Passive seismic surveying for depth to base of paleochannel mapping at Lake Wells, Western Australia

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SUMMARY

Goldphyre Resources Limited (Goldphyre) undertook a passive seismic survey over parts of the Lake Wells project using Tromino 3G seismometers. Modelling of the passive seismic survey data has defined the depth to bedrock and location of a deep, E-W trending paleochannel system occurring beneath a broad salt lake playa, where underlying Cainozoic paleochannel deposits likely form a reservoir system for potash brines. Drilling by Goldphyre supports these findings. A total of 180 readings were acquired along six survey line traverses over the salt lake, spaced 1,200 m to 2,100m apart on average, using four Tromino seismometers and 20 minute recording times. The passive seismic data were analysed using the H/V spectral ratio (HVSR) method, whereby the spectral ratio of the horizontal and vertical component data are assessed to determine a resonant frequency of an upper softer layer having low S-wave velocity sitting above a high S-wave velocity bedrock. The depth of the upper layer is related to the resonant frequency and S-wave velocity by a simple formula: $f_0 = V_s/(4h)$, where f_0 = peak frequency in Hz, V_s = shear wave velocity in m/s and h = thickness in m.

The modelled passive seismic survey depth to bedrock estimation has delineated a paleochannel system over 20 km long, up to 4 km wide and up to 170 m deep. In addition, the paleochannel system was found to branch to the northwest and southwest, and remains open in these directions. A paleochannel of these dimensions can potentially provide significant high-grade sulphate of potash (SPO) mineralisation hosted in the paleochannel brines.

The passive seismic method is commonly used for seismic hazard mapping, and has not been used extensively for mineral exploration up to now, as very broadband seismometers have typically been used in array configurations that take significant time to setup and record data. The Tromino seismometers are self-contained, lightweight, portable and very simple to use. The HVSR method of analysis allows the user to quickly estimate the thickness of softer sediment cover over hard basement rocks ranging from 0 to 500m. This method has many applications for mineral exploration, and it may become a standard survey tool to predict thickness of cover deposits and reduce drilling costs.

Key words: passive seismic, Tromino, paleochannel, HVSR, potash brines, resonant frequency

INTRODUCTION

Goldphyre are exploring the Lake Wells project area for high grade potash brines located within Cainozoic palaeochannels sitting below a broad, Quaternary salt lake playa system. The Lake Wells Potash project is located approximately 180 km to the NNE of Laverton in Western Australia (Figure 1, inset). Paleovalleys are interpreted to occur underneath the thin salt lake sediments, and may provide a reservoir for a significant volume of potash brines. The salt lake sediments overlie Archaean granitic and greenstone rocks of the north-central Yilgarn Craton (Figure 2).

The contrasting acoustic impedance properties (density multiplied by the shear wave velocity) between the soft, low impedance porous salt lake sediments, and the high impedance, hard Archaean fresh bedrock, provides an ideal geological setting for passive seismic surveying using the H/V method (Nakamura, 1989 and 2000) to estimate the thickness of the paleovalley prior to drilling, and to thereby reduce the number drillholes needed to map paleochannel geometry in detail.

A passive seismic survey was undertaken at Lake Wells in late 2015 to ascertain the depth of paleochannel sediments under the salt lake, which was considered to be too conductive for using EM or galvanic resistivity methods to map the paleochannel thickness. The passive seismic survey was carried out using four Tromino 3G ENGY seismometers. Readings were taken over 20 minute periods at a nominal station spacing of 100 m along six traverses oriented in various directions perpendicular to the inferred paleochannel strike, and line spacing varied from 1,200 m to 2,100 m (Figure 3). A bucket was placed over the Tromino instruments to reduce wind noise, and the instruments performed well under high temperatures (40-50°C).

The Tromino data were checked for noise levels and then processed, modelled and interpreted. The base of the paleochannel was modelled from depths of less than 10m to as deep as 170 m across the survey area and the data were tied to bedrock depths from ten existing drillholes. Drilling is currently being planned to uncover the geological and geochemical nature of the channel fill in terms of sediment type, porosity, permeability and potash brine contents.

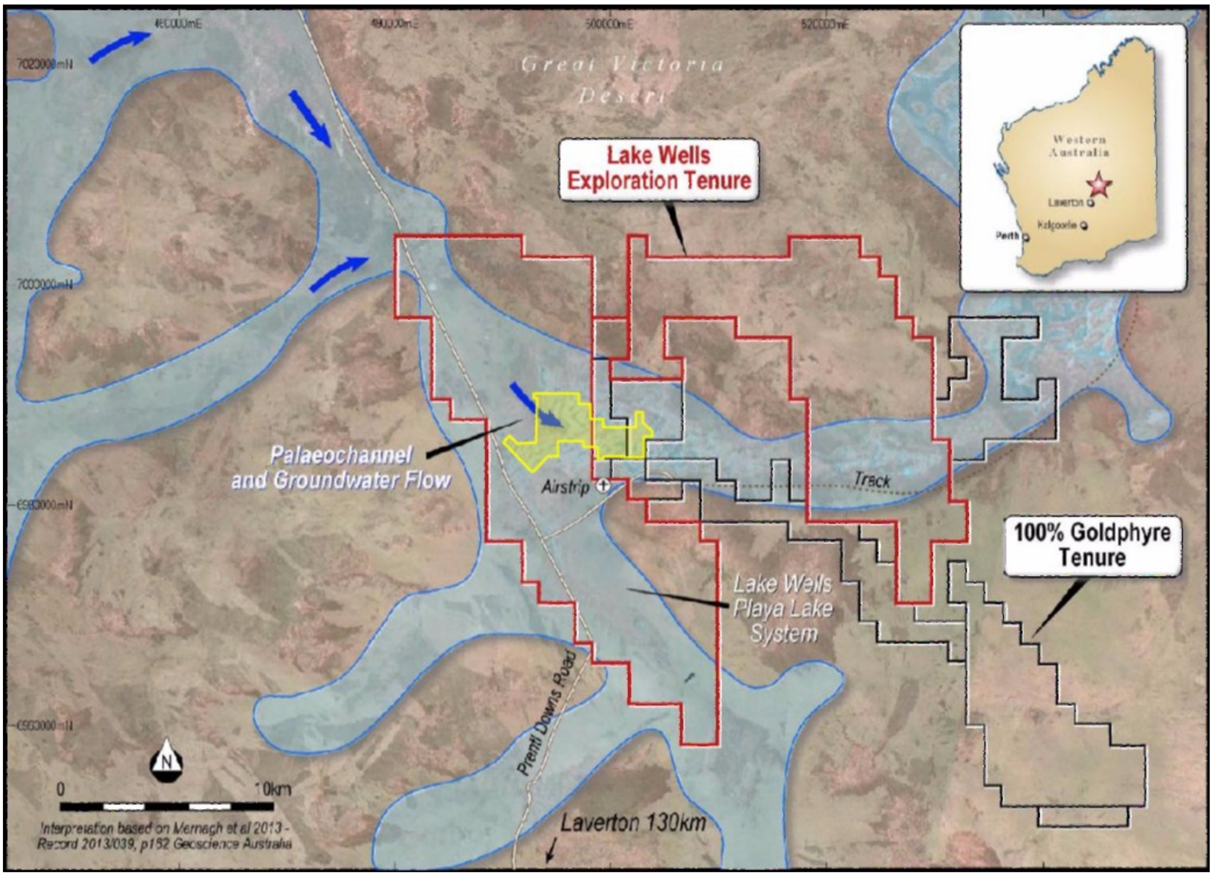

Figure 1: Goldphyre's Lake Wells Project. An aerial photograph underlies an image showing the bounds (yellow) of the passive seismic survey undertaken in 2015 and the salt lake system at Lake Wells (outlined in blue). Image modified from Goldphyre Resources.

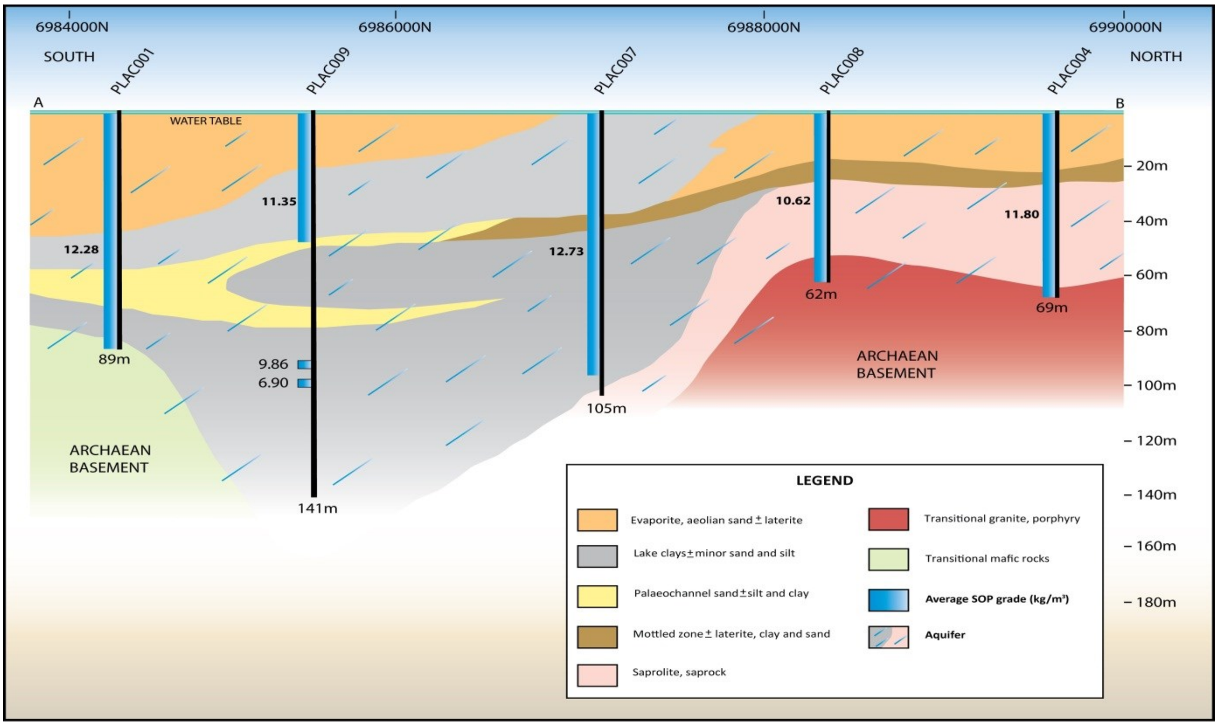

Figure 2: Geological cross-section of the Lake Wells Project showing typical paleochannel architecture.

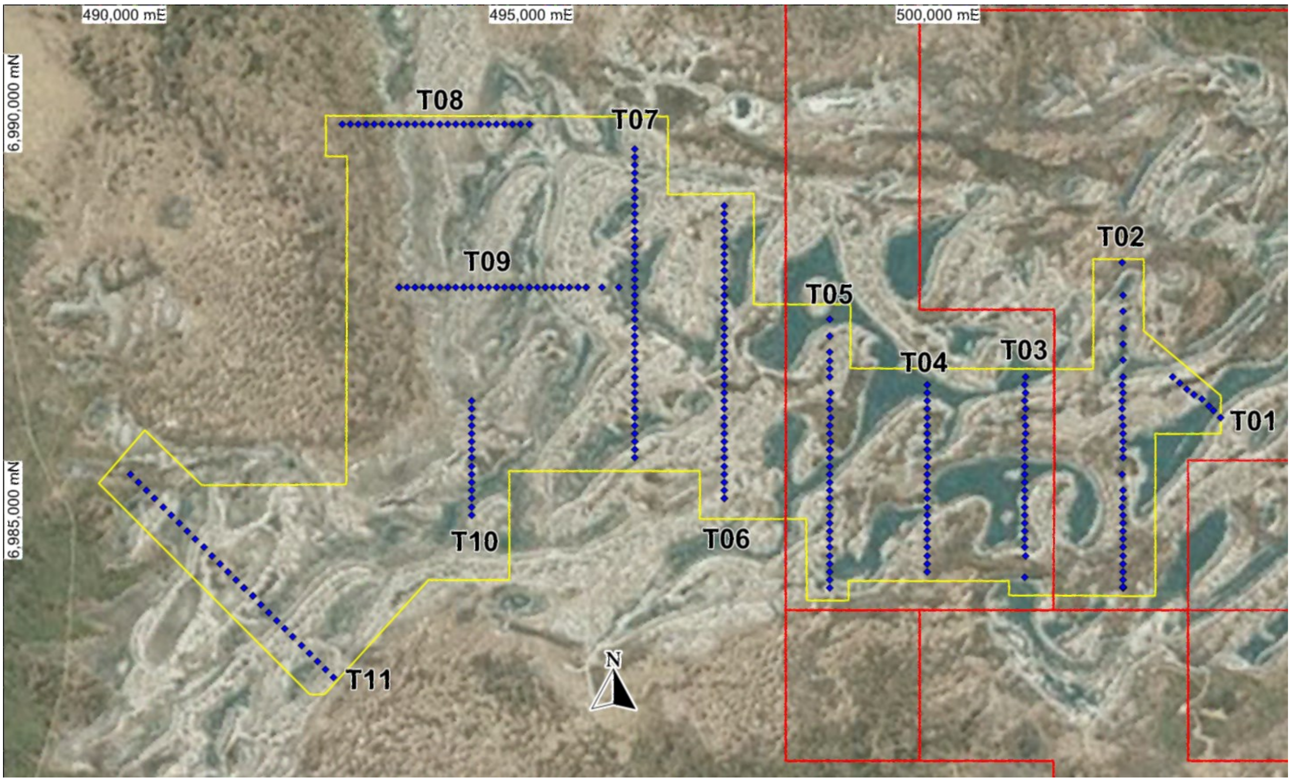

Figure 3: Aerial photograph of the Lake Wells project area showing the passive seismic survey line numbers and station locations (blue diamonds) for the 2015 survey (outlined in yellow). Goldphyre's tenements are shown as red outline.

METHOD AND RESULTS

The passive seismic HVSR method employed at this project relies on the horizontal to vertical spectral ratio (HVSR) as described by Nakamura (1989 and 2000) to determine the peak frequency of the soft sedimentary layer above a harder layer, providing a strong impedance contrast, and from that, estimate the depth of the observed interface between the soft and hard layers.

Theory Behind the Passive Seismic Method

The theory behind the passive seismic method is that resonance of surficial shear waves (Rayleigh and Love waves) develops in a soft, shallow layer overlying a hard layer with much higher seismic impedance. Data are recorded over a long period of time (5 to 30 minutes) and over a wide range of frequencies, compared to conventional active seismic survey methods which record body waves over a short time and over higher frequencies and mute out the surface waves or "ground roll". 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 (Figure 4). This resonant frequency is related to the thickness and shear wave velocity of the resonant layer by the following equation from Nakamura (2000):

Equation 1: $f_0 = V_s \,/(4h),$

where f_0 = peak H/V frequency (Hz), V_s = S-wave velocity of upper layer (m/s), h = thickness of layer (m).

Three approaches are available to extract cover thickness information from the data once the H/V peak frequency has been determined. The first method is to apply the known layer thickness obtained from nearby drilling to constrain the model and characterise the layer velocities. The second method is applied when no drilling data are available: layer velocities are estimated from 1D modelling and then applied to model data from other passive seismic stations to estimate the layer thickness across the survey area. The third method for determining the layer thickness across a prospect area uses the depth of interfaces from existing drillholes, and the peak H/V frequencies observed in Tromino readings at those drillholes. The mathematical trend-line equation between the peak H/V frequencies and the geologically logged interface depths can then be used to compute the thickness of the cover layer at Tromino readings away from drillholes based on the measured H/V peak frequency alone. This method, therefore, requires a sufficient number of drillholes to produce a statistically valid trend, and a relatively high correlation coefficient, to give a meaningful relationship between the two parameters (e.g. Figure 5).

Application of the Passive Seismic Method at Lake Wells

Grilla software was used to import, QC, process and model the Tromino data. The main processing steps carried out in Grilla are to statistically analyse the data for quality, remove any noisy or low signal portions of the recordings, convert the three component vibrations into frequencies using a Fast Fourier Transform (FFT), calculate the H/V ratio between the averaged horizontal components (H) and vertical component (V), and then present the result as a power spectrum (e.g. Figure 4). By applying restrictions or removing unwanted or noisy parts of the readings, the H/V peaks within the spectral response are enhanced. These H/V peaks occur at resonant frequencies which correspond to interfaces at which there is a strong contrast in acoustic impedance. Peaks that occur at higher frequencies relate to shallow interfaces, and lower frequency peaks relate to deeper layer interfaces (e.g. Figure 6).

The Grilla software also provides the capability to 1D forward model the Tromino data. The depth to the bottom of the upper layer, corresponding to the first H/V frequency peak must be entered manually, and then Grilla computes appropriate shear wave velocities and generates a synthetic velocity model response profile. The model is then manually adjusted to achieve a "best fit" between the actual field data response and the synthetic response (e.g. Figure 7).

Geological and drilling information usually provides the initial depths to constrain the modelling, but the western part of the survey area contained no drillholes, so the frequency-depth equation derived in the eastern part of the survey (Figure 5; Equation 2) was used to convert the H/V peak frequencies to depths at each Tromino station recorded in the western half of the survey. However, a number of stations along survey line T06 were also modelled individually to compare the modelled shear wave velocities and depths with the computed depths (Figure 9). In this case, the upper layer seismic velocity modelled for the eastern half of the survey (Vs = 380 m/s) was applied as the initial constraint in place of the depth (Figure 7; Table 1).

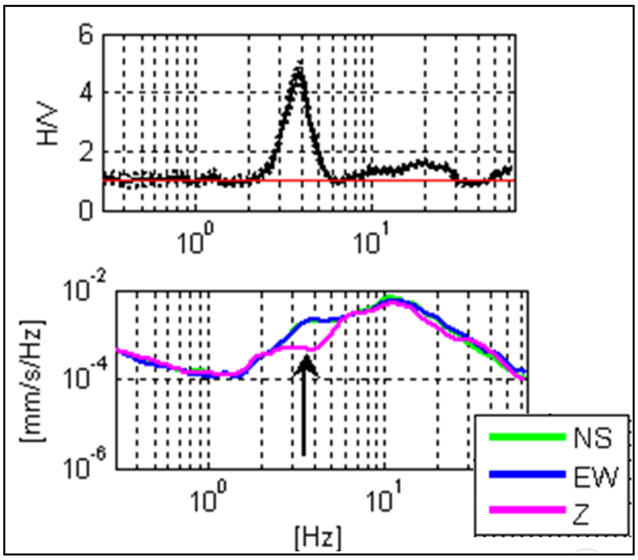

Figure 4: Example of seismic shear wave resonance peak for a single layer appears as a "dip" in the vertical seismometer component (pink line in lower panel). When ratioed with the averaged horizontal components, a peak results at the resonant frequency (black profile, upper panel at 2.8 Hz).

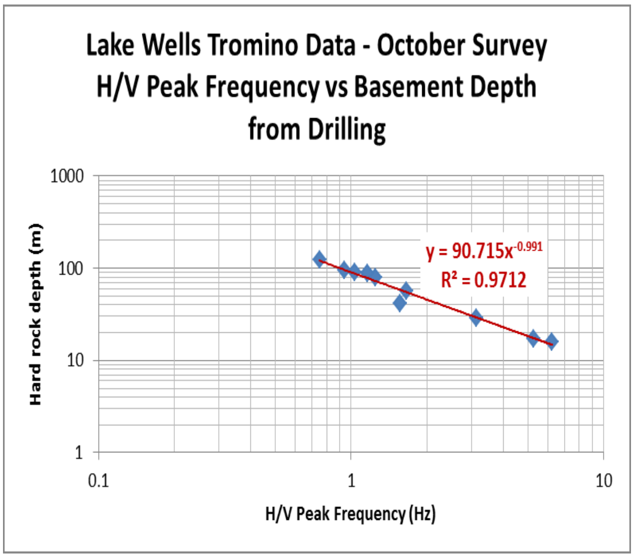

Figure 5: The frequency-depth relationship obtained by plotting the log of the peak H/V frequency against the log of the geologically observed depths to fresh bedrock/basement at Lake Wells determined by drillholes from the eastern part of the Tromino survey. The very good correlation here suggests a rather uniform S-wave velocity in the paleochannel sediments. The resulting mathematical relationship is expressed by Equation 2.

Equation 2: $$d = 90.715{f_0}^{-0.991},$$

where d = estimated depth (m), f_0 = peak H/V frequency (Hz).

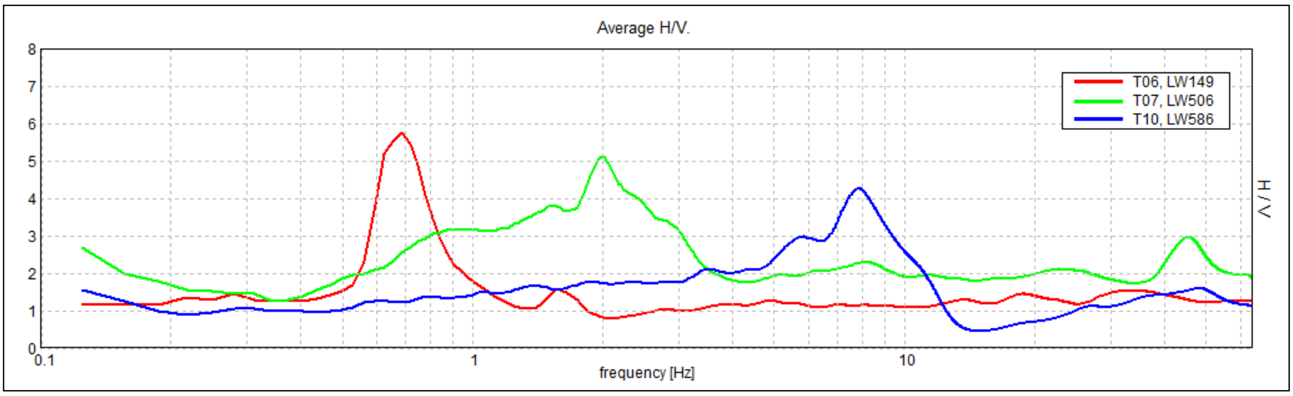

Figure 6: Sample H/V spectral plot presenting H/V amplitudes for three different readings with variable bedrock depths. The peaks occurring at different frequencies correspond to interfaces with significant acoustic impedance contrasts occurring at different depths: the low frequency peak (red) occurs at the deepest interface (130 m), the green peak at a moderate depth (50 m), and the high frequency blue profile relates to the shallowest interface (10 m).

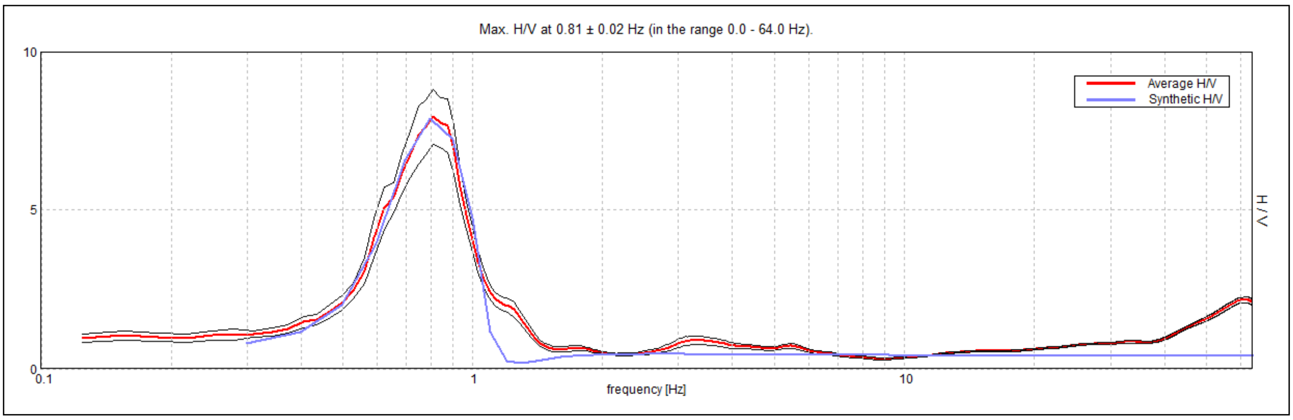

Figure 7: Sample H/V spectral plot displaying the peak H/V amplitude (red and black profiles) and corresponding forward model response (blue profile). Table 1 presents the model parameters used to achieve this fit.

Layer #	Thickness	Vs (m/s)	Density (t/m³)
1	130	380	1.9
2	---	950	2.2

Table 1: Model parameters used to achieve the synthetic response shown in Figure 7. The initial thickness was obtained from a nearby drillhole, from which the velocity was determined by modelling using the known bedrock depth.

Figure 8 exhibits a cross section with drillholes (pink lines) modelled to fit at each end of the survey line. The resultant layer 1 S-wave velocity was found to be 380 m/s. This figure proved to be quite reliable as it repeatedly characterised models created at other drillholes, where passive seismic readings were recorded (e.g. Table 1). Figure 8 displays the three drillholes along line T02; drillhole SDNI29 did not intersect basement.

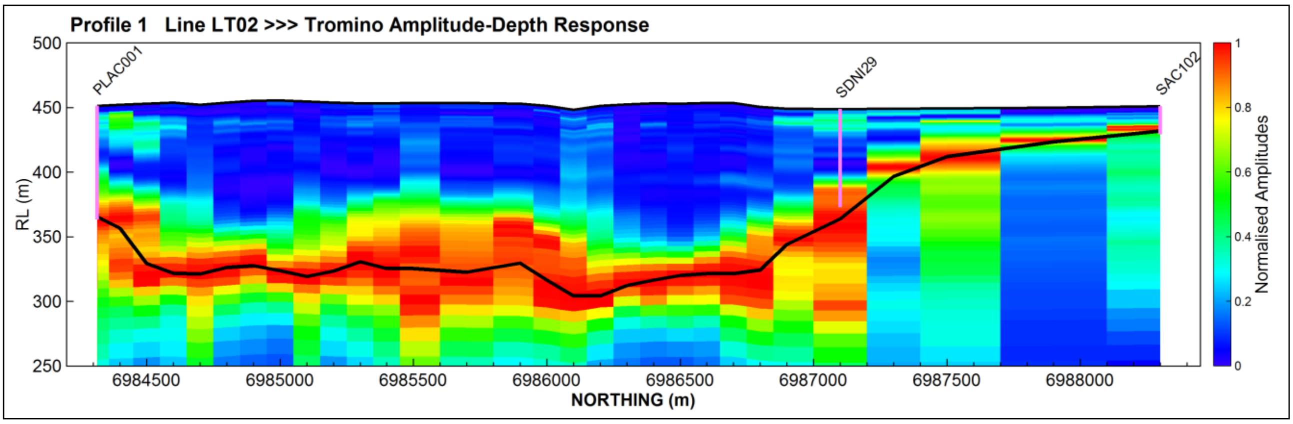

Figure 8: Cross section of modelled passive seismic depth to bedrock results (black profile) for survey line T02 overlaying the amplitude-depth section computed using Vs = 380 m/s from Equation 1. The drillholes (pink lines) at either end were modelled to the depth where the drilling intersected bedrock; however, drillhole SDNI29 did not reach bedrock. VE = 1:5

The depth to fresh bedrock was computed using Equation 2 for each passive seismic station. Cross section plots were then created along the survey lines to display the depth at each station as a profile overlaying a section coloured according to its H/V amplitude frequency response with depth. Figure 9 shows the amplitude-depth section for survey line T06. The thick white line in this profile indicates the depth computed from the peak frequency, and the two thin dashed white profiles effectively give an indication of the possible error range associated with the computed depths. The black crosses mark the modelled depths. Figure 9 shows that there is an excellent correlation between calculated depths (white lines) and the modelled depths (black crosses) to bedrock.

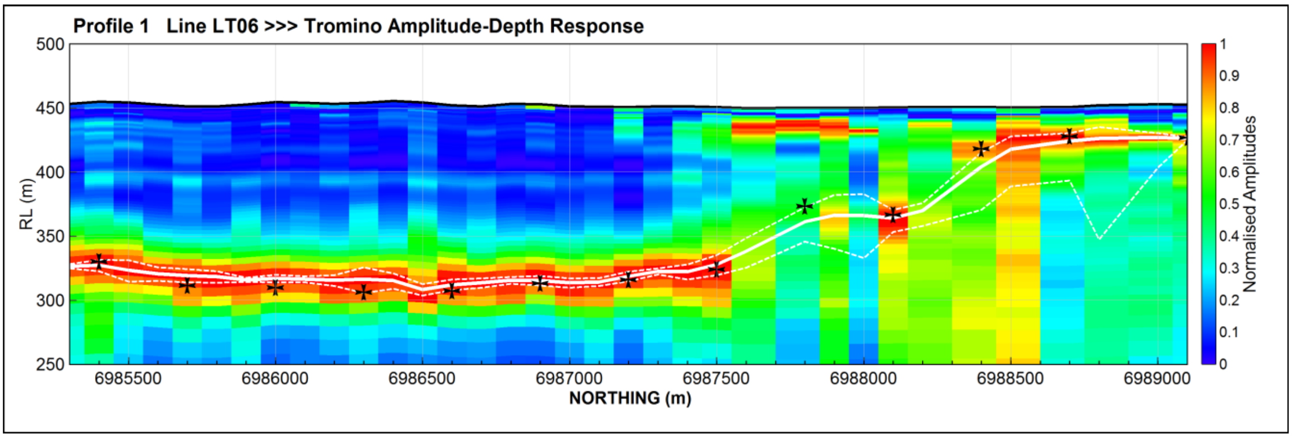

Figure 9: Cross section of survey line T06 showing the H/V amplitude data versus depth. The thick white profile represents the depth computed from Equation 2 derived in the eastern half of the Lake Wells Tromino survey. The thin dashed white profiles exhibit the error associated with the depth computation, while the black crosses are the modelled depths. The modelled depths generally fall within, or very close to, the error envelope of the computed depths, showing an excellent correlation between these two depth estimation approaches. VE = 1:4

As a final validation of the Tromino passive seismic data processing procedures, Equation 1 was also applied to the peak frequency data using a constant velocity of 380 m/s. The resultant depths differed to the depths calculated using Equation 2 by an average of 3.5 m. Using the modelled depth values, a depth-to-fresh rock grid was created using a minimum curvature gridding algorithm. Figure 10 shows an image of the gridded model of the depth to fresh bedrock.

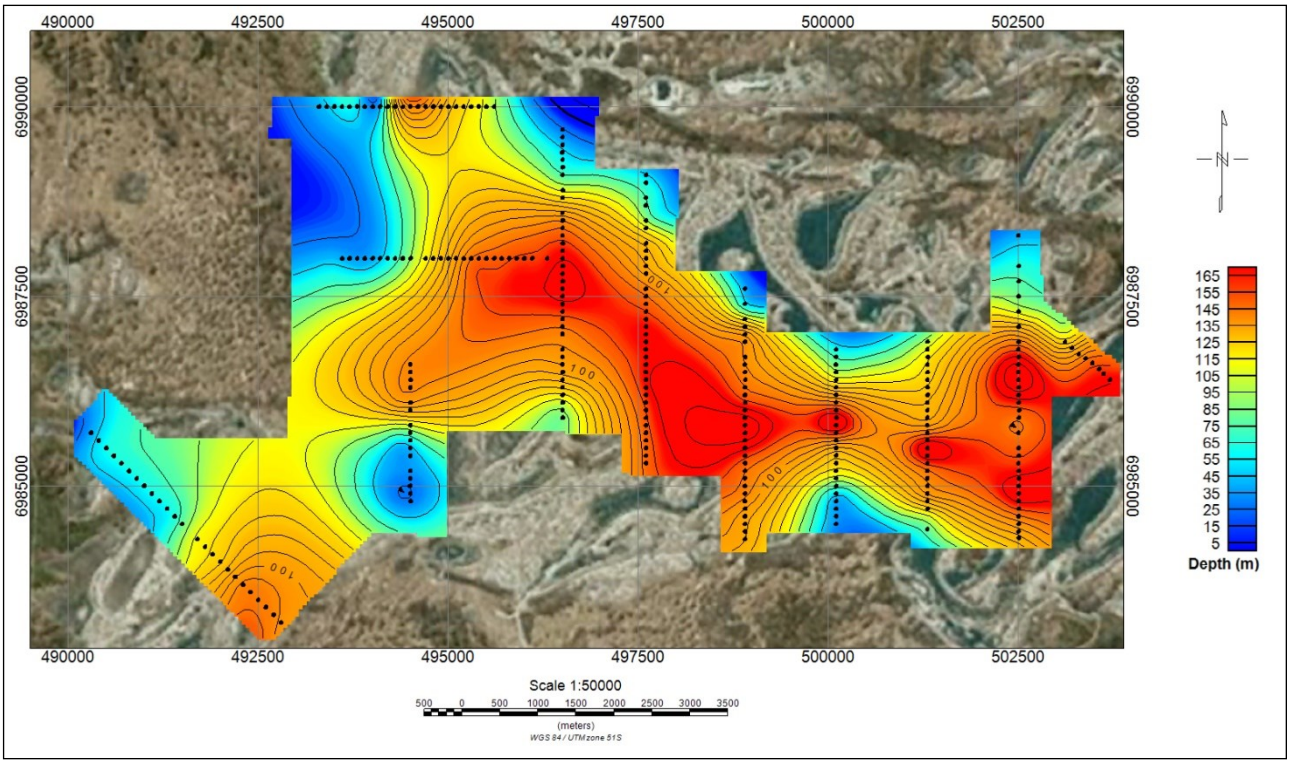

Figure 10: Image and contours representing the thickness of the paleochannel axis below the salt lake playa at Lake Wells, overlaying an aerial photograph. Depth contours are at 10 m intervals and Tromino survey stations are shown as black circles.

The interpreted paleochannel depth was transformed into a 3D body bounded by the SRTM surface at the top and the depth to fresh bedrock at the bottom. The volume of the 3D body was computed as 3.385 billion m³. Figure 11 presents the interpreted paleochannel as a transparent 3D body (in grey) with thickness surface displayed in colour underneath.

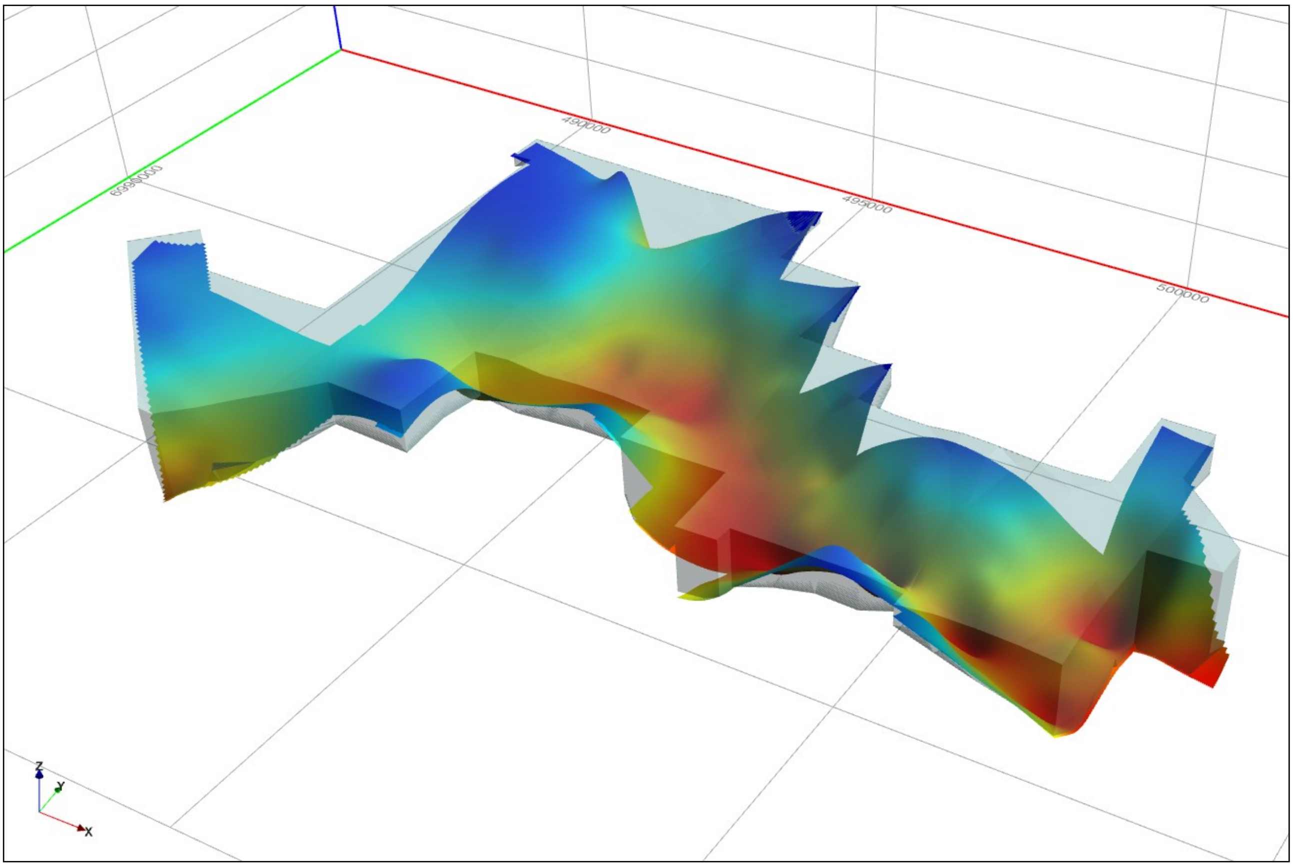

Figure 11: 3D view of the interpreted paleochannel presented as a transparent 3D body and the base of the paleochannel displayed in colour, with hotter colours showing greater depths, viewed from the southeast. Vertical exaggeration = 1:10. The volume of the paleovalley as surveyed by drilling and the passive seismic survey is estimated to be 3.385 billion m³.

The amplitude-depth sections shown in Figures 8 and 9 are a recent improvement in displaying passive seismic survey data results. They give more information about subtle response layers in the paleochannel sediments that are often overlooked in H/V frequency graphs (e.g. Figure 12). These subtle H/V peak responses from within the paleochannel deposits appear to be quite persistent in places (Figure 13). The subtle horizontal frequency responses likely relate to changes in sediment type, sands, silcrete/calcrete layers, clay layers, or leached zones, which may form reservoirs or aquitards to potash brines. Goldphyre intend to drill test sites along these survey transects in the near future to properly identify the lithology, porosity and permeability, and potash brine contents.

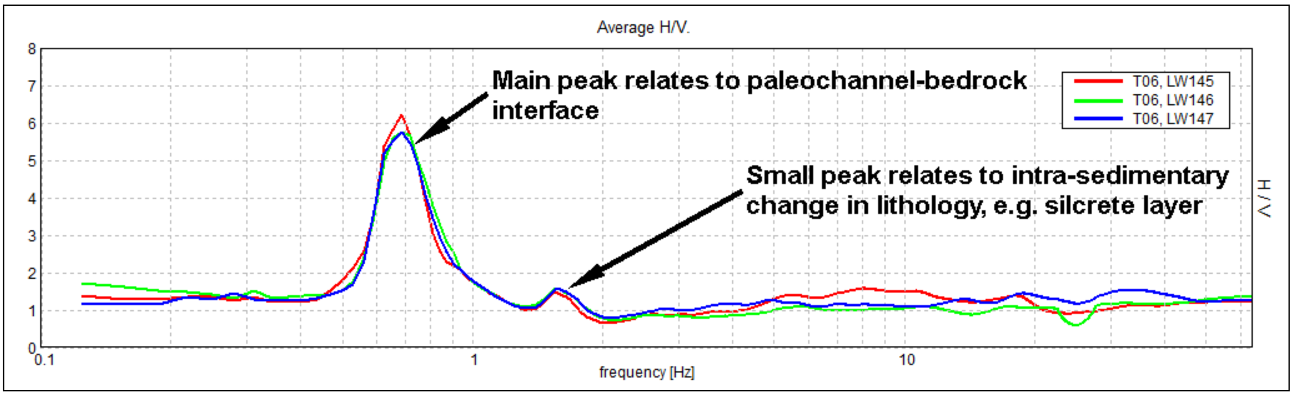

Figure 12: H/V profiles of three adjacent readings (red, green and blue). The main peak corresponds to the paleochannel-bedrock interface, and the small, higher frequency peak, relates to a more subtle interface within the paleochannel deposits, quite possibly a thin silcrete or calcrete layer. This small peak, however, was observed across more than these three readings, indicating that it is a fairly persistent lithological layer (see Figure 13).

The passive seismic survey line spacing at Lake Wells was quite broad, and the volume estimate of the paleochannel deposit is at a target to inferred stage. To get to a more indicated volume estimate, infill lines of Tromino readings could be carried out with additional drilling to map out the paleochannel geometry in more detail. Despite this, gridding the depth of the paleochannel system using the Tromino station data from both passive seismic HVSR surveys, indicates that the paleochannel has branches to the northwest and southwest, with depths commonly greater than 100 m from surface, and the paleochannel system remains open in these directions.

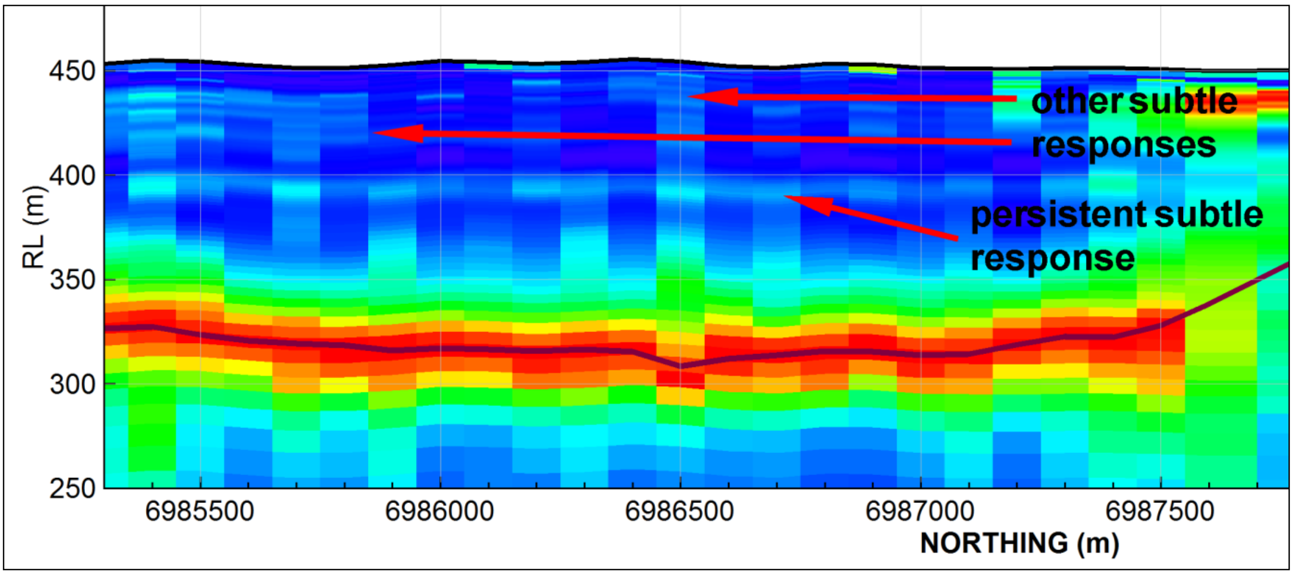

Figure 13: Detailed view of passive seismic traverse Line 06. The amplitude-depth sections highlight subtle H/V frequency responses, some of which persist right across the paleochannel. Other subtle responses, often closer to surface, are less persistent but may still be help in understanding the paleochannel architecture. VE = 1:4

CONCLUSIONS

The Tromino HVSR passive seismic survey at Lake Wells has provided excellent results which maps out the geometry of an extensive paleovalley system with far less financial outlay than other geophysical methods or a detailed drilling campaign to obtain the same paleochannel geometry information. In addition, the HVSR passive seismic method has been successful under highly conductive ground conditions that are unsuitable for electrical geophysical methods, such as airborne and ground EM, resistivity sounding, IP profiling, or GPR, which are often used to map paleochannel depths. The Tromino instruments also performed well at high temperatures of 40-50°C.

Modelled paleochannel depths reached 170 m below surface, with an average depth of 100 m, and when plotted spatially, successfully outlined the location of the paleochannel axes below the salt lake playa and sediment cover. The paleochannel system can now be considered to be at least 13 km in length and 2 km wide, but is likely longer as it remains open to the east, northwest and southwest. A 3D body of the interpreted paleochannel was also created and the volume of the modelled channel was estimated to be 3.385 billion m^3.

The passive seismic method using the portable and “user-friendly” Tromino seismometer will impact the future of exploration in regolith covered areas and for the direct detection of paleochannel and other basin-related mineral deposits, as this case study reflects. Tromino seismometers are small, lightweight, fully self-contained, and easy to use – a pair of Trominos can collect about 40 stations per day, per operator. Such is the ease-of-use of the Tromino, this survey was acquired by operators who were not geophysicists, and yet they were capable of taking readings using pairs of Trominos. Data processing and interpretation is carried out by specially trained geoscientists using Grilla and other software.

ACKNOWLEDGMENTS

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