Case studies on the application of passive seismic horizontal to vertical spectral ratio (HVSR) surveying for heavy mineral sand exploration

**SUMMARY**

This study presents the results from several case studies on the application of passive seismic Horizontal to Vertical Spectral Ratio (HVSR) surveying methods for Heavy Mineral Sand (HMS) deposit subsurface layer detection for exploration and mining. The results from these case studies demonstrate the usefulness of this rapid and low cost survey method to complement HMS deposit mapping and its ability to provide additional stratigraphic information in gaps between drillholes.

HMS deposits typically occur in geological settings that are ideal for the application of the passive seismic HVSR method, because HMS deposits are typically shallow and may demonstrate acoustic impedance contrasts relative to surrounding sedimentary deposits or underlying acoustic bedrock. Trial HVSR survey results vary between different styles of heavy mineral sand deposits, from providing a direct estimate of the depth to the top of known HMS mineralisation based on a positive HVSR response from more dense and higher velocity HMS lenses, to detecting parallel silt and clay horizons, sometimes producing an inverted HVSR response, to be used as a bounding marker for HMS deposits, and in many cases detecting the acoustic hard rock basement forming the base to the unconsolidated, young sedimentary deposits and basin fill containing HMS layers.

In each case study, the use of a lightweight, self-contained and simple to use seismometer has allowed HMS explorers to carry out surveys quickly and cost effectively, in some remote areas with difficult access, mostly using company field staff following a short training session. The techniques and approaches to process and model HVSR data for shallow stratigraphic mapping during these trial surveys have contributed to advancing the passive seismic HVSR surveying method to become more commonly used for large production surveys.

**Key words:** Heavy Mineral Sands (HMS), passive seismic, Horizontal to Vertical Spectral Ratio (HVSR), Tromino, seismometer

**INTRODUCTION**

In recent years the passive seismic Horizontal to Vertical Spectral Ratio (HVSR) method of Nakamura (2000) has been gaining greater recognition in the mineral exploration industry as a valuable tool for quickly estimating thickness of sedimentary layers and regolith sitting above hard bedrock (e.g. Owens et al., 2016; Meyers, 2017). The HVSR method is suitable for estimating the depth to the base of relatively soft sediments and regolith materials sitting above harder sedimentary layers and/or a sediment to crystalline bedrock interface. Accurate depth estimates can be obtained using the HVSR method, particularly when drillhole data into the acoustic bedrock are available to constrain either a constant average shear wave velocity (Vs), or a variable Vs, which is dependent on the fundamental resonance frequency of the soft layer measured by the seismometer. The Tromino® seismometer is small, lightweight, very simple to use and is well designed for shallow (e.g. <500 m) HVSR investigations of regolith cover, sedimentary deposit thickness, and some intra-sedimentary layering and hardness variations, and this seismometer was utilised in all case studies presented by this paper.

This study presents the results from five trial case studies on the application of passive seismic HVSR survey methods for HMS exploration in different geological settings in Australia, New Zealand and Kazakhstan.

**CASE STUDY 1: SONORA**

The Sonoran HMS deposit is located 200 km to the NW of Ceduna in the Eucla Basin, South Australia. Sonoran is a satellite deposit to the Jacinth-Ambrosia zircon rich HMS deposits. The Sonoran HMS deposit consists of ilmenite and zircon heavy minerals hosted in Cenozoic eolian dune and beach sand deposits of the Ooldea Range, which overly Proterozoic granite-gneiss basement rocks. The HMS deposits are believed to have been trapped around paleo beach headlands during episodes of higher sea level.

Passive seismic HVSR data were acquired at Sonoran for Iluka by a university student, where 10 traverses for a total of 136 survey stations of passive seismic data were acquired in a grid pattern across the Sonoran HMS deposit area. A 16-minute recording time was used at each station, and data were considered to be of good data quality, which is attributed to high...
ambient seismic signal levels and a clear seismic impedance contrast between the relatively soft sand cover and harder granite-gneiss basement. Detailed drillhole lithological information was available to calibrate the HVSR survey results (e.g. Cantwell, 2017).

An HVSR cross section with drillholes ending at the top of hard granite-gneiss basement is shown in Figure 1. A constant average shear wave velocity of 480 m/s has been used to generate this HVSR section, which was determined from analysis of existing drillhole data and the observed HVSR fundamental frequency recorded at the drillhole collar. A comparative HVSR cross section generated by using a frequency-depth trendline from passive seismic readings taken next to drillholes will also be shown in the presentation. There is a good correlation between drillhole depth and the modelled interface between the Ooldea Range sands and the granite-gneiss basement depth across the entire length of the survey traverse, and this is represented by the high amplitude HVSR response in Figure 1.

![Figure 1. Normalised HVSR cross section model results for the Sonoran HMS deposit, using a constant average Vs of 480 m/s, where black line marks the modelled top of hard granite-gneiss basement, and white lines are air-core drillholes. Note also a shallow layer in the cross section.](image)

The modelled depth to basement varies between 20 to 60 m over the Sonoran project HVSR survey area, and a gridded image of the modelled basement surface (Figure 2), as determined from the HVSR results, provides clear interpretation of palaeo headlands that influenced the location of HMS deposition, and therefore permits the interpretation of thicker and higher-grade concentrations of HMS mineralisation in placer zones.

![Figure 2. Gridded image of the top of the granite-gneiss basement interface modelled from the HVSR data, where basement highs in RL elevation (red/white) define palaeo headlands, which helped to control deposition of HMS deposits in the project area. Passive seismic survey stations are shown by black dots.](image)

**CASE STUDY 2: THUNDERBIRD**

Thunderbird is the first significant HMS deposit to be discovered in the western Canning Basin of Western Australia, and is one of the largest and highest-grade HMS deposits globally. The ilmenite-rich HMS deposit is hosted in the highly weathered Broome Sandstone Formation, which was formed during an Early Cretaceous marine regression (Figure 3; Sheffield Resources, 2017).

![Figure 3. Geological cross section for the Thunderbird deposit (reproduced from Sheffield Resources, 2017).](image)

A trial passive seismic HVSR survey was carried out using 2 traverses across the Thunderbird HMS deposit. The normalised HVSR cross section model results for one of the survey lines is shown for the full cross section to acoustic basement in Figure 4, and a zoomed-in window of the data is shown as the shallow cross section in Figure 5. A deep basement interface of >500 m depth below surface is resolved in the full depth HVSR cross section, and is related to well indurated Mesozoic sandstone beds sitting below the Broome Sandstone (Figure 4). The zoomed-in window of the HVSR data in Figure 5 demonstrates a strong correlation between elevated >2% HMS mineralisation and elevated HVSR amplitude. The HVSR cross section model was generated using a constant average Vs of 780 m/s, which was determined from analysis of existing drillhole data. Note that using this Vs value, the modelled depth of the bedrock interface, highlighted in Figure 4 to be about 550 m deep, could be over- or under-estimated, because the average Vs of the total Broome Sandstone Formation may be lower or higher than 780 m/s.

![Figure 4. Normalised HVSR cross section model results for the Thunderbird HMS deposit, which was generated using a constant average shear wave velocity of 780 m/s. The pink outline shows the windowed area for the zoomed-in HVSR cross section in Figure 5.](image)
AEGC 2019: From Data to Discovery – Perth, Australia

Figure 5. Windowed normalised HVSR cross section model results for the Thunderbird HMS deposit, which was generated using a constant average shear wave velocity of 780 m/s, and high-grade HMS mineralisation where >1% (light grey) and >2% (black) intervals are shown alongside of selected drillhole traces (dashed black lines).

CASE STUDY 3: KAZAKHSTAN

Iluka Resources Limited have previously explored for Oligocene zircon and rutile HMS deposits overlying older Tertiary and Devonian “bedrock” sediments located in Northern Kazakhstan. A generalised geological cross section for the area is shown in Figure 6, which demonstrates “layer cake” Oligocene sedimentary deposits above rifted basement rocks.

Iluka Resources staff carried out the passive seismic HVSR surveying, with data processing carried out in Perth, Australia. An example HVSR cross section model of results for one of the survey lines is shown in Figure 7. The bottom of drillholes ended in the Chegan Clay unit, a fluid rich soft clay, which is correlated to an anomalous HVSR low response along the survey line, attributed to an inverted acoustic impedance contrast due to the clay unit having much lower seismic velocity and density compared to sediments sitting above and below it. In this project area it is possible to use the Chegan Clay unit as a marker horizon to infer the thickness of overlying sand-silt deposits containing HMS mineralisation. Note also how pervasive layering is also mapped within the shallow part of the HVSR cross section, between 0 to 30 m below surface, which agrees with drilling data and the generalised geological cross section in Figure 6; however the entire HVSR cross section showing the rifted acrostic bedrock at greater depth has not been shown here.

Figure 7. Normalised HVSR cross section model results for a traverse carried out by Iluka in Kazakhstan, which was generated using a constant average shear wave velocity of 250 m/s, with black line following an acoustic impedance contrast at the base of the sand deposits in contact with an underlying clay layer forming a strong negative acoustic impedance contrast and blue coloured band in the cross section. This is only showing the top of the HVSR cross section, where the acoustic basement layers occur at greater depth.

CASE STUDY 4: GINKGO

Cristal Mining are exploring for WIM-style strandline ilmenite, leucoxene, zircon and rutile HMS deposits at their Ginkgo Project, which is located approximately 90 km north of Mildura in the Murray Basin, New South Wales. The HMS mineralisation is expected to occur within Oligocene cover sediments that are overlying Mesozoic bedrock sediments. Passive seismic HVSR surveying was carried out by Cristal staff at 20 m station spacing along two trial survey lines. The resulting normalised HVSR cross section model results are shown for a full depth section in Figure 8, and a zoomed-in window section in Figure 9, for one of the survey lines. Figure 8 shows the HVSR model results from 0 to 350 m below surface, whereas Figure 9 shows a zoomed-in window of the model results from 0 to 50 m below surface. A low constant average velocity of 250 m/s has been used to generate the HVSR cross section model in order to better estimate the depth of the shallower HMS target horizon that is located within 50 m from surface. Note that because a lower Vs has been used, the modelled depth of the HVSR peak response from acoustic bedrock (possibly limestone) is likely greatly under-estimated in this model, and it is probably more like 450 m deep, or more.

Figure 8. Normalised HVSR cross section model results for a traverse carried out at the Ginkgo prospect, which was generated using a constant low average velocity of 250 m/s to focus on shallow responses from HMS deposits, and therefore the acoustic bedrock depth at about 225 m is probably underestimated, and is likely closer to 450 m or more. The pink outline shows the window area for the zoomed-in HVSR cross section in Figure 9.

Figure 9. Zoomed-in window of the normalised HVSR cross section model results shown in Figure 8. The cross section depth ranges from 0 to 50 m below surface.

HVSRS responses observed within 50 m from surface in Figure 9 appear to be layered in an imbricated fashion, which is typical for WIM-style HMS deposits, and agrees with drilling in this region.
CASE STUDY 5: AOTEA

The Aotea titanomagnetite ironsand deposit is located approximately 15 km southwest of Raglan along the west coast of the North Island of New Zealand. Sinosteel Australia have defined a JORC resource of 202 Mt of titanomagnetite ironsand in modern and ancient dune deposits at the Aotea Project (Wood et al., 2016). Passive seismic HVSR trial surveys were carried out over transects across the deposit, where existing ground penetrating radar (GPR) and ground magnetic data were also collected. An HVSR cross section model generated using a constant average Vs of 400 m/s is shown in Figure 10, and this HVSR cross section model provides a very good approximation of the total thickness of sand cover overlying basalt and limestone acoustic basement, and detected shallower clay band layers sitting in-between ironsand deposit layers (Wood et al., 2016).

Figure 10. Normalised HVSR cross section model for a traverse across the Aotea titanomagnetite HMS deposit, which was generated using a constant average Vs of 400 m/s. Drillholes typically end 1 to 2 m into the basalt and limestone basement rock.

Compare the results of the passive seismic HVSR cross section model in Figure 10 to deep penetrating GPR results along the same traverse in Figure 11. The GPR data provides great detail to allow for interpretation of ironsand zones with dune foreset bedding, and unwanted clay interbed layers, but was limited to a maximum depth of investigation of 20 m. In comparison to the passive seismic survey, the GPR was time consuming, expensive, difficult to apply in the rugged topography of the project area, and data processing was rather intensive.

Figure 11. GPR cross section for the same traverse as the passive seismic HVSR section shown in Figure 10.

CONCLUSIONS

The case study examples shown in this presentation have been selected to demonstrate applications of the passive seismic HSVR method for HMS exploration, whether estimating the depth to the top of an HMS deposit (e.g. Thunderbird and Ginkgo), estimating total thickness of softer sand deposit units hosting HMS sands above harder bedrock (e.g. Sonoran and Aotea), highlighting inverted HVSR responses from clay marker beds (e.g. Kazakhstan), which may be used to infer thickness of overlying sand deposits, or internal layering within the sand deposits (all trial surveys). In each example presented, the survey data were acquired at low cost and usually by mineral exploration company staff, and limited office data processing time was required to produce useful HVSR cross section models.

There are limitations with the passive seismic HVSR method, which include velocity measurements for reliable frequency to depth conversion, difficulties in resolving thin impedance contrast layers, different lithological units with the same acoustic impedance properties, and the occurrence of higher nodes of the fundamental frequency, which may complicate interpretation of intra-sedimentary layers in HMS settings. The limitations of the method do not seem to include having inadequate ambient seismic signal.

In summary, HMS deposits typically occur in geological settings that are ideal for the application of the passive seismic HVSR method for detecting acoustic bedrock depth in shallow basins, and detecting layering within the sedimentary deposits, either as direct detection of HMS beds or by detecting contacts with other marker horizons within the sequence.

ACKNOWLEDGEMENTS

The authors wish to thank all clients, contractors and fellow staff who have contributed to these trial surveys, and have been open minded about the application of the passive seismic HVSR method for HMS exploration and other types of mineral exploration over recent years. Iluka Resources, Sheffield Resources, Cristal Mining and Sinosteel Australia are especially thanked for providing permission to present their passive seismic HVSR results and other data sets.

REFERENCES


