie Arc

Anthony Reid[1], Adebayo Ojo[1], Timothy Jones[1], Nick Smith[1], Gerrit Olivier[1], Stephen Barber[1], Darren Burrows[1]*, Doug Menzies[2]

1. Fleet Space Technologies, 2. Inflection Resources

Mineral exploration proceeds by a process of scale-reduction. Decisions need to be made at all stages as the physical search space becomes progressively reduced from regional through to district, camp and tenement/deposit scale. While there are many regional scale datasets available to explorers through public geoscience agencies, one of the most difficult steps to make is from the regional-scale down to the district- and camp-scale, particularly in areas with post-mineral cover. Three dimensional models of subsurface geology at the district- to camp-scale can provide a means to filter for areas of enhanced prospectivity, for example by looking for broad structural or lithological features that are favourable for mineralisation.

For the most part, 3D models of subsurface geology are developed by relying on inversions of potential field data coupled with other constraints such as surface mapping, drilling, electrical geophysics and, if available, reflection seismic data. Passive seismic methods are less commonly used by the exploration industry to image subsurface geology, despite the method being able to provide depth-constrained, 3D seismic velocity information that is complementary to potential field data.

As an example of the use of a district-scale passive seismic array to image the upper crust and architecture of possible mineral systems, we present a 3D velocity model derived from an ambient noise tomography (ANT) survey across an area of 1,800 km2 in the northern Macquarie Arc under >100m of Mesozoic to Cenozoic cover. The ANT velocity model extends to depths of ~5km and reveals velocity features that are ~1-1.5 km thick and are spatially correlated with granitic plutons evident in potential field data. These larger, apparently magmatic bodies may represent multi-stage granitic plutons, and could represent source zones for possible magmatic-associated hydrothermal mineralisation. The ANT model also clearly delineates the steep, westerly dip on a major shear zone that runs through the centre of the survey area.

Joint inversion of ANT and ground gravity data from a prospect scale survey from within the larger area is also presented to highlight the opposite end of the scale. Preliminary results suggest that integrating ANT and gravity surveys is highly effective, delivering significant value for prospect scale porphyry copper exploration.

Combining Passive Data from Seismic Reflection and Ambient Noise Tomography Data Sets for an Enriched Subsurface Velocity Model

Dan Hollis

Sisprobe SAS and IGPP/SIO/University of California San Diego

Both seismic reflection and ambient noise tomography methods are becoming more common exploration tools in mineral exploration. Ambient noise tomography, or ANT, is generally used early in the greenfield mineral exploration process due to its low cost per square kilometer and seismic reflection is generally used later in the exploration process before a significant core hole drilling program is begun. Both methods commonly use nodal seismometers for data collection and the resulting data sets have both common and unique data qualities. This presentation will discuss combining passive data collected from both type of surveys to provide a richer ANT image of the subsurface

Active seismic is where a controlled seismic source is used to propagate and record a known seismic signal through the subsurface in order to image the locations where the seismic signal is reflected by changes of acoustic impedance. Ambient noise surface wave tomography uses seismic vibrations generated by natural Earth processes and human activity to create virtual shot gathers and uses the dispersive nature of surface waves to image the subsurface in the form of a shear wave velocity model.

Nodal seismometers are now the norm for field crews collecting active source seismic reflection data and passive data for ANT imaging, and allow for collecting economical, high density continuous passive seismic data. The nodal arrays used for each type of survey have generally different station designs: reflection nodal arrays use a high density of one-component nodes (100 or more per square kilometer) and ANT nodal arrays use a lower density of three-component nodes (less than ~20 per square kilometer). Spatial resolution of ANT imaging is controlled by station spacing and is about one-half of station spacing. The passive data from a seismic reflection survey's smaller station spacing can be incorporated with the Love wave ANT data to create a higher resolution velocity model with more accurate velocities and a map of subsurface azimuthal anisotropy.

This presentation will give a brief overview of both seismic reflection and ANT survey designs, ANT data processing flow, points to consider when designing seismic surveys to facilitate combining passive data, the process used to combine the two passive seismic data sets, and the benefits of an enriched velocity model.

Uranium exploration with real-time ambient noise tomography

Tanya Coetzee[1]*, Bronwyn Murphy[1], Adabyo Ojo[1] and Darren Burrows[2]

1. Axiom Geophysics & Remote Sensing   2. Fleet Space Technologies

In the past year, ambient noise tomography has been applied to mineral exploration at a rate never before seen. Across multiple terranes and commodity types, this passive seismic method is increasingly being utilised as a method to image the subsurface. A revolution in computing power and instrument sensitivity coupled with real-time instrument monitoring and data quality control has meant that alteration systems are now able to be imaged in 3D and with a fidelity previously unattainable. We review these developments with reference to exploration for uranium in the Athabasca Basin where hydrothermal fluids have caused texturally destructive alteration in basin sediments and basement rocks that can be linked to uranium mineral system when coupled with other, established exploration techniques that will potentially lead to a new wave of discoveries in the region.

A revolution in instrument sensitivity coupled with real-time data quality control has meant that alteration systems are now able to be imaged by ambient noise tomography in 3D and with a fidelity previously unattainable. We review these developments with reference to exploration for uranium in the Athabasca Basin where hydrothermal fluids have caused texturally destructive alteration linked to uranium mineral systems and resulting in decreased seismic velocities. When coupled with established exploration techniques, ANT that will potentially lead to a new wave of discoveries in the region.

Innovative Seismic Monitoring in Underground Mining: Enhancing Accuracy and Hazard Mitigation through Mine Seismology

Sebastian Braganza, Erin Bailey, Dave Collins, Alexander Mataseje

ESG Solutions

Seismic monitoring is pivotal for advancing the understanding and management of seismic hazards in underground mining. This presentation presents a comprehensive approach to leveraging seismic data for both real-time hazard assessment and long-term safety protocols. We demonstrate the use of seismic systems to collect high-precision location data and source parameters, enabling the creation of detailed seismic catalogs. These catalogs are essential for mapping critical variables such as peak particle velocity (PPV) and seismic hazard distributions, which inform mine safety strategies, including data-driven re-entry protocols.

In addition, we explore the optimal design of seismic arrays tailored for underground mining environments, focusing on improving the accuracy in establishing event locations and source parameters. Factors such as sensor type, sampling frequency, sensor spacing, and array geometry are explored when modelling performance metrics related to detectability, location uncertainty, and source mechanism characterization.

Finally, we discuss a key advancement in determining more accurate event locations in complex geological settings. By incorporating detailed geological and geotechnical data, 3D velocity models provide significant improvements in the precision of seismic event localization compared to conventional 1D velocity models used prevalently across the industry today.

This presentation provides practical insights for geophysicists and industry professionals, offering strategies to optimize seismic monitoring systems, improve location accuracy, and enhance seismic hazard mitigation in underground mining operations.

The Geophysical Open Seismic Hardware (GOSH) project: opening a world of collaboration

J. Christian Dupuis*, Arnaud Mercer, Bernard Giroux, Simon Dourlet, Benjamin Girard and Rosalie Tremblay

Université Laval

As the climate warms many of our societies will need to adapt. Geophysicists are well positioned to contribute to the solutions required to adapt to consequences of high intensity meteorological events that can lead to landslides, permafrost degradation and other hazards. Unfortunately, at a time where the world may need geophysics more than ever, several university programs around the world are struggling to recruit the workforce needed to replace the current generation. One of the significant stumbling blocks for the discipline is that geophysics is largely unknown to most students when they choose a career.

The Geophysical Open Seismic Hardware project is a means to increase the visibility of geophysics by bringing seismic methods to classrooms around the world. This project originally developed a multi-channel 24-bit acquisition system and an electromagnetic vibrator to spur the development of vertical seismic profiling in non-energy fields such as ground water, geotechnical and mining applications.

The open hardware ecosystem of this project allows users to customize the design to their experiments and understand how each component works. The affordability of the system means that physics teachers around the globe can now consider adding an introduction to seismic methods in high-school physics curricula. It also means that tinkerers and university researchers can dream of new experiments where the system is adapted to the experiment and not the other way around. The system also opens the door to collaborations in countries where it can be difficult to import and export geophysical instruments.

Over time, the Geophysical Instrumentation Group at Université Laval aims to introduce more open hardware instruments to improve the visibility of geophysics in schools and colleges and help leverage the significant advances in Open Source software packages that have emerged over the last decades. Geophysicists have a role to play in climate action, we should make sure that there will be a future generation to answer the call.

Improved Hard Rock Seismic

Heather Schijns

Teck Resources Ltd.

The global trend towards undercover mineral exploration and discovery can be expected to generate a corresponding trend towards deeper open pits and more numerous underground mining operations. With this, the mining community will face higher upfront costs and increased risk associated with the characterization of orebody characterization and mine development. In these deeper geological settings, adequate de-risking is difficult to achieve from drilling alone, and the potential for seismic to add value through improved geotechnical characterization and ore body knowledge is high. In order to add this value - beyond what can be achieved with drilling - the confidence of the seismic interpretation, and therefore the resolution and quality of the seismic image, must be high. Obtaining the required standard of seismic reflection imagery in hard rock settings presents unique challenges.

Technology advances in recent years, both in terms of equipment and processing, have had significant impact on the achievable seismic reflection image quality as well as the costs associated with the acquisition of hard rock seismic data. In the last decade, the introduction of high-count nodal geophone systems has improved our ability to design surveys able to record our target signal in these settings, where the complicated geometry of orebodies and host rocks can result in complex travel paths for seismic waves through the subsurface. Corresponding improvements in seismic processing capability and computational power have simultaneously impacted our ability to process seismic data, enhancing our ability to image the subsurface in hard rock terranes.

Wiggle into your Geology

Andy Dyke and Greg Turner

HiSeis Canada Ltd.

Active seismic geophysical techniques image the subsurface and retain a resolution of tens of metres from the surface to well below economic mining depths. This contrasts with diffusive geophysical techniques (e.g.: gravity, magnetics, MT, EM and IP) where the resolution degrades with depth particularly below the top few hundred metres. This level of detail is critical to delineate the key geometries which control mineral systems and to provide a means to optimise drill targeting particularly below approximately 300 m depth.

Active Seismic images can, however, be complex and, until now, a certain level of seismic interpretation experience and specialised software has been required to extract much of the detailed information contained in the data. This has impeded the incorporation of the data into standard workflows. In turn, this has limited the potential value-add provided by the ongoing integration of the seismic data with other new datasets (particularly core logs and elemental assays) as they come to hand.

This has been addressed by developing and adapting data driven approaches to convert complex seismic data into more geological outputs that are easily brought into the standard geological software packages used by the minerals industry and more readily comprehensible by a wide range of geoscientists – not just specialist seismic interpreters.

Examples of these approaches include: Automated fault mapping; 3D solid geology models generated using Seismic inversion, Textural analysis; Regolith depth mapping.

We will present recent project examples of these approaches plus some really exciting derivatives that are currently in development.

3D seismic at Neves-Corvo

Joel Jansen[1]*, Scott Napier[2] and Vitor Araújo[3]

1. Lundin Mining 2. Mira Geoscience 3. Somincor S.A.

Discovered in 2010, a full 22 years after the previous discovery at Lombador, Semblana is the sixth of seven known deposits within the greater Neves-Corvo mining concession. Located in a mature terrain less than 3 km from the operation’s headframe, the lengthy time it took to discover Semblana was affected by macroeconomics, multiple changes in company management, and technological advances in equipment, inversion methods and visualisation tools. The fact that Semblana lies 800 m below surface and has neither a strong gravity anomaly nor a stellar EM response didn’t help.

Exploration is always challenging in areas of complex geology and at great depths. The discovery happened because the expected prize was substantial, persistence was maintained, teamwork was emphasised and best practice was expected, and because people were given the time to think.

West and Penney (2017) first presented the story of Semblana at Exploration ’17 in Toronto: a +0.25 g/cm3 relative-density iso-shell coincident with a weak-to- moderate 1D TEM conductor (now known to be spurious), three barren drill holes, but… two weak yet significant late-time BHEM responses that pointed towards an off-hole conductor. In retrospect, had 3D seismic or airborne gravity gradiometer (AGG) data been available earlier, history would likely be different.

A 3D hard-rock seismic survey was first conceived shortly after Lundin’s acquisition of Neves-Corvo but given the lengthy lead time required to plan a survey of this scale it became a casualty of the Global Financial Crisis of 2008. However, the idea remained active, and a four-month survey was eventually completed in June 2011. The 6 km × 4 km survey block consisted of orthogonal source and receiver lines and a square 7.5 m bin size with >100 fold in the centre of the grid. Mine infrastructure posed huge challenges by limiting locations for sources and receivers, in addition to the noise generated by the trucks, trains, hoist and mill.

To aid in the processing and interpretation of the data, 150 core samples representing the different lithological and ore units at Semblana were analysed for density velocity. Borehole full-waveform sonic (FWS) data were also collected in two holes and vertical seismic profiling (VSP) surveys acquired in two other holes. Combined, those surveys provided detailed information on P-wave and S-wave velocities and the acoustic impedance within the host and the deposit. Unsurprisingly, the core analysis, FWS and VSP data all predicted a significant acoustic impedance contrast between the massive sulfide ore and the host rocks.

Semblana’s sub-horizontal orientation made it a perfect target for reflection seismology as borne out in the first processed results delivered in August 2011. Figure 1 shows a SSW-NNE vertical slice through the seismic cube and crossing through the middle of Semblana. The accurate depth of 800 m was helped by the velocity model provided by the VSP surveys. The existence of the strong reflector in the

3D seismic cube was very useful in completing the delineation drilling of the deposit in general, and specifically of its southern extent of the deposit which had not been tested at that time.

Regionally, the new seismic data were added to the existing Neves-Corvo 3D geology model, which generated a plethora of secondary and tertiary targets for follow-up. The 3D geologic model was in turn used to add coherency and geologic meaning to the reflectors in the seismic cube that in turn fed back into the 3D geologic model in an iterative way, resulting in a vastly improved geological model between drill holes. This was especially true in areas where the drilling had stopped in PQ but where the seismic data indicated the thrusting of PQ over VSC. This was tested in one area and proved to be the correct interpretation, which in turn opened new exploration areas, like what happened with the original 1977 discovery of Neves where "conventional wisdom" interpreted the gravity anomaly to be much shallower than it truly was.

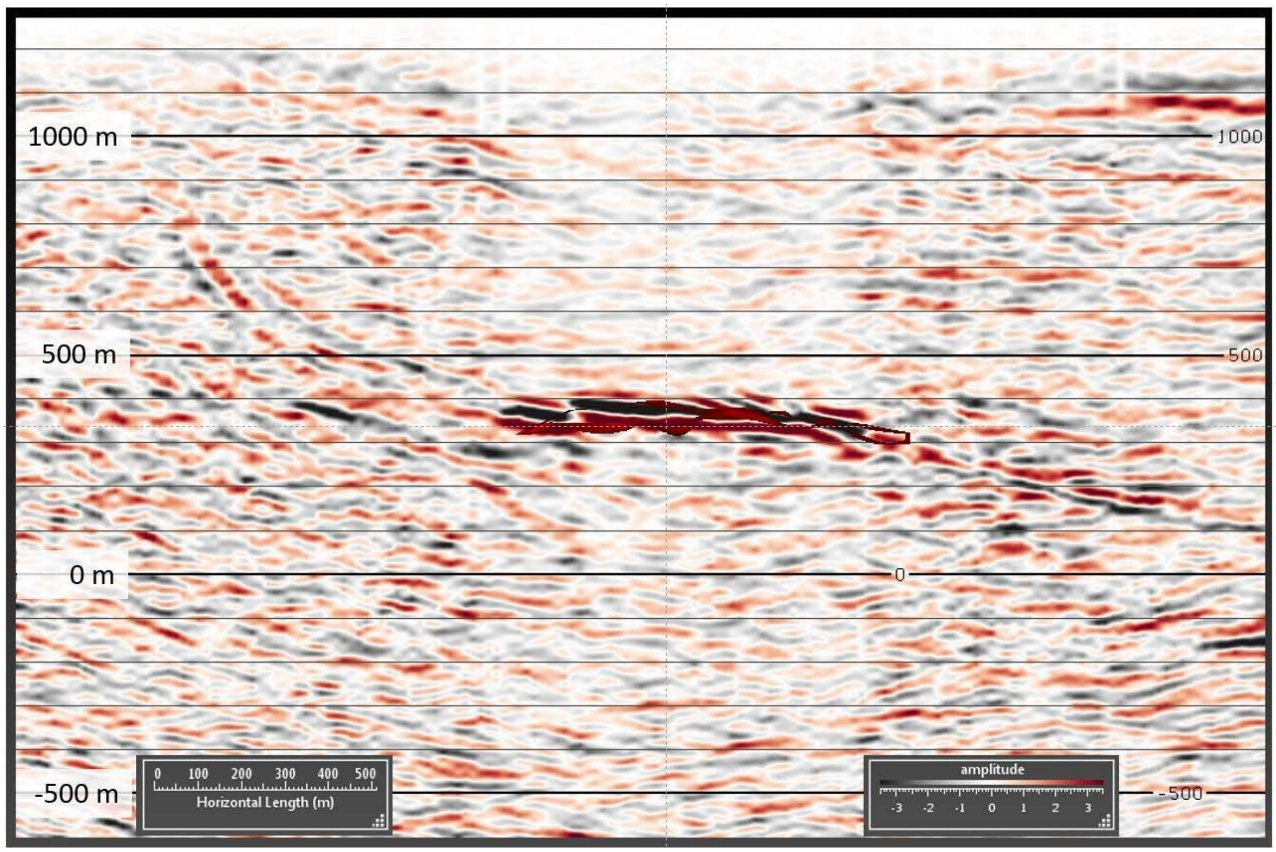


Figure 1: Vertical slice through the 3D seismic cube with the Semblana deposit represented by the strong, central reflector.

Hardrock 3D Seismic for BHP's Copper South Australia

Jared Townsend

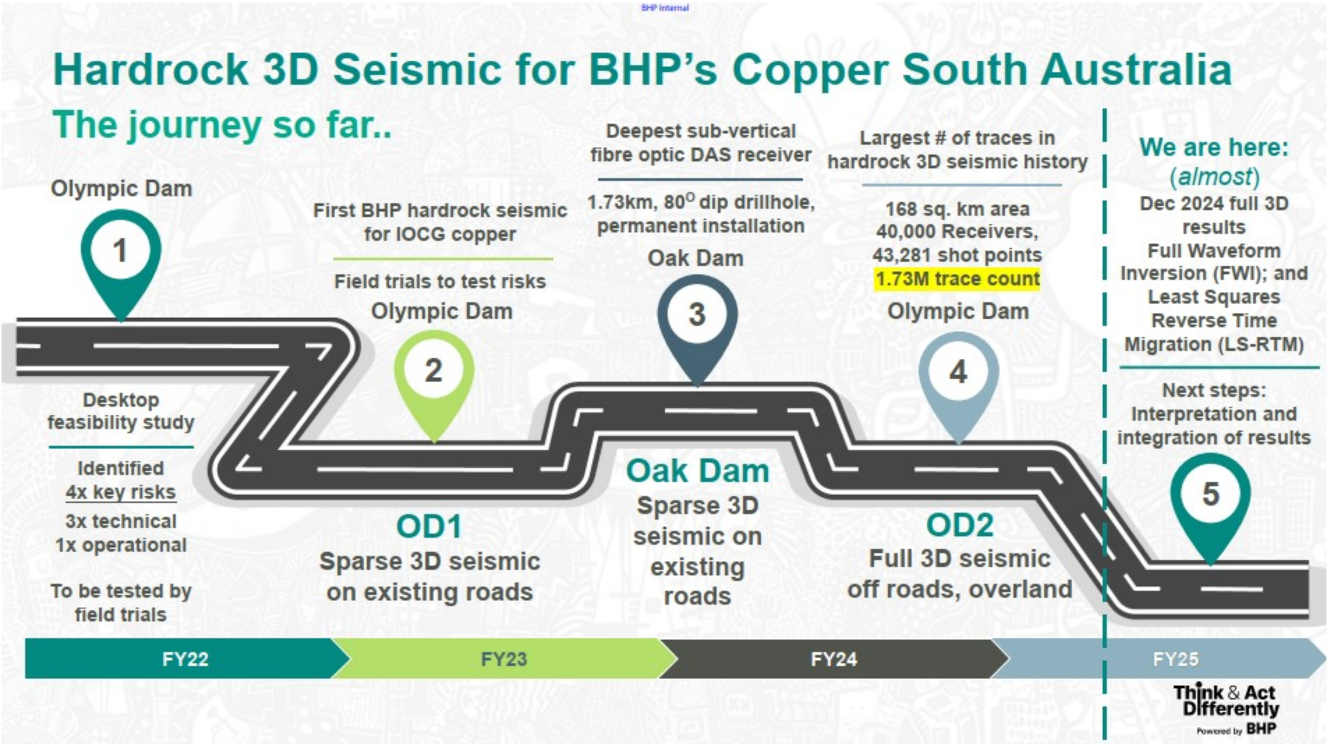
Think & Act Differently, Powered by BHP

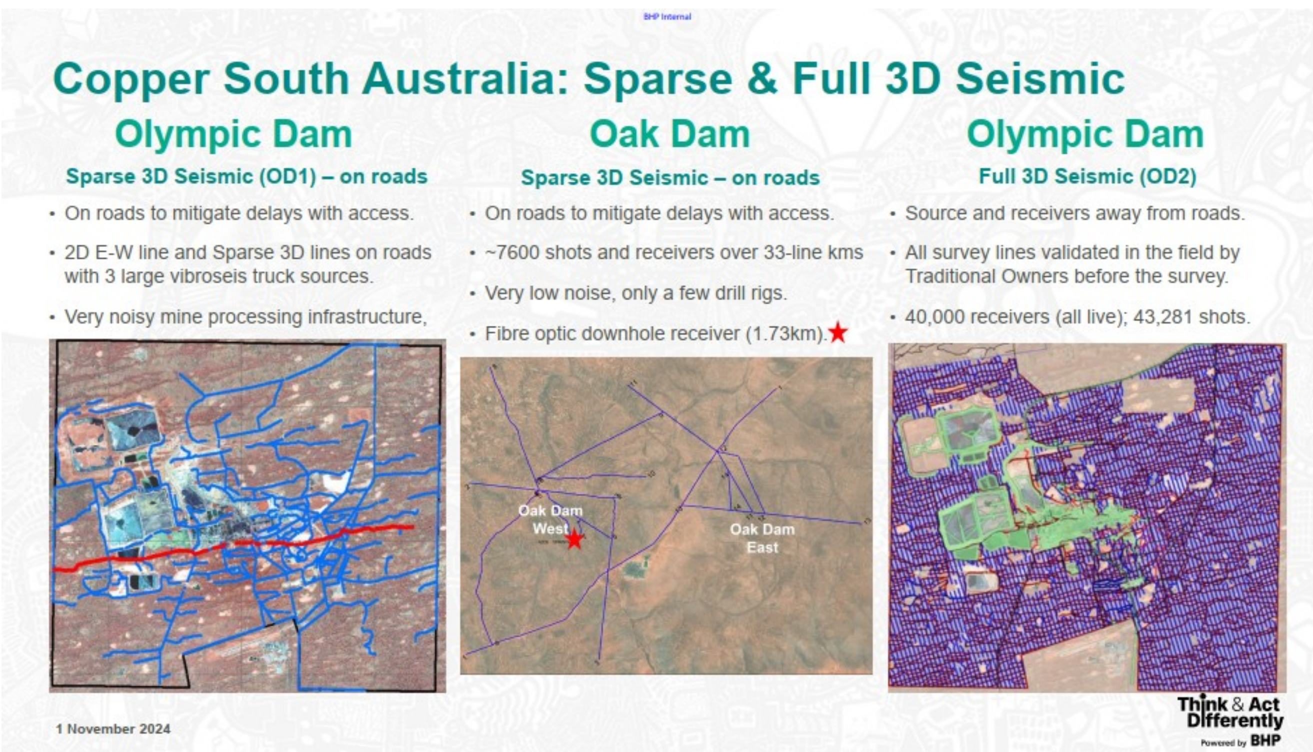
Hardrock seismic is an emerging technique in mining which has been adapted from oil & gas seismic for the purpose of high-resolution imaging of mineral deposits to great depths. The resulting 3D seismic cube at Olympic Dam is a 10 x 10 x 5 metre 3D volume over the entire 12 x 13 km mining lease. 40,000 nodal geophone receivers were all active during the acquisition of over 43,000 shot points from four large Vibroseis trucks operating in separate quadrants across the mining lease in slip-sweep acquisition mode.

The Hardrock Seismic technique is not a lift-and-shift from oil & gas seismic, where hydrocarbon accumulations are typically sub-horizontal with predictable velocity gradients increasing with depth. Hardrock seismic is inherently challenged by sub-vertical geological structure, difficult to image using surface source and receiver combinations. Hardrock geology also has inherently sharp lateral geological velocity changes, which are challenging for data processing to create a representative 3D model of the subsurface. A phased approach of de-risking was undertaken to achieve the full 3D seismic survey at Olympic Dam. An initial desktop feasibility study identified 3 technical and 1 operational risk, which led to the initial field trial. A 2D seismic traverse east-west across the property, and a Sparse 3D field trial on all existing roads and tracks was acquired in 2022.

Extensive land access efforts were led by David Haddow in the Olympic Dam geoscience team, working closely with the Environmental and Cultural Heritage teams. The Resource Centre of Excellence (RCoE), led by Heather Schijns, designed all phases of seismic data acquisition. BHP Innovation - now called Think & Act Differently, Powered by BHP - led by Jared Townsend, was responsible for procurement and achieving the Hardrock Seismic surveys on the ground at both the Olympic Dam and Oak Dam properties. The on-ground execution team had to consider Cultural Heritage, surface infrastructure, and buried infrastructure, on an enormous mining operation where this was the first time that these stakeholders had heard of seismic acquisition. There were many concerns about the damage that could be done by the survey equipment, particularly around tailings and buildings. All BHP Copper SA seismic data acquisition efforts have avoided Environmental and Cultural Heritage sites.

HiSeis won two diligent BHP tender processes to acquire all Copper South Australia Hardrock Seismic data acquisition phases to date. Separate data processing vendors have also worked on various approaches to date. Advanced, new-to-world Hardrock Seismic data processing outcomes have been developed in collaboration with Viridien (formerly CGG).


BHP Internal
Hardrock 3D Seismic for BHP's Copper South Australia
The journey so far..
Olympic Dam
1
Desktop feasibility study
Identified
4x key risks
3x technical
1x operational
To be tested by field trials
First BHP hardrock seismic for IOCG copper
Field trials to test risks
Olympic Dam
2
OD1
Sparse 3D seismic on existing roads
Deepest sub-vertical fibre optic DAS receiver
1.73km, 80° dip drillhole, permanent installation
Oak Dam
3
Oak Dam
Sparse 3D seismic on existing roads
Largest # of traces in hardrock 3D seismic history
168 sq. km area
40,000 Receivers,
43,281 shot points
1.73M trace count
Olympic Dam
4
OD2
Full 3D seismic off roads, overland
We are here: (almost)
Dec 2024 full 3D results
Full Waveform Inversion (FWI); and Least Squares Reverse Time Migration (LS-RTM)
Next steps: Interpretation and integration of results
5
FY22
FY23
FY24
FY25
Think & Act Differently
Powered by BHP


BHP Internal
Copper South Australia: Sparse & Full 3D Seismic
Olympic Dam
Sparse 3D Seismic (OD1) – on roads
• On roads to mitigate delays with access.
• 2D E-W line and Sparse 3D lines on roads with 3 large vibroseis truck sources.
• Very noisy mine processing infrastructure,
Oak Dam
Sparse 3D Seismic – on roads
• On roads to mitigate delays with access.
• ~7600 shots and receivers over 33-line kms
• Very low noise, only a few drill rigs.
• Fibre optic downhole receiver (1.73km).★
Oak Dam West
Oak Dam East
Olympic Dam
Full 3D Seismic (OD2)
• Source and receivers away from roads.
• All survey lines validated in the field by Traditional Owners before the survey.
• 40,000 receivers (all live); 43,281 shots.
1 November 2024
Think & Act Differently
Powered by BHP

High-end seismic imaging application in the Olympic IOCG Province, South Australia

Max Norman*, Robert To, Min Lee Chua, Mengmin Huang

Viridien

With higher spatial and temporal resolution potential over other geophysical methods, active source seismic data imaging has the potential to transform mineral exploration programs. However, widespread adoption has been limited thus far due to the inherent challenges faced by hard rock seismic exploration including low impedance contrasts, lack of coherent sub-horizontal reflectors, and fast subsurface velocities, as well as uncertainty over its efficacy in imaging high-angle features. In the past few years, use of state-of-the-art seismic imaging has begun the process of overcoming these challenges.

High-end seismic processing techniques were recently applied to a sparse 3D surface seismic survey at the Olympic Dam iron-oxide copper gold (IOCG) deposit. Following this successful test at Olympic Dam, a sparse 3D surface seismic survey and distributed acoustic sensing (DAS) vertical seismic profile (VSP) were acquired at the nearby Oak Dam IOCG deposit. Advanced seismic processing technologies including 30Hz Dynamic Resolution Time-lag Full-waveform Inversion (FWI), iterative Least-Squares Kirchhoff PSDM, and 80Hz Reverse Time Migration (RTM) were employed to obtain a high-quality structural image and P-wave velocity model.

At the Oak Dam deposit level, there is a clear low velocity zone that correlates well with the hematite breccia (HemQ) geometry estimated from numerous drillholes. A similar low velocity zone is observed on the FWI velocity field at the core of the Olympic Dam deposit. Although numerous potential geological causes could explain these low velocity zones, higher porosity in brecciated zones compared to the surrounding intact basement is considered the most likely based on the currently available data.

The 80Hz RTM gave the best overall imaging of structure and contacts. The resulting image shows clear delineation of the Hardy Hill Fault, which is a key fault interpreted as bounding the deposit to the west. The fault position agrees well with the velocity contrast in the FWI model, further validating the velocity model. With the well-defined fault image, a new structural style has been observed. Specifically, sinistral transcurrent offsets are interpreted, which have implications for the deposit geometry.

High-end seismic processing in the Olympic IOCG Province has overcome significant challenges and produced imaging that is redefining understanding of the target deposits. It contributes to the development of more robust geological models, shapes ongoing exploration efforts, and enables the optimization of drilling programs. Additionally, for Oak Dam, low velocity zones in the 30Hz FWI model represent new exploration targets with potential for hematite breccia associated high-grade copper mineralisation.