APPLICATION OF PASSIVE SEISMIC IN DETERMINING OVERBURDEN THICKNESS: NORTH WEST ZAMBIA

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SUMMARY

There are several ways to estimate overburden cover thickness. One of the non-invasive and inexpensive ways to rapidly estimate the cover thickness is the Horizontal-to-Vertical Spectral Ratio (HVSR) of the ambient seismic noise method. This approach utilises a broadband three-component sensitive seismometer to record ambient noise (or microtremor) induced by the wind, ocean waves and several anthropogenic activities. These microtremors are mainly composed of Rayleigh Waves which propagate in the surface layer.

The Tromino® seismometer, which works on the HVSR principle, is a very light and portable instrument that records seismic noise in the frequency range of 0.1 to 1024 Hz, and is capable of estimating overburden cover up to 100's of metres depth, depending on the ambient noise strength and geological setting of the survey area.

The ratio of the horizontal-to-vertical (H/V) component of the shear wave (Vs) spectrum is used to calculate the peak resonance frequency at a particular survey station, which is used to estimate the overburden thickness by using one or more existing drill holes in the area, 1D modelling, or local geological knowledge about the overburden to get velocity information for calculating depth. This paper discusses different methods used to calculate the overburden thickness, which includes calculations using a hybrid approach and a regression equation.

This paper shows the results of a Tromino® HVSR survey in North West Zambia and comparison of estimated overburden thickness using different methods. The results were further compared with those determined from Audio-MagnetoTellurics (AMT) and drilling data. Tromino® successfully estimated the overburden thickness and mapped the bedrock topography with reasonable accuracy.

Keywords: Tromino®, Passive Seismic, AMT, Kalahari, HVSR, Air-Core

INTRODUCTION

There are numerous survey methods that can be applied to determine overburden thickness, some of these include interpolation between drill holes, mapping conductivity structures using electrical techniques, depth to source estimation from potential field data, and seismic reflection and refraction surveying. Passive seismic surveying has mainly been the subject of research and has been commonly used by seismologists interested in earthquake hazard mapping. Recently, the Passive Seismic technique is starting to be used in several mineral exploration projects for estimating the overburden thickness, for regolith cover mapping, either as a stand-alone survey method or in conjunction with other potential or electrical field methods.

A shallow passive seismic survey using Tromino® 3G ENGY seismometers was completed by Rio Tinto Mining and Exploration ("RTX") at its project in North-West Zambia. RTX engaged Resource Potentials for sourcing the seismometers and for initial processing and modelling of the passive seismic data. The objectives of this survey were to:

a. Compare the Kalahari thickness cover derived from Tromino® with AMT data and drilling data.
b. Define the thickness of Kalahari cover deposits ahead of an Air-Core drilling program to get samples from below the Kalahari cover.

SURVEY LOCATION AND SPECIFICATION

The survey block lies in North-West Zambia, close to Katala Village, and is a six-hour drive from Solwezi. The square survey block is 16 square kilometers in area. The topography is flat, with a dambo in the north-west portion of survey block. Survey lines were oriented in a northwest-southeast direction, using a survey line spacing of 400 metres, and planned survey line length of 4 km as shown in Figure 1. HVSR readings were taken over a 20 minute recording period at a nominal station spacing of 100 m along eleven traverses. Due to thick vegetation and the dambo in north-east part of the survey block, the field crew were unable to acquire Tromino® stations in this part. In addition to this, a faulty Tromino® unit resulted in poor recordings and therefore there are some missing sections along Tromino® survey line number 5.

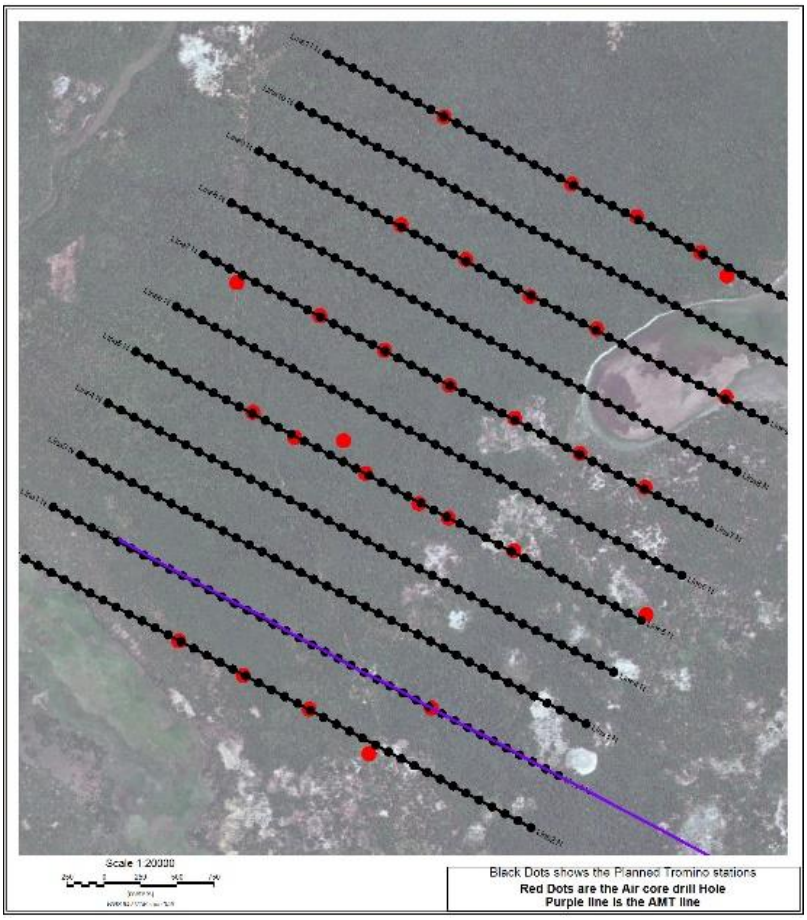

Figure 1: Black circles showing the Tromino® recording stations, Red circles shows Air-Core drill locations, and the purple line is the AMT profile.

METHODS AND RESULTS

The passive seismic HVSR method consists of recording ambient or natural seismic energy vibrations using a seismometer, such as Tromino®, which uses three velocimeters to record the horizontal (relative north-south or X, and relative east-west or Y) and vertical (up-down or Z) components of ground motion over a broad range of frequencies (0-128 Hz), and over a long time-period (1 min to 60 min, usually 20 min). The ambient signal recorded consists primarily of surface Rayleigh and Love waves, which are generated from natural sources, primarily ongoing crustal microtremors, but also vibrations from distant ocean waves, rain and the wind, as well as from sources, such as traffic movements, construction and factories. The ambient seismic energy acts as a continuous excitation source, creating seismic resonance within the near surface strata and regolith over fresh or hard “bedrock”. This resonance is a function of the thickness and the shear-wave velocity of the subsurface layers, and is particularly amplified when layers have a strong and sharp acoustic impedance contrast boundary. Acoustic impedance is a function of the density multiplied by the shear wave velocity of a layer.

The recorded time series data (X, Y and Z) is then converted to the frequency domain using a Fast Fourier Transform (FFT), and the two components are displayed as a power spectrum. The shear wave resonance manifests itself as a local minimum in the vertical velocity component in the frequency domain, such that when a ratio is taken between the averaged horizontal vibration components (H) and vertical vibration component (V), a peak occurs in the spectral response at the resonant frequency as shown in Figure 2. This resonant frequency is related to the thickness and shear wave velocity of the resonant layer by the following equation from Nakamura (2000):

$f_0 = Vs/4h$, Equation (1)

where f_0 = peak resonant frequency (Hz), Vs = shear wave velocity (m/s), and h = layer thickness (m).

In a two-layered earth model, resonance frequency (f_0) can be used in estimating the overburden thickness (h) using the equation

$h = Vs / 4 f_0$ Equation (2)

In the absence of sufficient acoustic impedance contrast, and in areas with reversal velocity (a high-velocity layer above a low-velocity layer), this method would be less effective. Modelling has suggested that minimum overburden to bedrock impedance ratio should be 1:2 for H/ V spectral ratio to be effective.

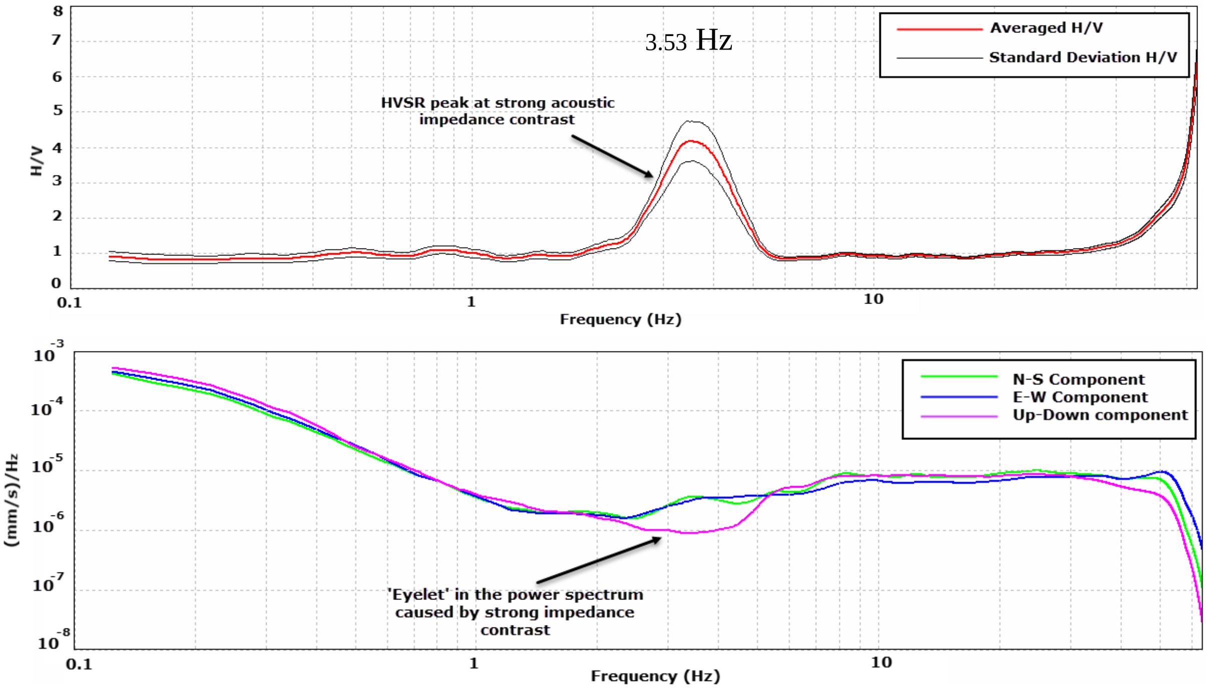

Figure 2: Reading from a Tromino® seismometer. HVSR in the top panel, and the power spectrum of the three axial components in the bottom panel. The vertical component (pink profile in the lower panel) shows a minimum where constructive interference has occurred due to trapping and resonance of vertical shear waves, causing a peak at 3.53 Hz in the HVSR plot in the top panel.

The approach used in this project was to apply the known layer thickness obtained from one drill hole (KATA004) to constrain the model bedrock depth by determining the shear wave velocity. Drill hole KATA004 intersected the bedrock at 99 meters, and using a two-layer earth model, the resulting shear wave velocity was 600 metres/second as shown in Figure 3.

After completion of an Air-Core drilling program, Tromino® readings were also used to calculate a regression equation between overburden thickness and peak resonant frequency. Resonant frequency, to first order approximation, is a function of overburden material and inverse of the thickness, which may be represented by an expression below:

$h = a\ f_0^b$

Where **h** = overburden thickness, **a** and **b** = constants determined from the regression. The regression equation will vary from survey area to survey area depending on the acoustic properties of the rocks, and therefore the regression equation from one area cannot generally be used for other areas.

DATA PROCESSING AND MODELLING

The ambient seismic energy recorded in three components by the Tromino® instruments for each station were processed using Grilla software. The Grilla software enables the user to convert the three component time series recordings into frequency spectra using a Fast Fourier Transform (FFT). These component frequency spectra are then used to compute the HVSR between the averaged horizontal components and the vertical component, with the results displayed as a power spectrum.

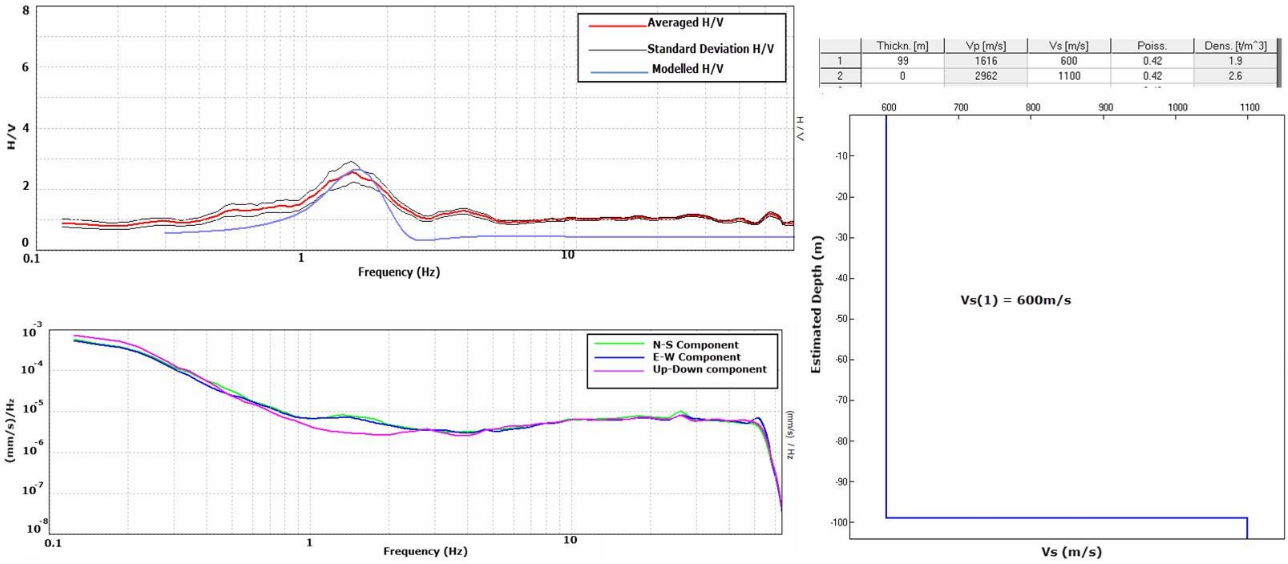

Figure 3: 1D forward modelling from the Tromino® station modelled using drill hole KATA004 for "top of bedrock" depth control. Measured (red line in top left panel) and modelled (blue line in top left panel) HVSR profiles with the synthetic velocity model and model parameters on the right.

The overall quality of the passive seismic data was acceptable, with some stations requiring the removal of noisy time windows to enhance the HVSR peak and decrease the standard deviation. Out of the planned 429 stations, 367 Tromino® passive seismic stations (85%) were acquired. Out of these 13 (3%) stations were discarded due to high noise levels.

The Tromino® passive seismic data from final processed station recordings were used to compute layer thicknesses using a 1D forward modelled shear wave velocity of 600 m/s from Equation 1, which fitted the observed data very well. Normalised amplitude-depth cross-sections were produced for each of the 11 survey lines. The depth to fresh bedrock was computed using the average velocity from the 1D modelling and Equation 2 for each passive seismic station. The cross section plots displayed the depth at each site as a profile overlaying a section coloured according to its H/V amplitude frequency response with depth. The black profile marks the modelled depth. Figure 4 shows an example of cross section with depth to basement marked in black dotted lines.

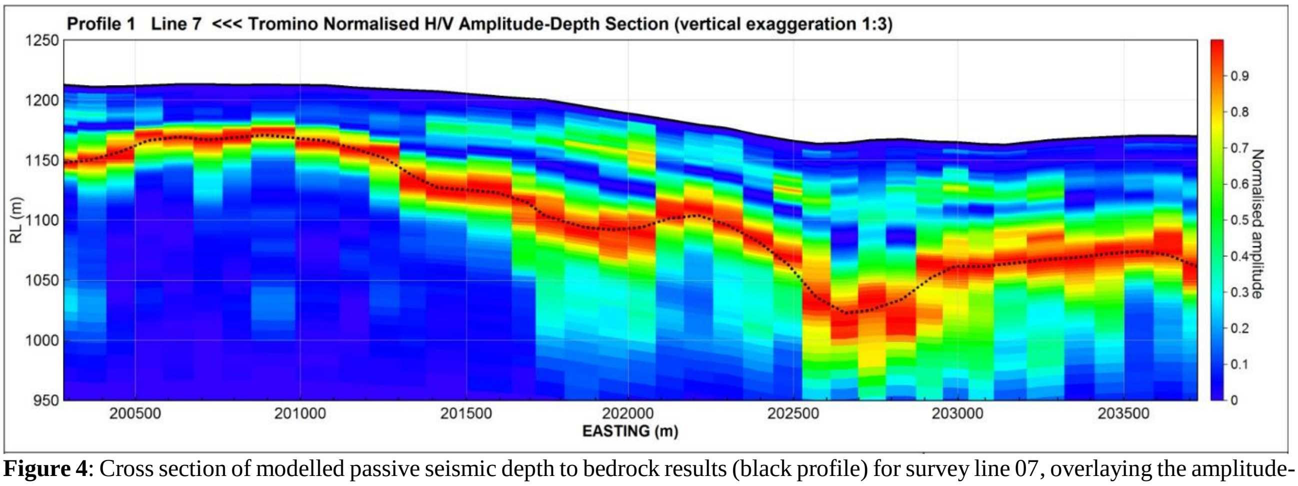

Figure 4: Cross section of modelled passive seismic depth to bedrock results (black profile) for survey line 07, overlaying the amplitude-depth section computed using Vs = 600 m/s from Equation 1 and 1D modelling.

In addition to detecting the high acoustic impedance contrast between the overlying Kalahari sediments and the underlying hard bedrock layer, the survey also showed smaller amplitude HVSR peaks in the higher frequencies. These secondary peaks are believed to be formed from the stratigraphic layering in the overlying Kalahari sedimentary deposits. These subtle horizontal frequency responses likely relate to changes in sediment type, sands, silcrete layers, clay layers, or leached zones. A depth to bedrock grid was created using the modelled depth values from Tromino®.

Due to their high clay content, the Kalahari sediments have low resistivity values and show up as conductors in the AMT survey results. The high resolution of the Tromino® survey delineates the bedrock topography better than the AMT survey. AMT conductivity section along KATA004 is shown in Figure 5.

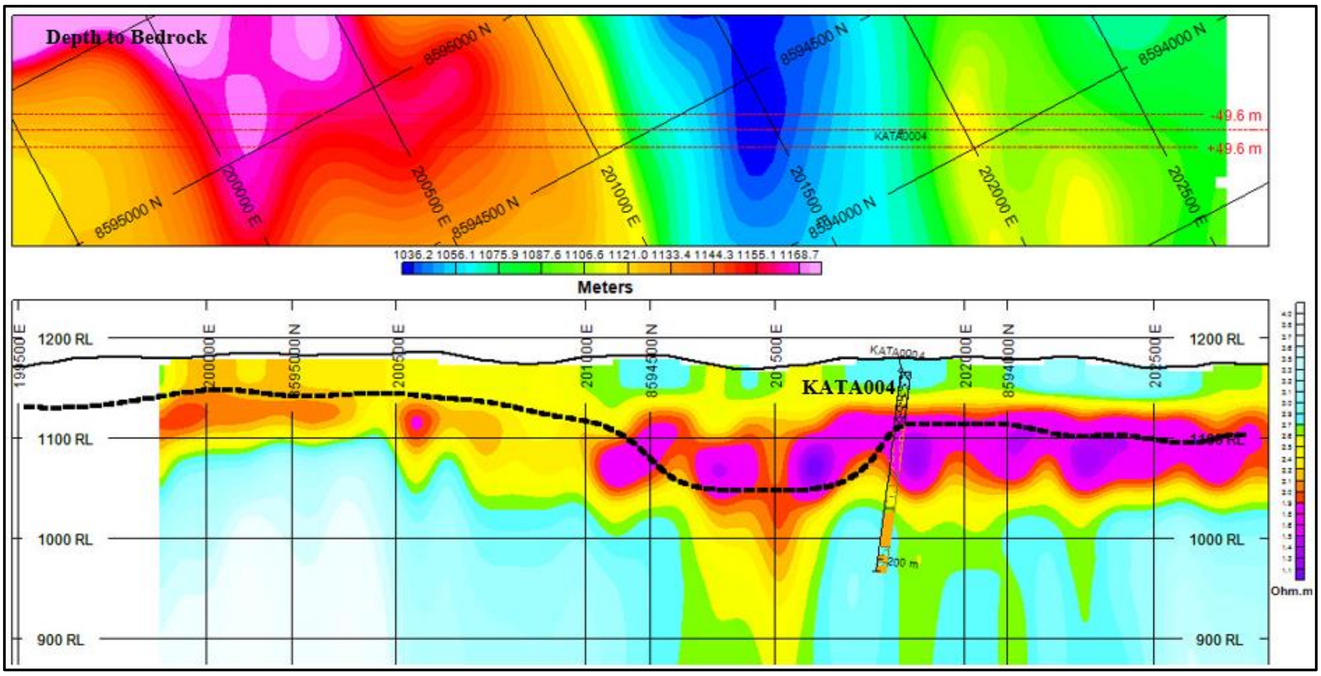

Figure 5: AMT section across line 01, with the estimated depth to bedrock grid image shown on top. Black dotted line is HVSR peak frequency converted to depth using Equation 1 and plotted against the AMT section depth. Hotter colours show low resistivity values. Drill hole KATA004 plotted on the AMT section.

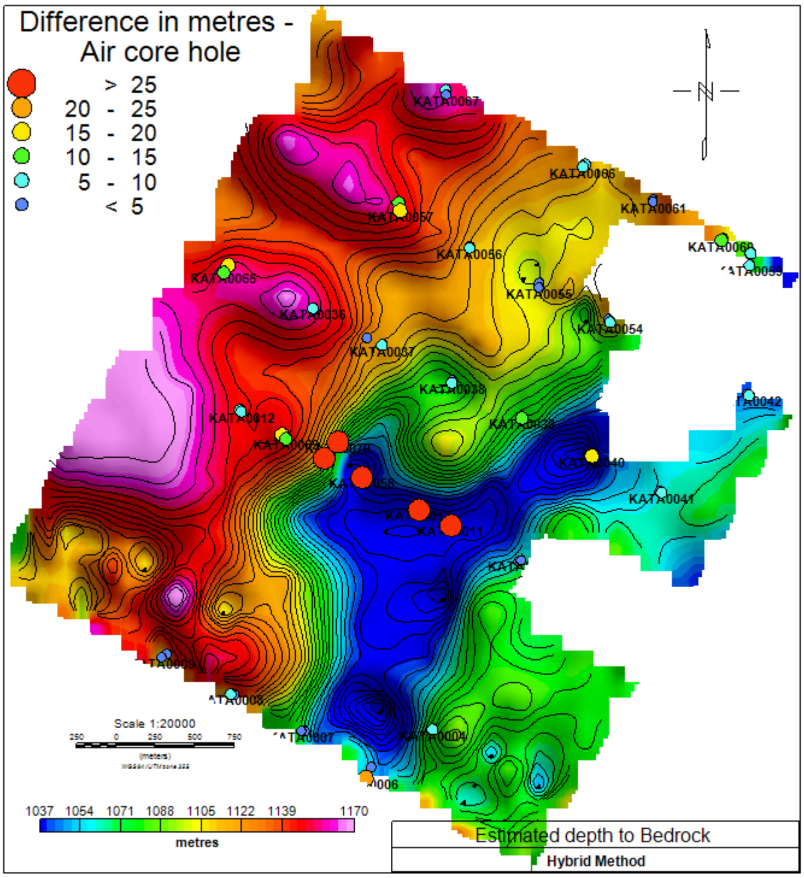

Figure 6: Basement elevation grid generated from peak frequency using hybrid approach.

The project team had drilled thirty Air-Core holes in the survey block, and almost all of them intersected the hard bedrock underlying the Kalahari deposits. The comparison of the estimated depths from Tromino® and Air-Core drill depths showed that 80% of the holes had a difference in the predicted depth of less than +/- 20 metres (Figure 6 and 7). The main difference occurs in a deep paleochannel where compaction of the deposits likely caused an increase in S-wave velocity to above 600 m/s.

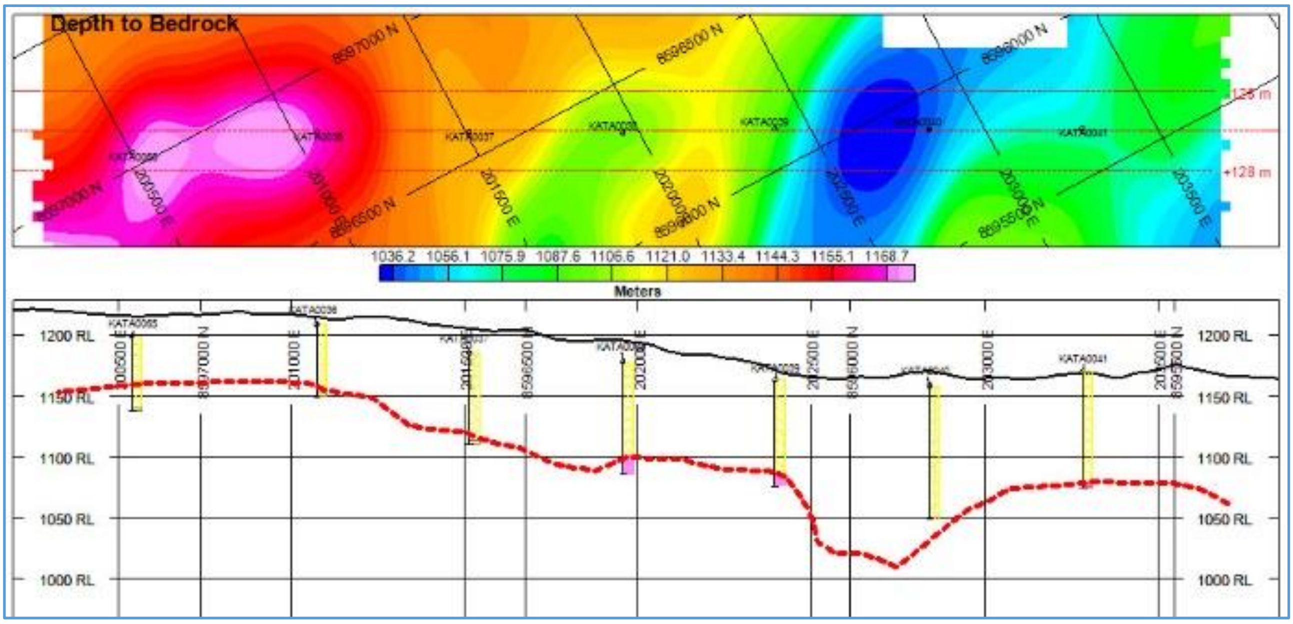

Figure 7: Cross-section from Tromino® passive seismic line 07. The red dotted line shows the depth to the bedrock displayed over the drill sections.

Using a hybrid approach, Tromino® **had overestimated the overburden thickness by more than 20 metres for five holes. These holes are drilled deeper than 80 metres. The reason for this error could be that the modelled average shear wave velocity from KATA004 is quite high and a lower velocity should be applied to shallower areas to compensate.** Except for the five holes, there has been a good correlation between the estimated overburden depths using hybrid approach and depths from Air-Core drilling and AMT survey.

The basement depths from Air-Core drilling were used to generate a regression equation, which accounts for velocity gradients and is a more reliable method than using an average velocity for the entire Kalahari deposit sequence. The final basement elevation grid as shown in Figure 8 generated from a regression equation is much smoother then when compared to the one generated from the hybrid approach. The depth estimates using a regression equation appear to show a reasonable match over the entire survey area, and the estimation seems to be within ±20 m of the actual depths (Figure 9). The Tromino® underestimated the depth at KATA070 by more than 40 metres in both the hybrid and regression approach. This hole is located at an inflexion point, where the rate of change in Kalahari sediment thickness is high which could have resulted in underestimating the depths (Figure 10). The depth estimation errors can be reduced further by refining the regression equation by adding more control points in a larger depth range. The comparison of the difference of depths estimated from two methods suggest that if there are enough drill holes with varying depths to the basement, regression equation will provide better estimates. Hence the regression method should be applied when additional drilling data becomes available at later stages of exploration. Figure 11 shows the comparison of conductivity sections from AMT data and Tromino data which suggest both the methods can reliably estimate overburden thickness with latter being more cost effective.

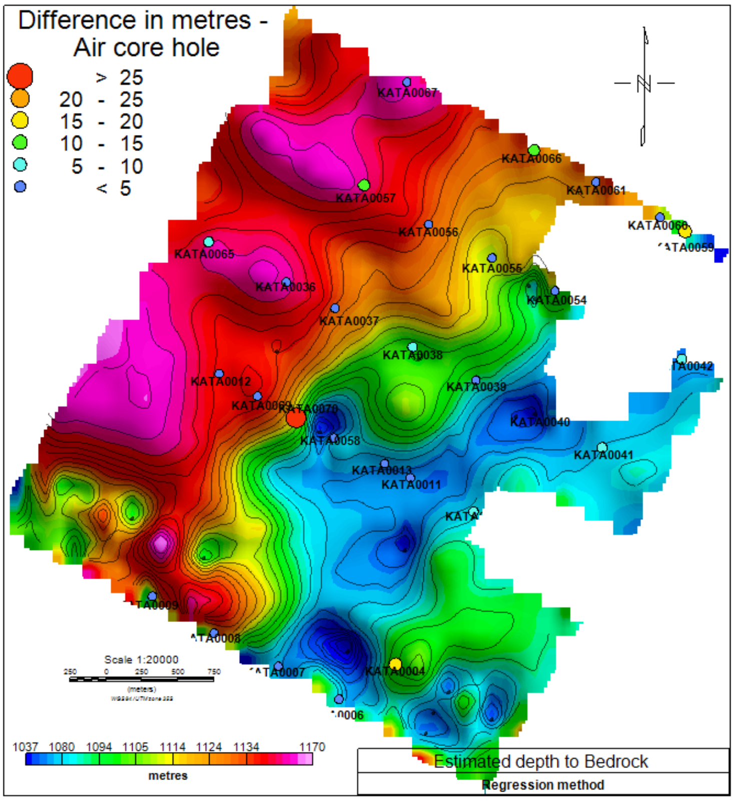

Figure 8: Basement elevation grid generated from peak frequency using regression equation method, showing that the error in depth estimation has been greatly reduced when compared to the results in Figure 6

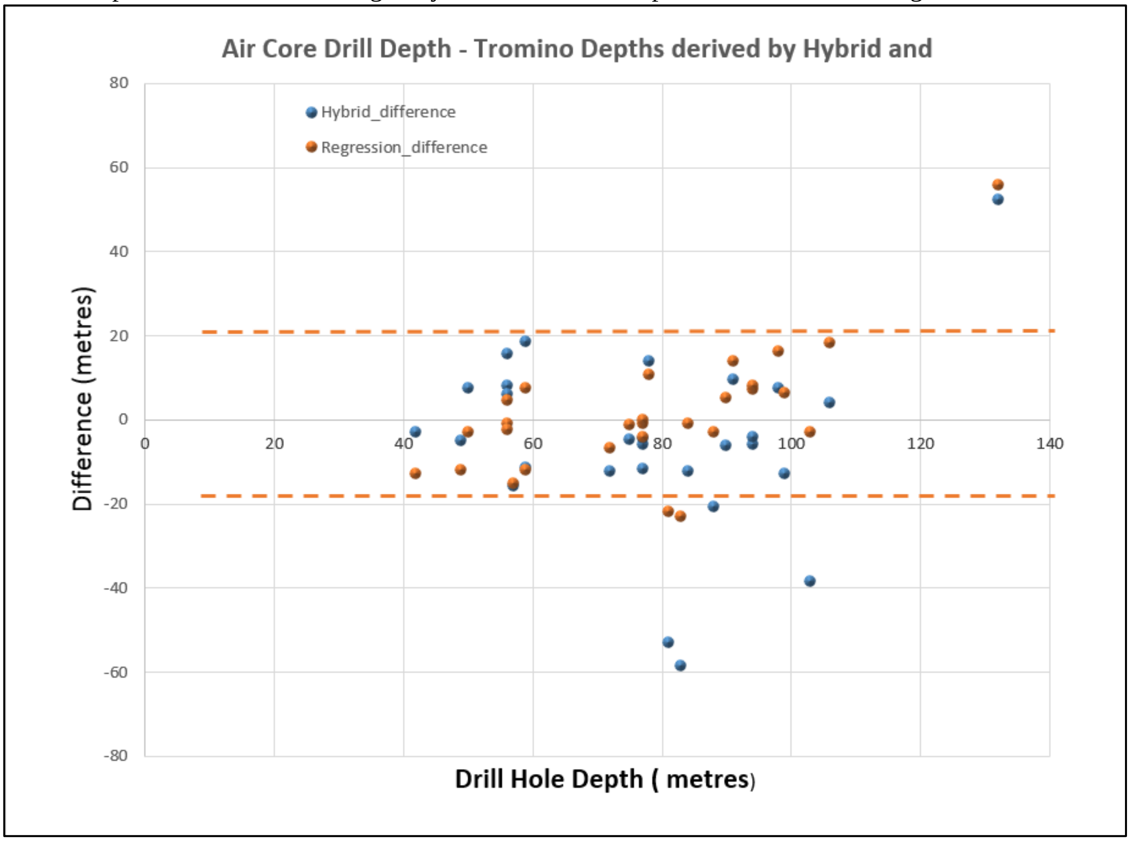

Figure 9: Graph indicating the difference in depths estimated from Tromino® (hybrid and regression methods) and Air-Core depths on the Y axis. The X axis shows the drill hole depths.

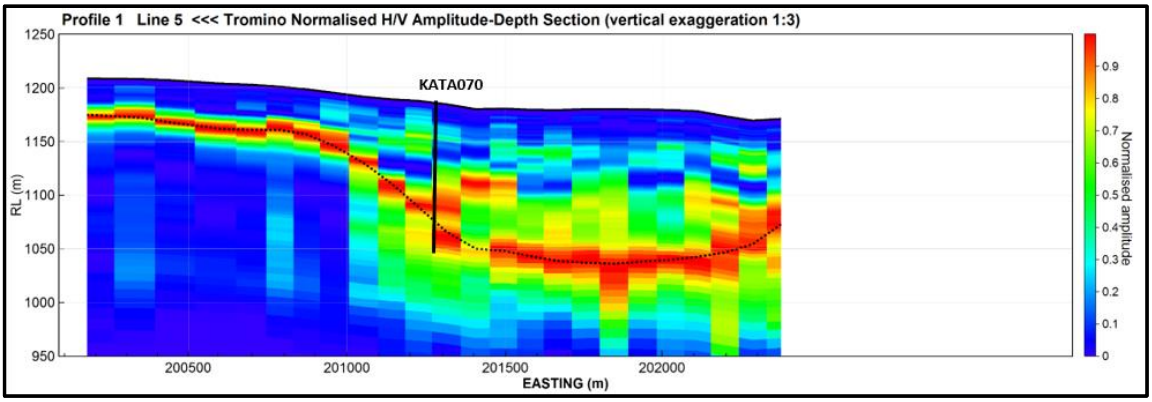

Figure 10: Cross section of Line 5 with the black line showing KATA070 drill trace plotting at the inflexion point.

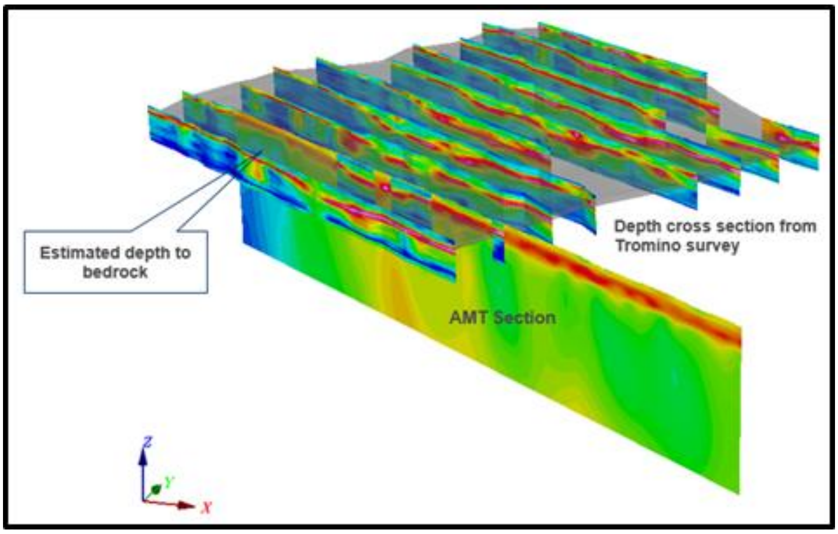

Figure 11: 3D view of the interpreted bedrock surface presented as a transparent surface with the AMT section and Tromino® depth cross section, viewed from the south-east.

CONCLUSIONS

The Tromino® data from North West Zambia has shown that the passive seismic HVSR technique can work very well in detecting depth to the bedrock layer with reasonable accuracy where suitable acoustic impedance contrast exists with the underlying bedrock. Tromino®'s high cost- effectiveness, relatively low environmental impact with minimal labour, makes it a very useful tool for mineral exploration. Using an average shear wave velocity is a good approximation for estimating depth, but the regression method is more reliable when there are sufficient drillholes available for such calibration.

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REFERENCES

Buckerfield, S., Czarnota, K., Gorbatov, A., 2016: Benchmarking passive seismic cover depth assessments: 25th ASEG conference, Adelaide, Expanded Abstracts.

Morgan, D. J. R., Raines, M.G., Thorpe, S., Castellaro, S., Bailey, E., Wilby, P.R., 1988, Passive Seismic Surveying: A new and Cost-effective site-assessment tool for the quarrying industry: www.Agg-Net.com pp 20-22.

Nakamura, Y., 2000, Clear identification of fundamental idea of Nakamura's technique and its applications, Proc. 12WCEE, No. 2656, 177–402.

Owers, M.C., Meyers, J.B., Siggs, B., Shackleton, 2016, Passive Seismic surveying for depth to base of paleochannel mapping at Lake wells, Western Australia: 25th ASEG Conference, Adelaide, Expanded Abstracts pp 42-50.

Smith N. R. A., Reading A. M., Michael A. W., Charles F.W., 2013, Depth to basement and seismic velocity structure from passive seismic soundings in central Australia: 23rd ASEG Conference, Melbourne, Expanded Abstracts, pp1-4

Raines, M.G., Banks, V.J., Chambers, J.E., and Collins, P.E.F., 2015, The Application of Passive Seismic Techniques to the detection of Buried Hollows: 14th Sinkhole Conference, Rochester, Expanded Abstracts, pp 423-429.