Resource Potentials

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

for

AEGC2019
Data to Discovery

Australasian Exploration Geoscience Conference
2-5 September 2019 • Perth, Western Australia

Incorporating the **AIG**, **ASEG**, **PESA**, and **WABS**

3rd September, 2019

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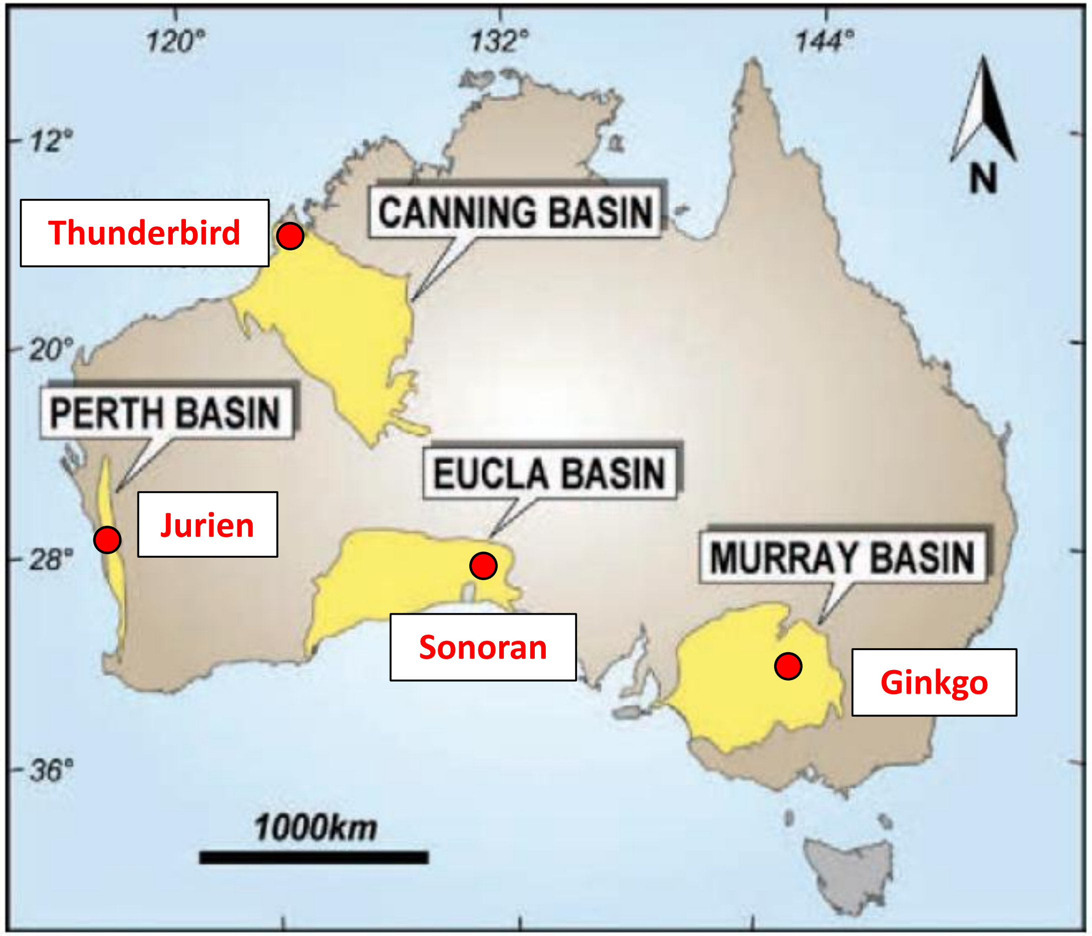
» Presentation Outline

Resource Potentials

- ❑ Passive seismic HVSR survey method
- ❑ Acoustic impedance contrast
- ❑ Case Studies
    - Ginkgo, Murray Basin, NSW
    - Sonoran, Eucla Basin, SA
    - Thunderbird, Canning Basin, WA
    - Aotea, North Island, NZ
    - Kazakhstan
    - Jurien, Perth Basin
- ❑ Summary of applications

Heavy mineral sand (HMS) provinces in Australia



Modified from AusIMM Monograph 32

» HVSR In Action

Resource Potentials

» HVSR Survey Method 1/2

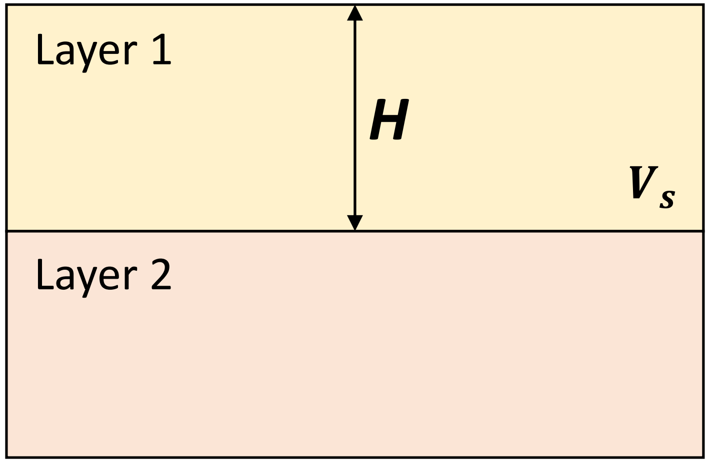
Resource Potentials

- Relatively new technique for mineral exploration as a sedimentary and regolith cover thickness mapping tool.

- Ambient shear waves (SH) become trapped in relatively soft and slow velocity sedimentary and regolith cover deposits overlying harder and higher velocity fresh bedrock or lithified sediments.

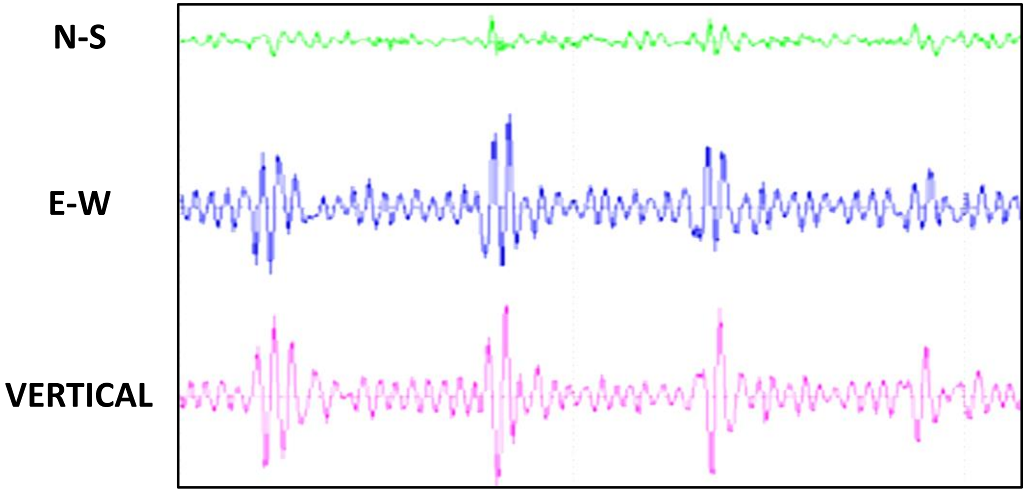
- Trapped shear waves in the soft cover layer over hard "acoustic basement" will have a resonant frequency (f_0), which is related to the average shear wave velocity (V_s) and thickness (*H*) of the softer cover layer by the formula:

$$f_0 = \frac{V_s}{4H}$$

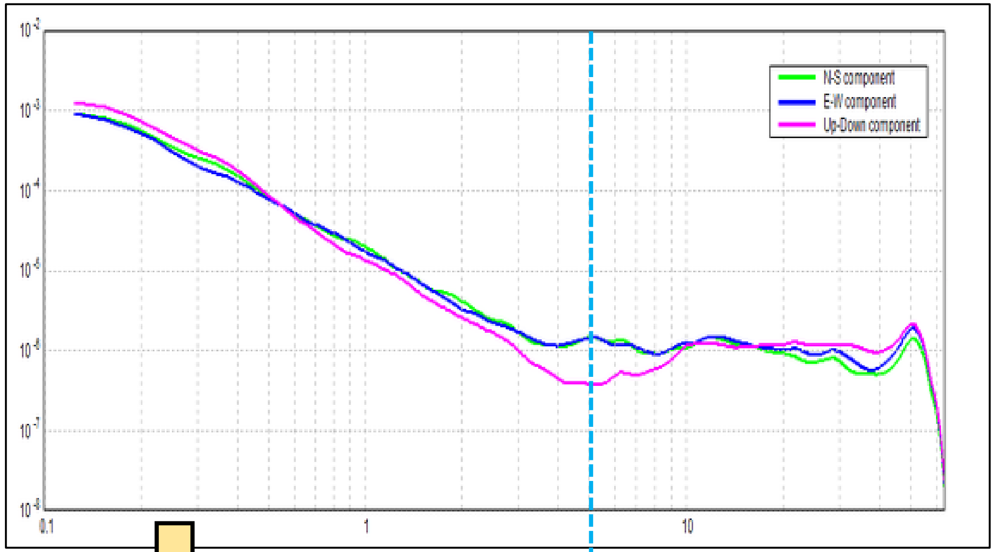


» HVSR Survey Method 2/2

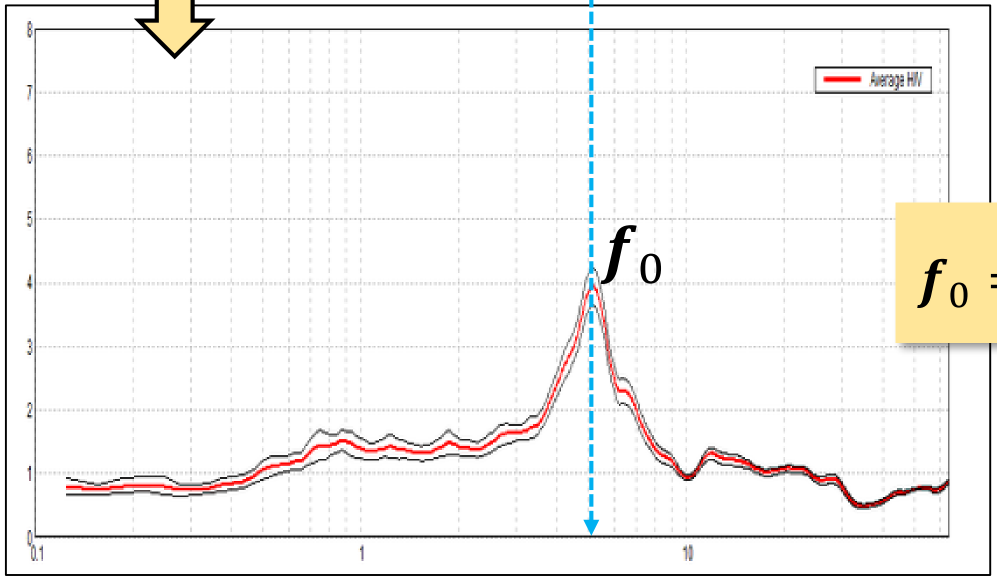
Resource Potentials



FFT



H/V



Frequency

$$f_0 = \frac{V_s}{4H}$$

- ❑ Measurement of ambient seismic vibrations in horizontal and vertical components over a recording time period for each passive seismic station, e.g. 10-20 minutes.

- ❑ Time series vibration data are converted to frequency spectra using Fast Fourier Transform (FFT).

- ❑ The resonant frequency is a peak in the Horizontal to Vertical Spectral Ratio (HVSR).

» Suggested HVSR References and Examples

Resource Potentials

- Historical and more recent papers by Nakamura – related f_0 to bedrock depth
- ASEG Conference Workshop 2016
- AIG Workshop 2017
- Other papers by Resource Potentials staff at this conference
- GSWA and GA, e.g. Buckerfield et al. (2016) – Benchmarking passive seismic cover depth estimates

» Acoustic Impedance Contrast

Resource Potentials

- A strong acoustic impedance (AI) contrast between each layer is required to generate seismic shear wave trapping and accompanying resonance.

- A layer's AI is given by multiplying its shear wave velocity and density.

- **AI contrast =** $\frac{AI_2}{AI_1}$

- A strong and sharp AI contrast boundary will produce a high amplitude HVSR response.

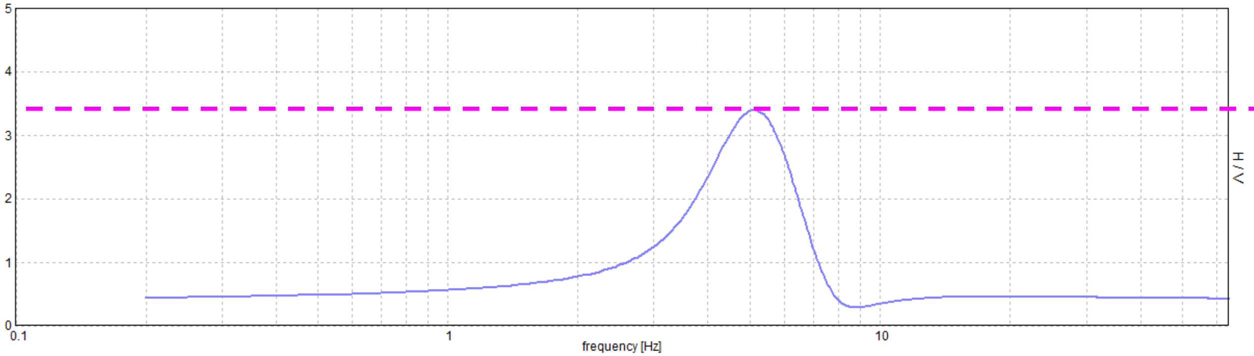
- HMS deposits may be directly resolved by the HVSR method if there is sufficient AI contrast, which may be more based on density rather than velocity difference to un-mineralised sands.

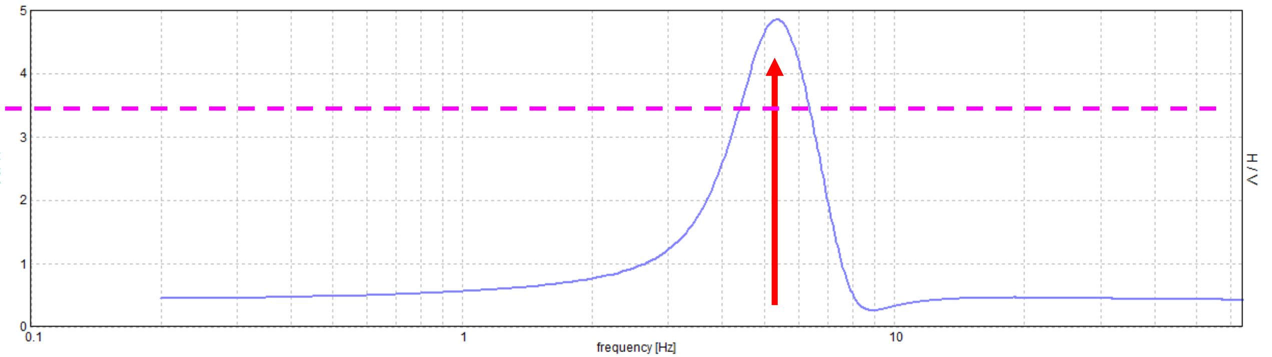
Layer 1 $AI_1 = V_{s_1} \cdot \rho_1$
Layer 2 $AI_2 = V_{s_2} \cdot \rho_2$

» Effect of Increased Density of Layer 2

Forward modelling the effect of increased density in Layer 2 for greater AI contrast:

Layer 1	Layer 1
V_{s_1} = 400 m/s	V_{s_1} = 400 m/s
ρ_1 = 1.4 g/cc	ρ_1 = 1.4 g/cc
Layer 2	**Layer 2**
V_{s_2} = 800 m/s	V_{s_2} = 800 m/s
ρ_2 = 1.9 g/cc	**ρ_2 = 2.2 g/cc**





Increased HVSR peak frequency amplitude due to higher density of layer 2

» HMS Mineral Density

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Heavy Mineral Density
(Not sand deposit bulk density)

- Rutile 4.2 to 5.5 g/cc
- Zircon 4.6 to 4.7 g/cc
- Ilmenite 4.7 to 4.9 g/cc
- Titanomagnetite 4.9 to 5.2 g/cc
- Monazite 5.0 to 5.3 g/cc

Case Studies

Ginkgo

Kazakhstan

Sonoran

Thunderbird and Jurien

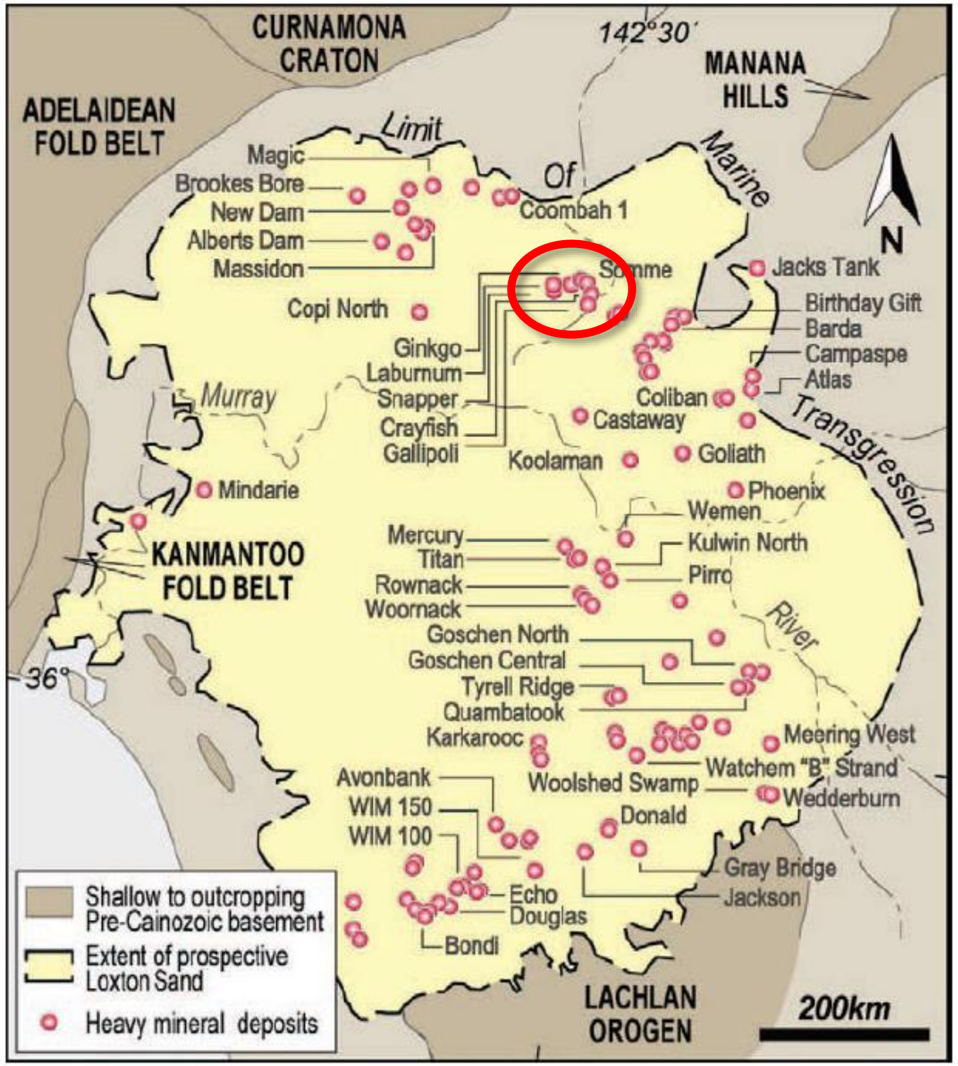
Aotea

Source: *Sand Atlas website https://www.sandatlas.org/heavy-minerals/*

» Case Study 1 > Ginkgo

Resource Potentials

- Ginkgo is one of a series of large strandline and "WIM" deposits containing ilmenite, leucoxene, zircon and rutile identified by Cristal Mining Australia Ltd in the late 1990's.
- Located in the Tertiary Murray Basin.
- Murray Basin covers an area 300,000 km2 across parts of NSW, VIC, QLD and SA, and is a low relief, saucer-shaped intra-cratonic basin, filled by a Cainozoic sequence of marine and terrestrial sedimentary deposits.
- Cainozoic sediments are weakly consolidated, with the HMS deposits forming near horizontally bedded sands that were deposited during marine transgressions and regressions in the Late Miocene to Late Pliocene period.
- Ginkgo is hosted within the Loxton Parilla Sands.

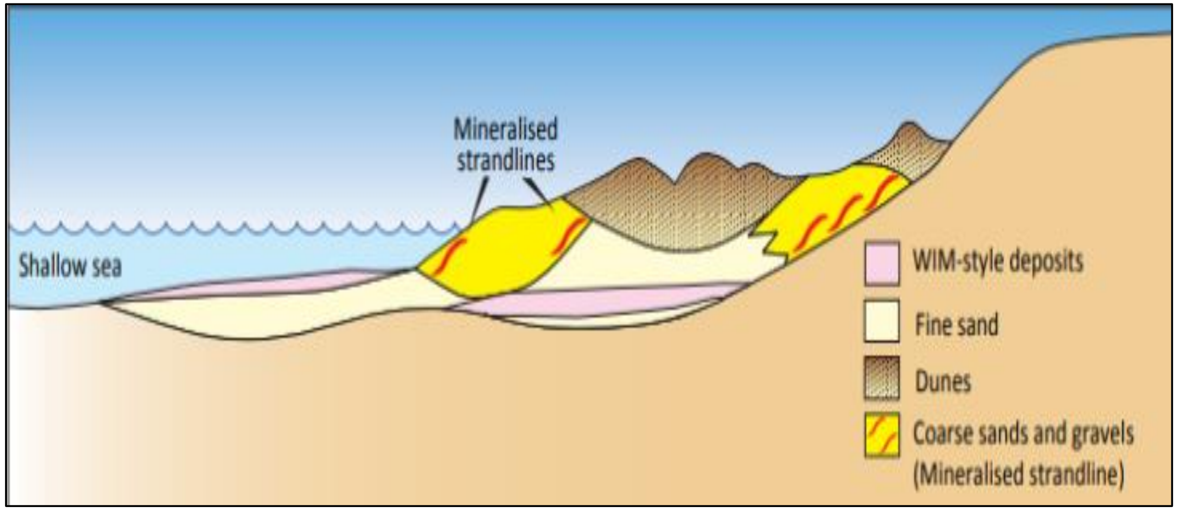


Reproduced from AusIMM Monograph 32, after Geoscience Australia

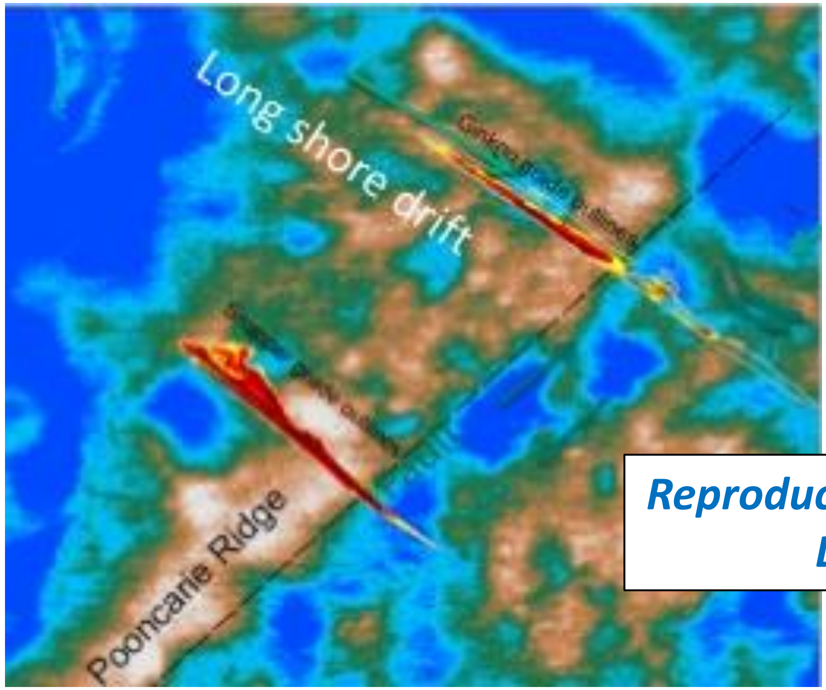
» Ginkgo Deposit Notes

- Ginkgo deposit dimensions:
  - NW-SE strike length of ~14km
  - Width varies from 250m to 900m
  - Overall thickness varies from 20m to 50m

- Ginkgo deposit is characterised by as many as five SW-dipping HMS mineralised zones with varying degrees of mineralisation grade.



DTM Image



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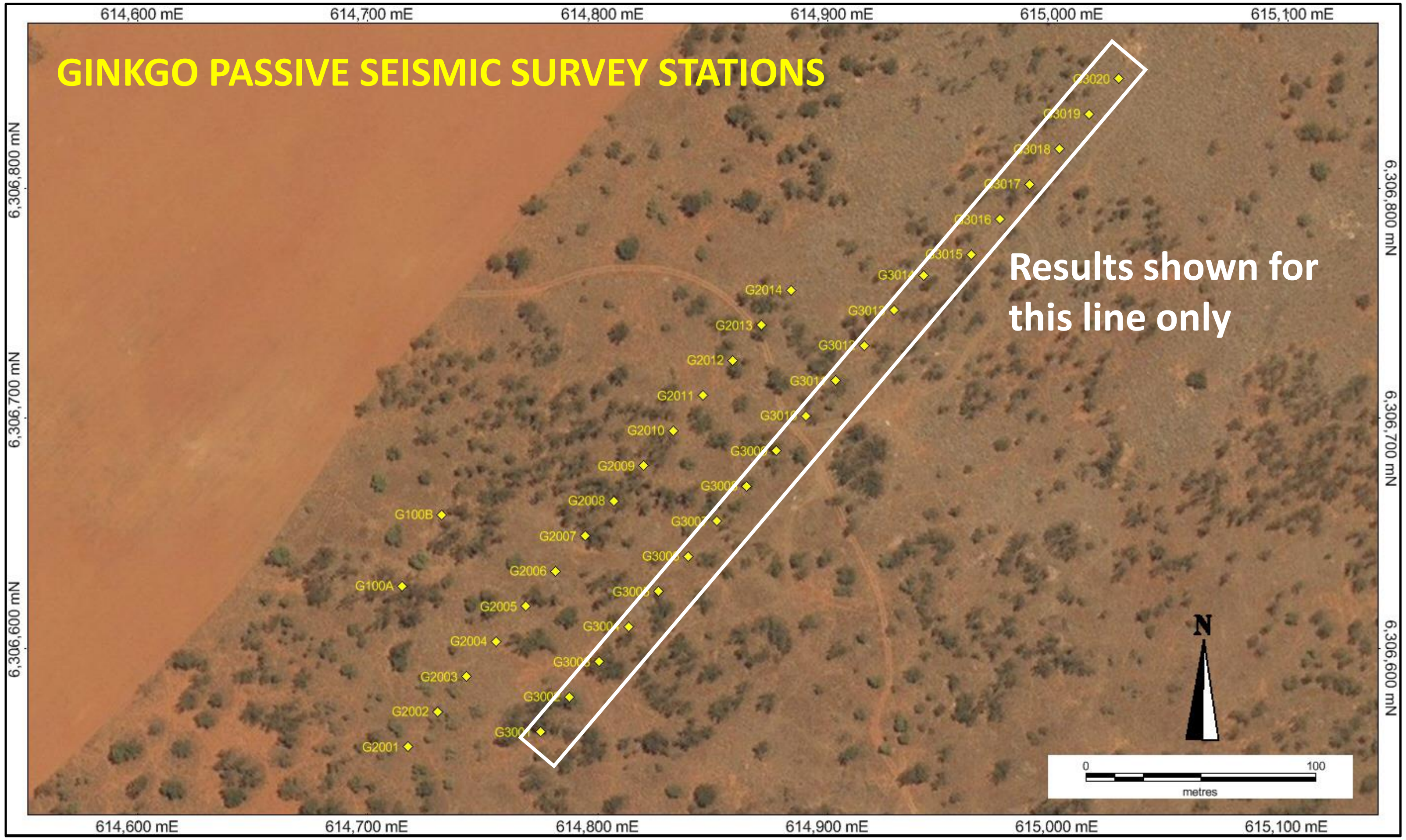
» Passive Seismic Survey Specifications

Resource Potentials

- Trial survey completed in a new prospect area with limited drilling information available to constrain the HSVR data modelling and to validate results and interpretation.



Station spacing: ~20 m

Acquisition time: 20 minutes

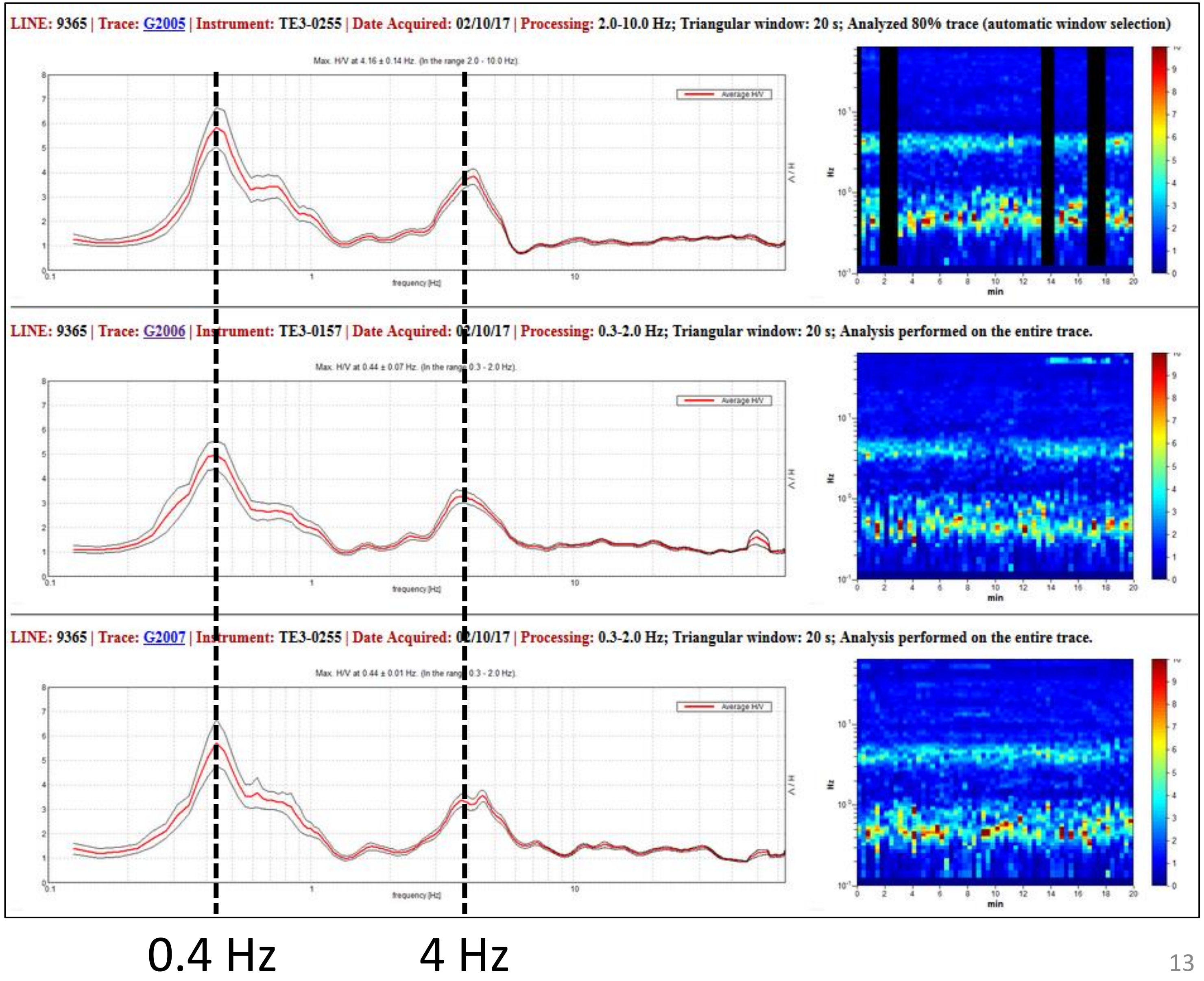
Total no. stations: 40 (~700m)

Just 1 day to complete this survey

» Typical HVSR Data Profiles From Ginkgo

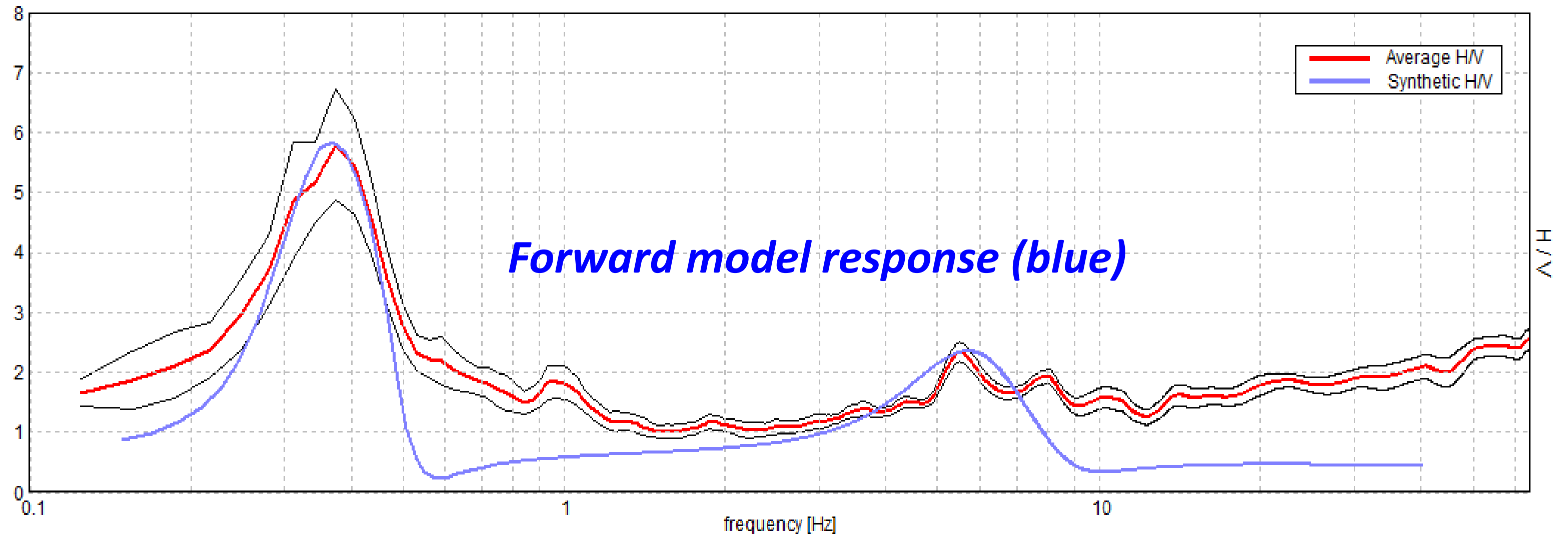
Resource Potentials

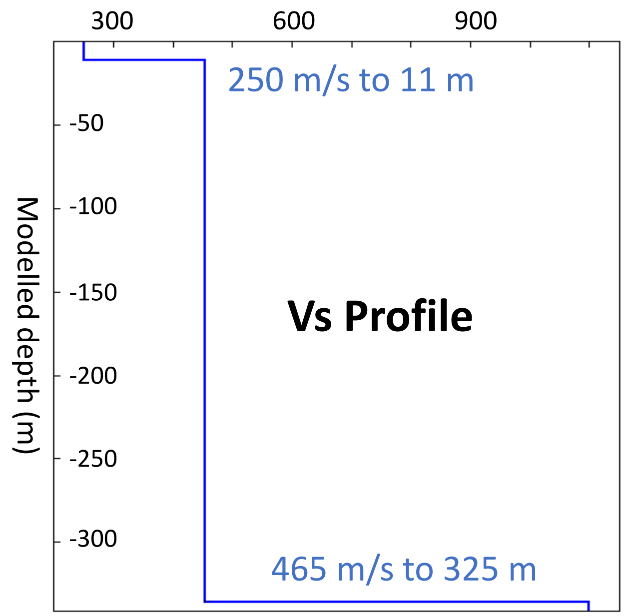
- ❑ Two main HVSR peaks resolved.
- ❑ A strong and broad HVSR peak at around 0.4 Hz ($\boldsymbol{f}_0$).
- ❑ A lower amplitude, but still very obvious peak at around 4 Hz.
- ❑ Minor additional peaks around these main peaks.



» 1D Modelling to Estimate Vs

Resource Potentials





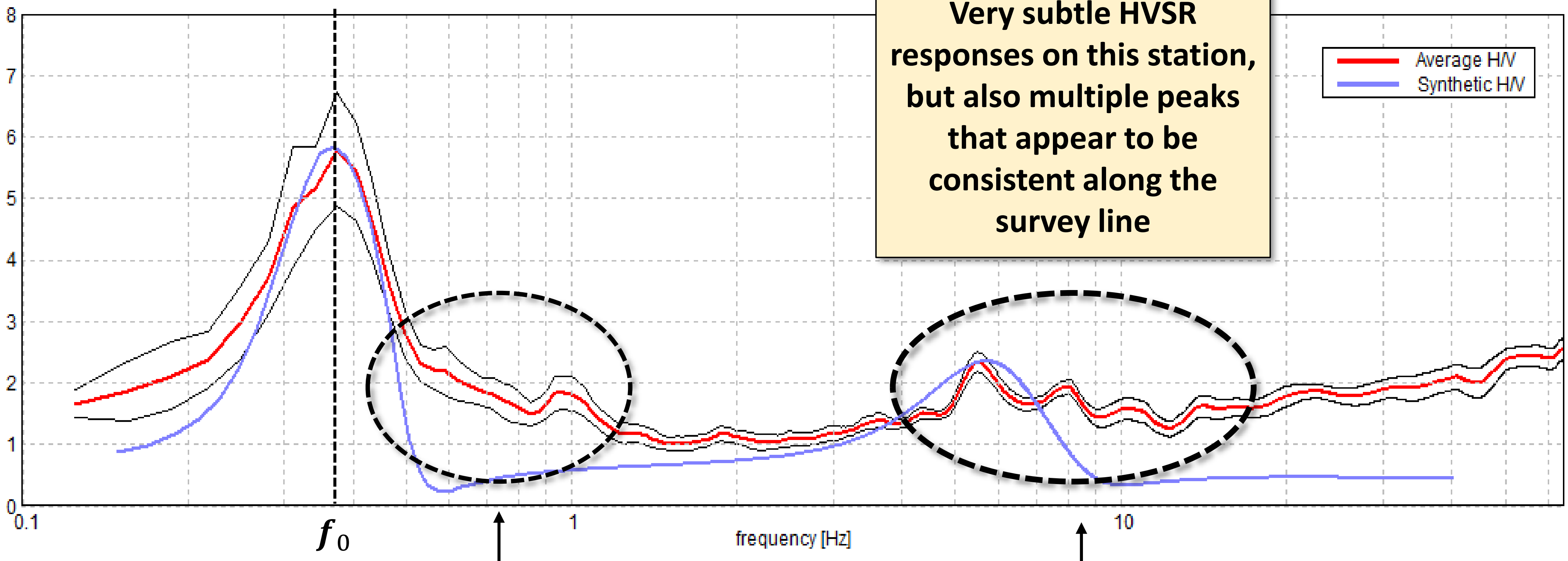
Using passive seismic data and drillhole data from nearby Snapper deposit

Hole ID	Tromino Station ID	Easting	Northing	Logged depth to top of Layer 1 (m)	Modelled Layer 2 Depth (m)	Peak Frequency (Hz)	Shear wave velocities for 3-layer model (m/s)			Density Layer 1 (g/cc)	Density Layer 2 (g/cc)	Density Layer 3 (g/cc)
							Vs1	Vs2	Vs3			
16SN177	SN0004	603665.9	6302846.7	10	325	5.53	250	460	1120	1.8	2.2	2.5
16SN178	SN0002	603684.6	6302863.4	11	320	5.53	250	480	1150	1.8	2.2	2.5
16SN179	SN0003	603703.1	6302880.1	11	325	5.49	250	465	1120	1.8	2.2	2.5
16SN180	SN0001	603721.7	6302896.9	11	340	5.81	250	475	1125	1.8	2.2	2.5

250 m/s

» Complex HVSR Responses

Resource Potentials



Very subtle HVSR responses on this station, but also multiple peaks that appear to be consistent along the survey line

HVSR anomaly peaks sitting above f_0 – gradational weathering into acoustic basement layer, limestone?

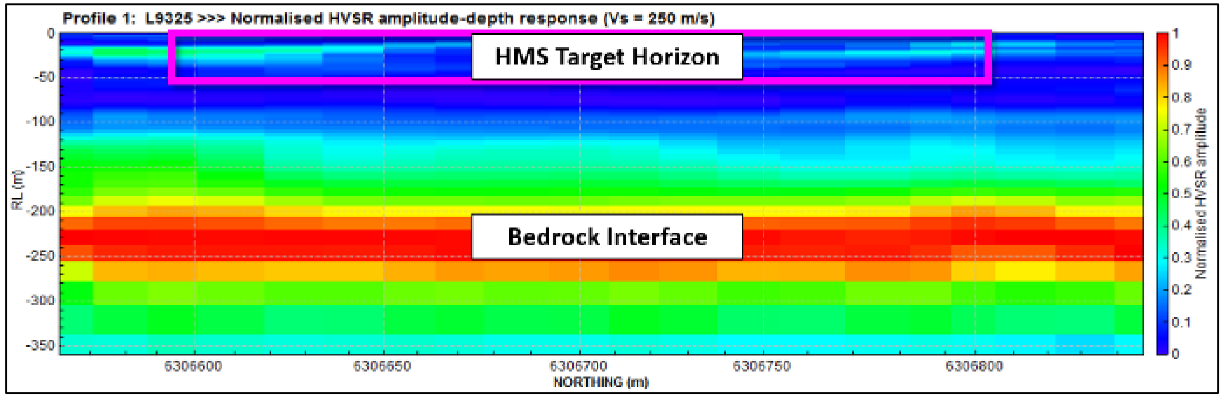
Cluster of HVSR peaks related to HMS layers

» HVSR Results

Resource Potentials

Full HVSR cross section:

350m

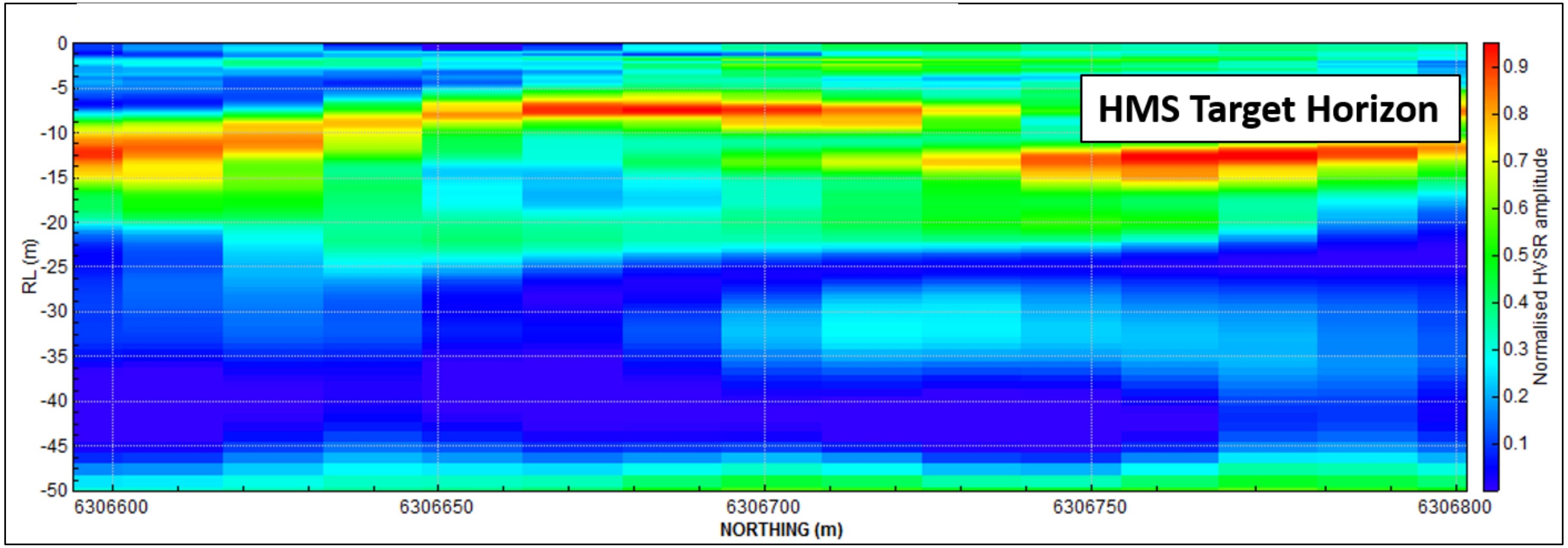


Average constant Vs 250 m/s

Basement interface depth is likely under-estimated when using a constant average Vs of 250m/s, because modelled velocity for 2nd layer is 465m/s

Zoom-in HVSR cross section:

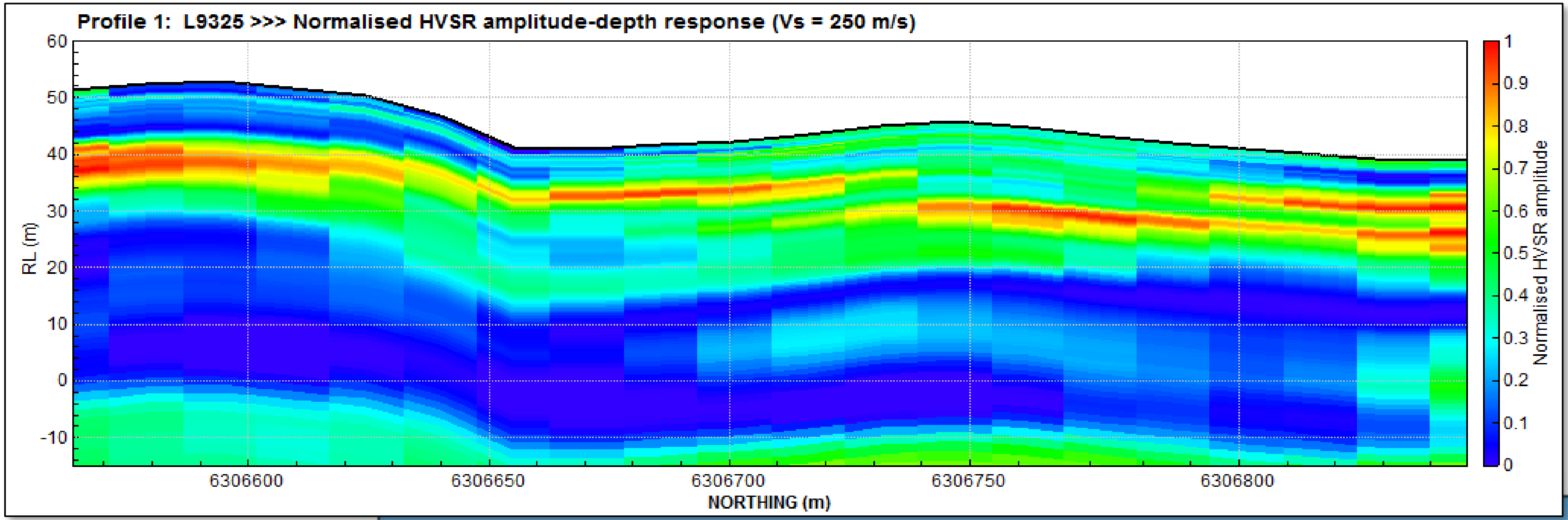
50m

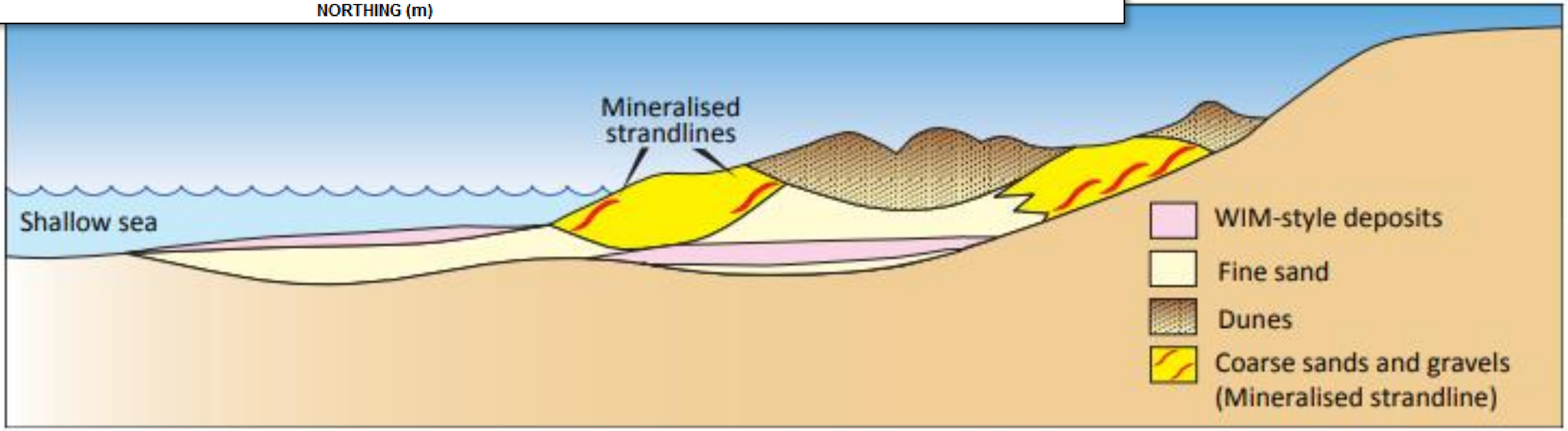


Multiple shallow dipping interfaces identified in the HMS deposit zone

» HVSR Section Drape to Hi-res DEM, Flatter WIM

Resource Potentials





» Case Study 2 > Sonoran

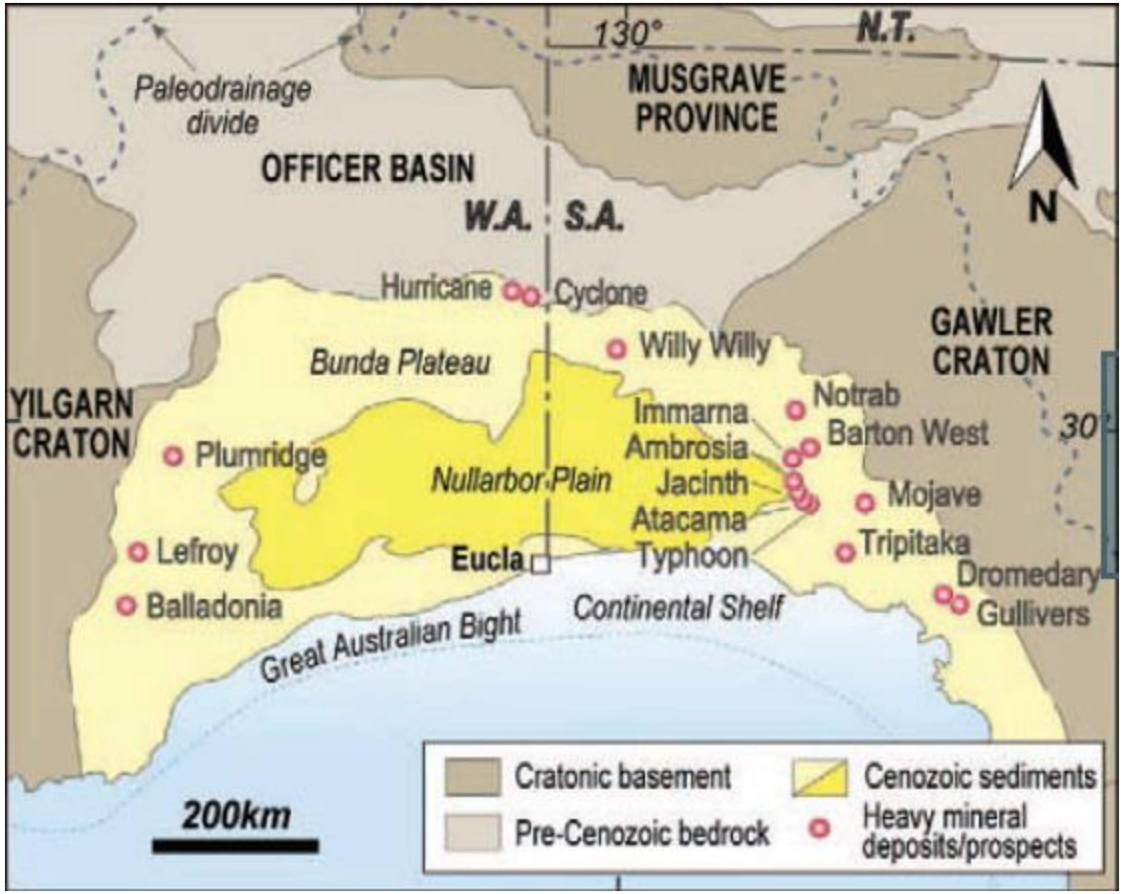
Resource Potentials

- Sonoran is a zircon-rich satellite deposit to the Jacinth-Ambrosia deposits, which all lie along a palaeo-shoreline of the Eucla Basin, SA.

- The eastern margin of the Eucla Basin contains Cainozoic coastal barrier systems containing HMS concentrations, which are now blanketed by aeolian dune and sandplain cover.

- Concentrations of coarse grained heavy minerals occur as beach placers in palaeo-barriers behind headlands and dunal systems, which are now represented by the Ooldea, Barton and Paling Ranges.

- Cainozoic sand ranges overly Proterozoic granite and greenstone bedrock forming palaeo-topography.



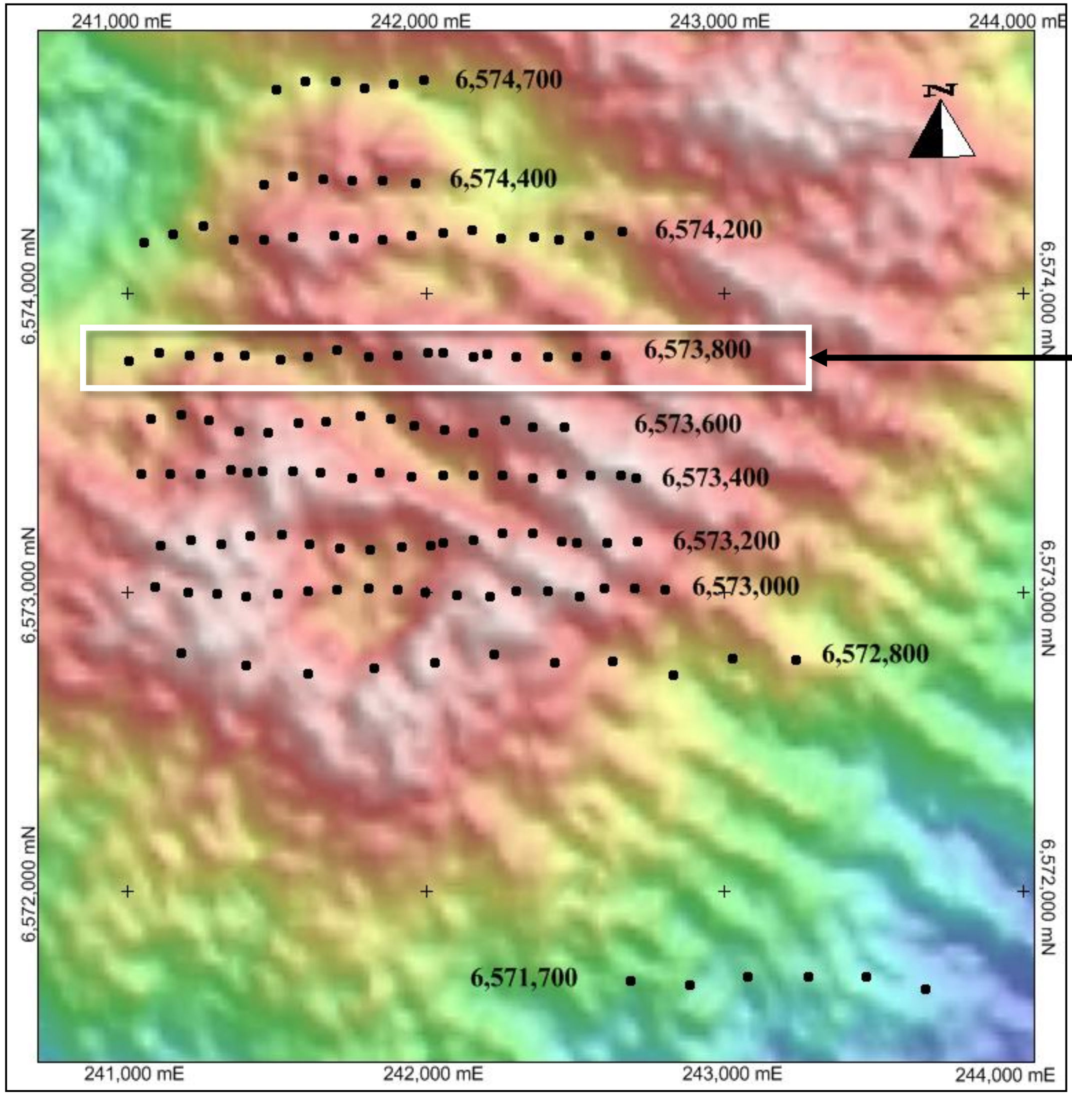
Reproduced from AusIMM Monograph 32

» Passive Seismic Survey Specifications

Resource Potentials

- ❑ Acquisition in 2015, uncompleted honours thesis
- ❑ 136 survey stations
- ❑ 10 survey lines
- ❑ 16 minute recording time
- ❑ Approximately 4 days to complete for 1 person with 2 seismometer units

Survey stations over DTM image



HVSR cross section results shown for this line

» Alternative Methods of HVSR Depth Conversion

Resource Potentials

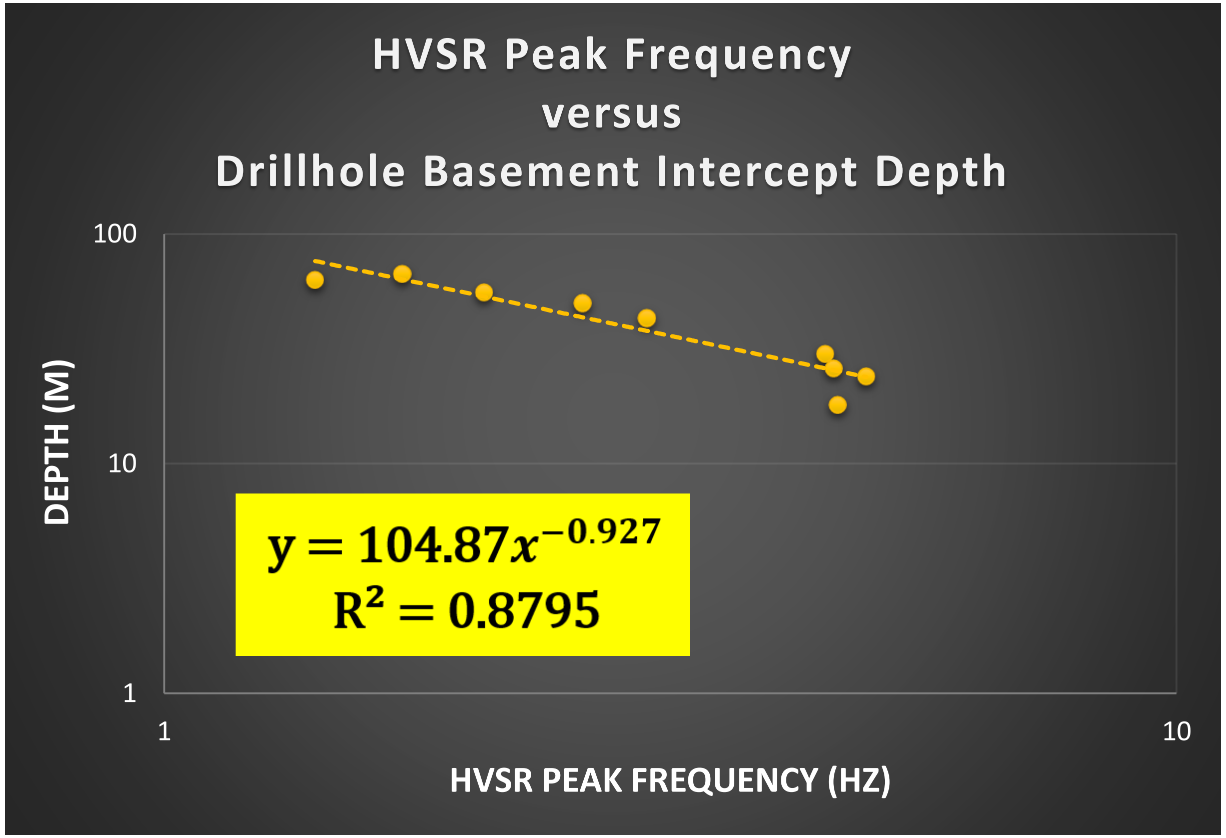
- ❑ Two alternative methods of HVSR frequency-depth conversion were trialled.

1) Using a constant average Vs calculated from drillhole information and the measured HVSR peak frequency from survey stations at or near the drillholes.

$$f_0 = \frac{V_s}{4H}$$

ID	Hole ID	Basement Depth (m)	HVSR Peak Frequency (Hz)	Vs (m/s)
1	SN0280	41	3.66	600
2	SN0281	26	4.81	500
3	SN0283	29	4.69	544
4	SN0353	31	3.94	489
5	SN0356	18	4.63	333
6	SN0357	26	4.59	477
7	SN0390	43	3.00	516
8	SN0391	50	2.59	518
9	SN0535	24	4.94	474
10	SN0562	67	1.72	461
11	YE4058	56	2.07	460
12	YE4059	30	4.50	540
13	YE4137	63	1.41	355
			Average Vs =	**482 m/s**

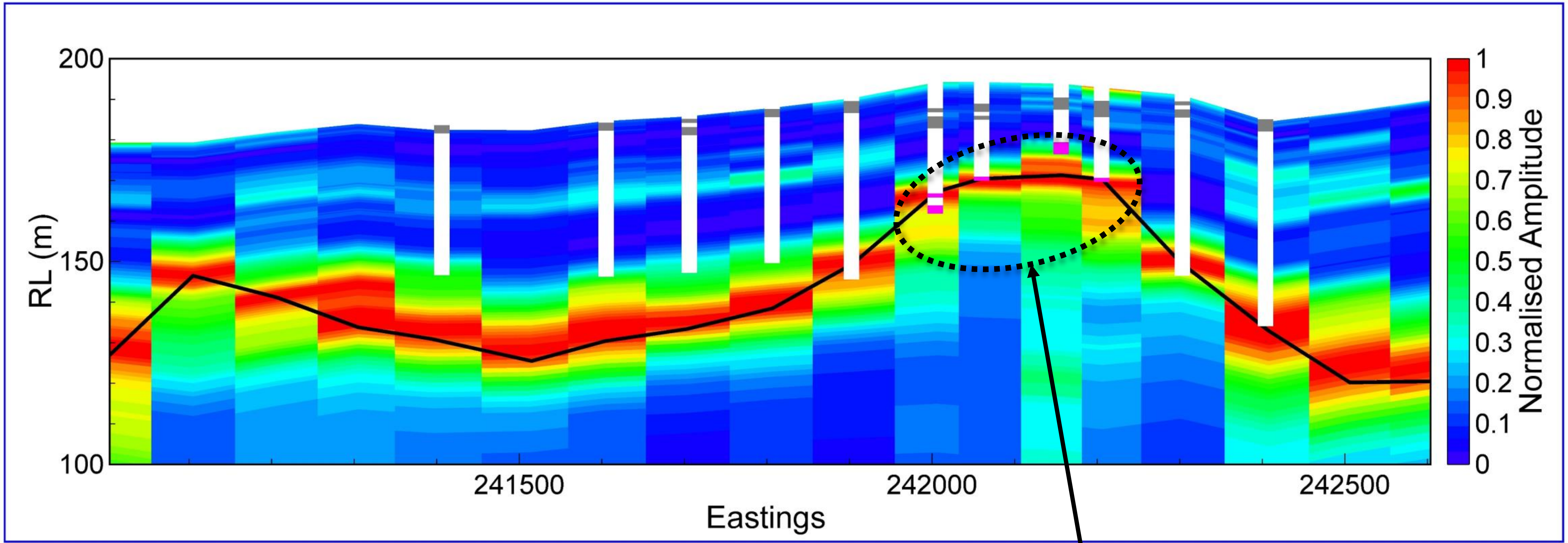
2) Using a frequency vs basement depth trendline equation by plotting drillhole information versus measured HVSR peak frequency at survey stations at or near drillholes; correlation co-efficient about 0.9. Accounts for compaction and velocity gradients.



» HVSR Results

Resource Potentials

- HVSR cross sections were produced from the trendline equation for depth conversion.
- Several drillholes reached granite-gneiss bedrock, especially over a basement high forming a palaeo-headland.



These drillholes intersected granite-gneiss bedrock towards the end of hole, whilst the other drillholes along this survey line did not intersect basement.

» Modelling of HVSR Peak Frequency Modes

Resource Potentials

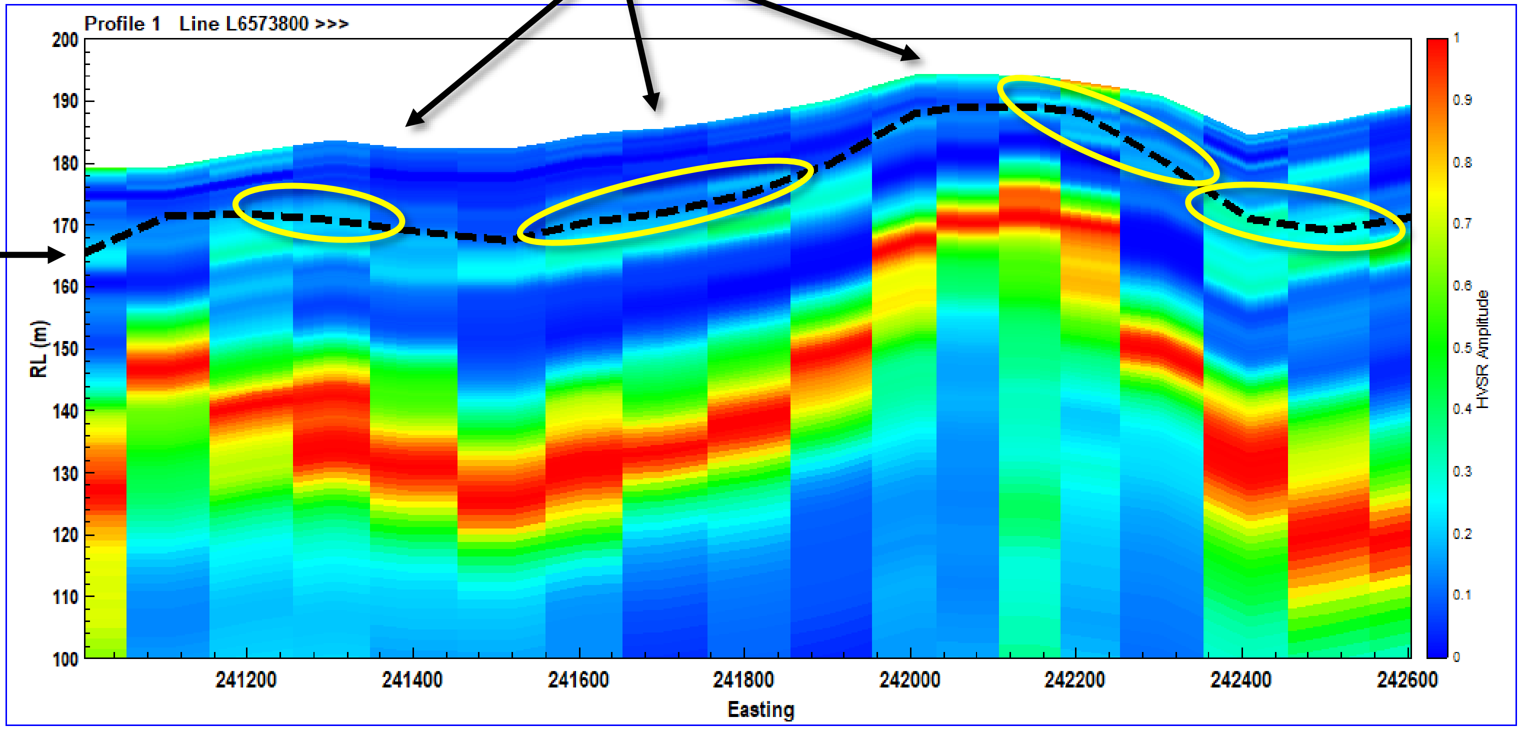
- A higher order mode of the HVSR fundamental frequency peak can sometimes be observed when there is a strong impedance contrast and the HVSR data are normalised to increase the amplitude of weak responses.

$$f_{\mathrm{r}} = \frac{n.V_s}{4H} \quad (\mathrm{n} = 1, 3, 5, \ldots)$$

- Higher order modes are plotted in order to cross-check shallower HVSR responses to make sure if they are real geological layers or artefacts; but sometimes they may overlap…

Possible modes or ferricrete hard bands

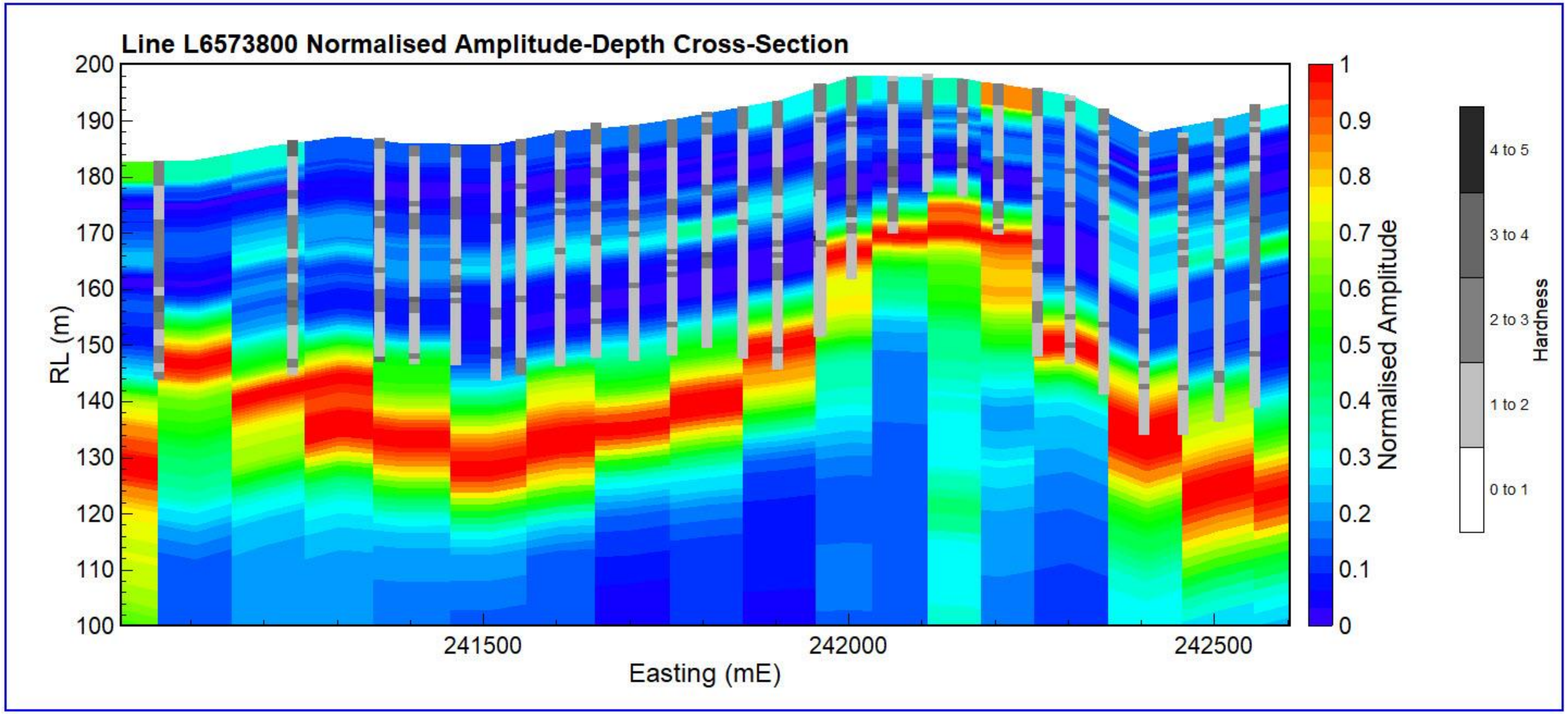
Calculated 1st mode of the fundamental frequency (dashed black line)



» Modelling of HVSR Peak Frequency Modes

Resource Potentials

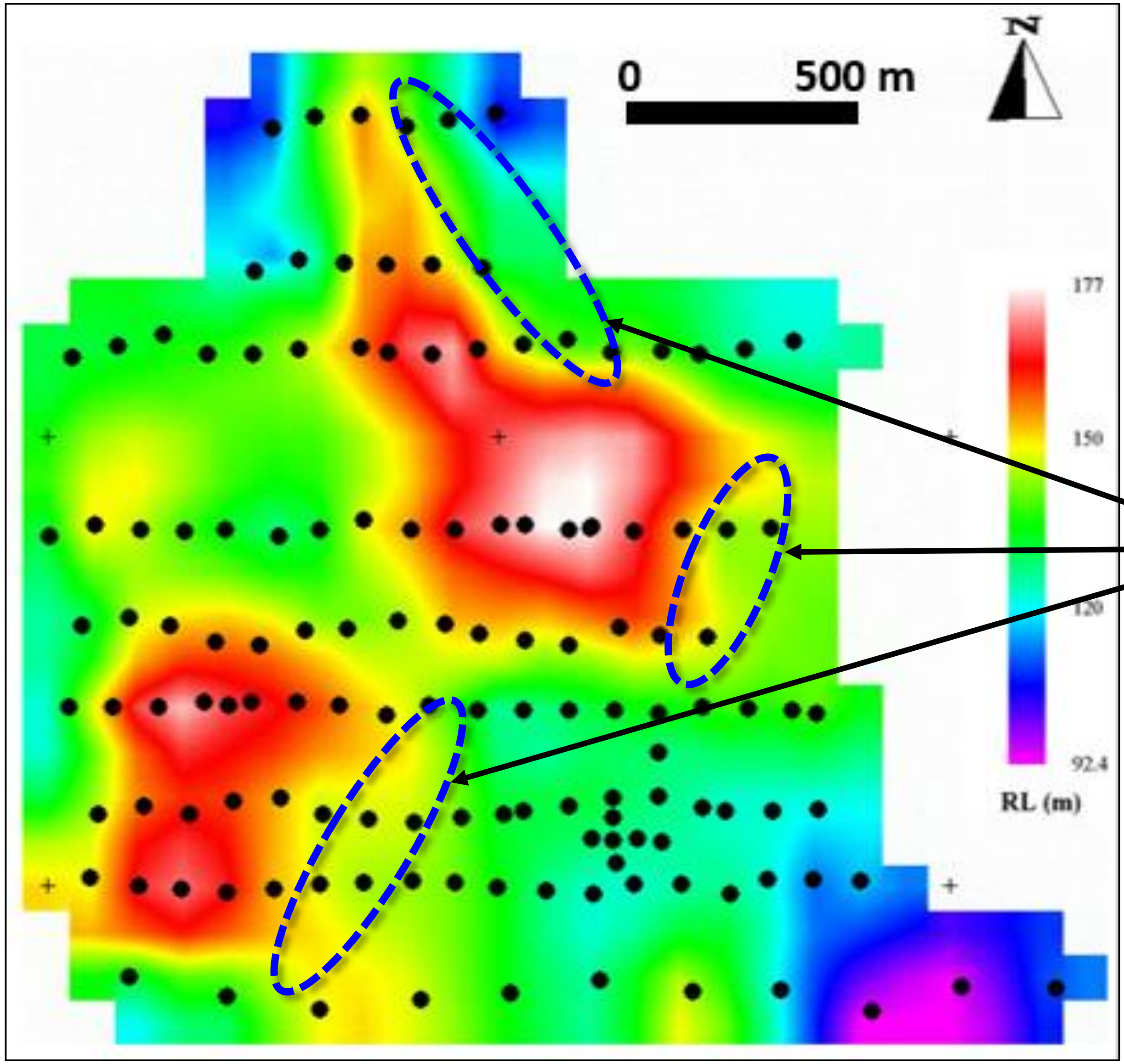
- A shallow response in the HVSR cross section correlates to a change in sand composition, but also occurs in the vicinity of the first fundamental mode; we believe that this is actually geological layering in this case.



» HVSR Basement Topography Model

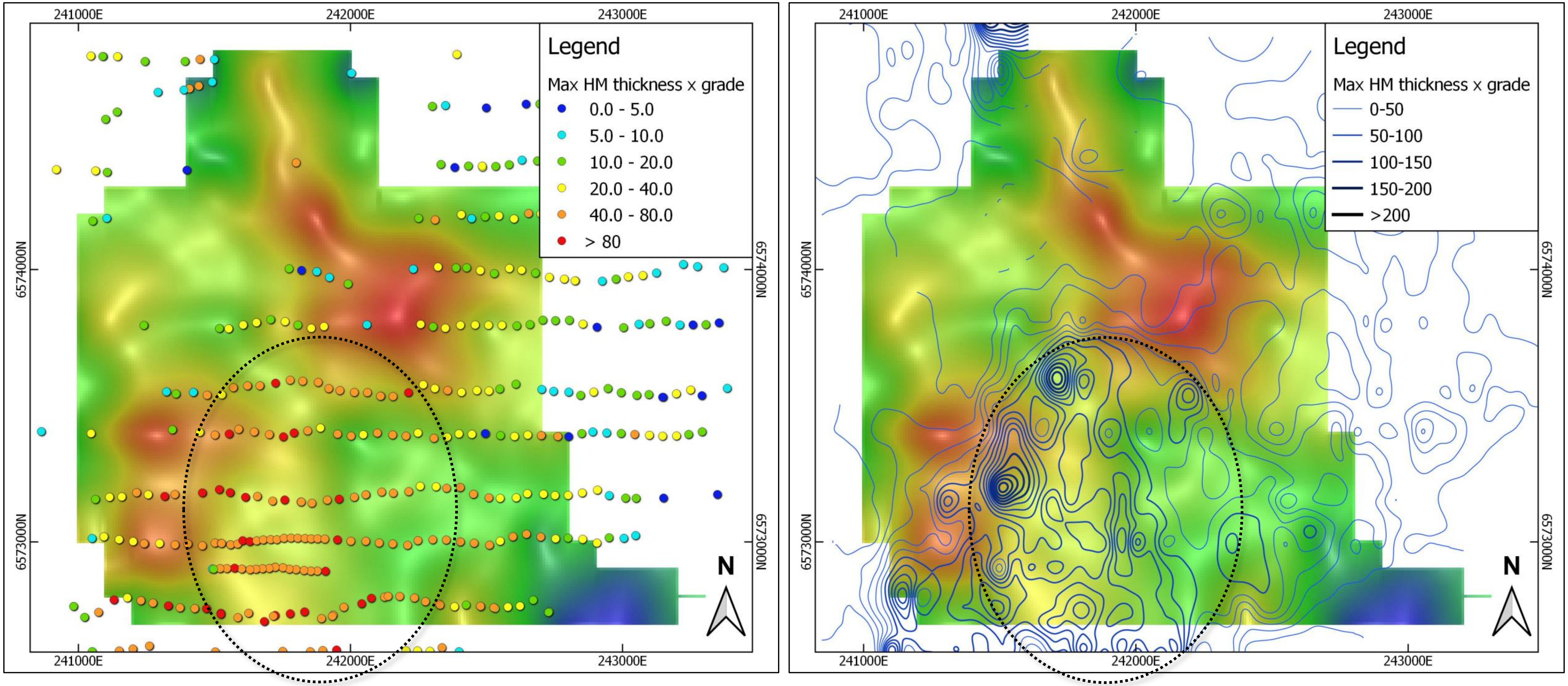
Resource Potentials

- Basement topography model calculated by subtracting HVSR cover thickness from DTM elevation.
- Only 9 drillholes intersected bedrock, so this image is based on the passive seismic data only.



Priority drill target positions where HMS may be concentrated around eastern sides of paleo-headlands

» HMS vs HVSR Bedrock Topography Model

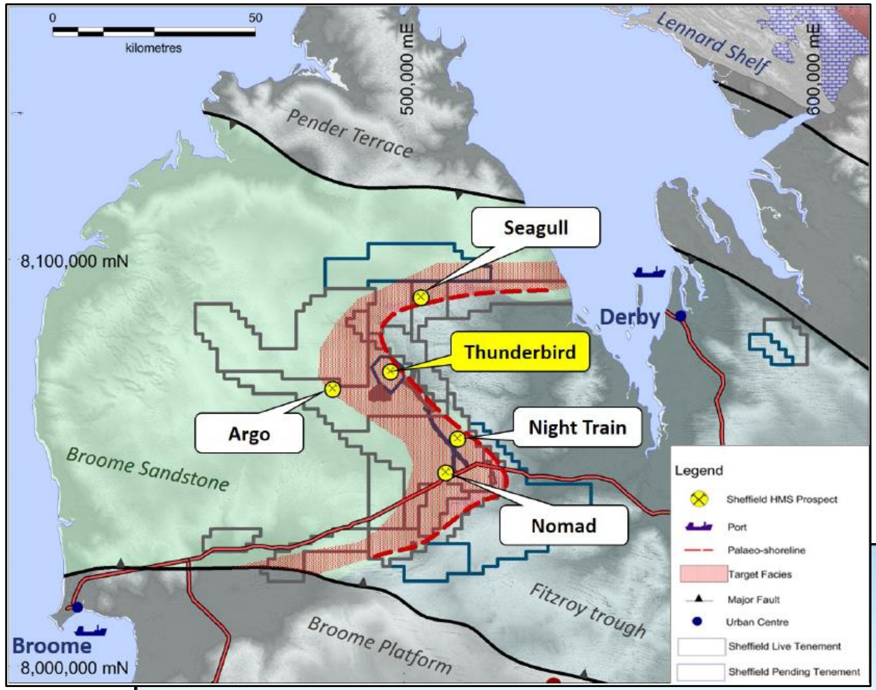


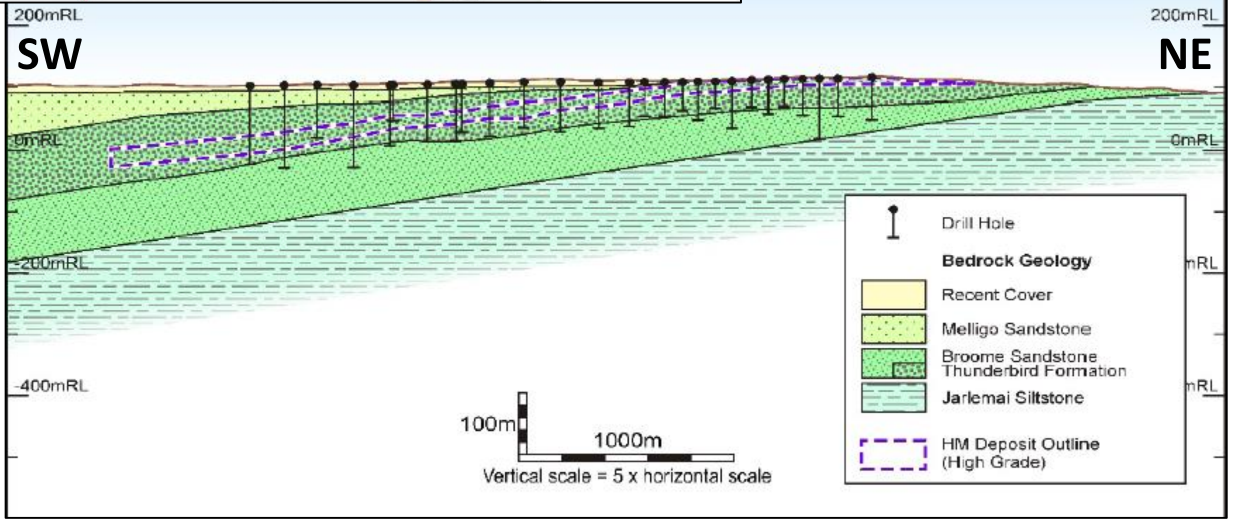
Maximum HM thickness x grade with 4% cut-off occurs on eastern side of a palaeo-headland

» Case Study 3 > Thunderbird

Resource Potentials

- Thunderbird is the first significant HMS deposit to be discovered in the 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 offshore and below wave base during an Early Cretaceous marine regression.
- The heavy minerals consist mainly of ilmenite, hematite, goethite, leucoxene, zircon, rutile, anatase and monazite.
- The deposit has a mineral resource of 3.2Bt at an average grade of 6.9% total heavy minerals, and the heavy mineral fraction contains 28% ilmenite, 8.3% zircon, 2.6% high titanium leucoxene and 2.9% leucoxene.





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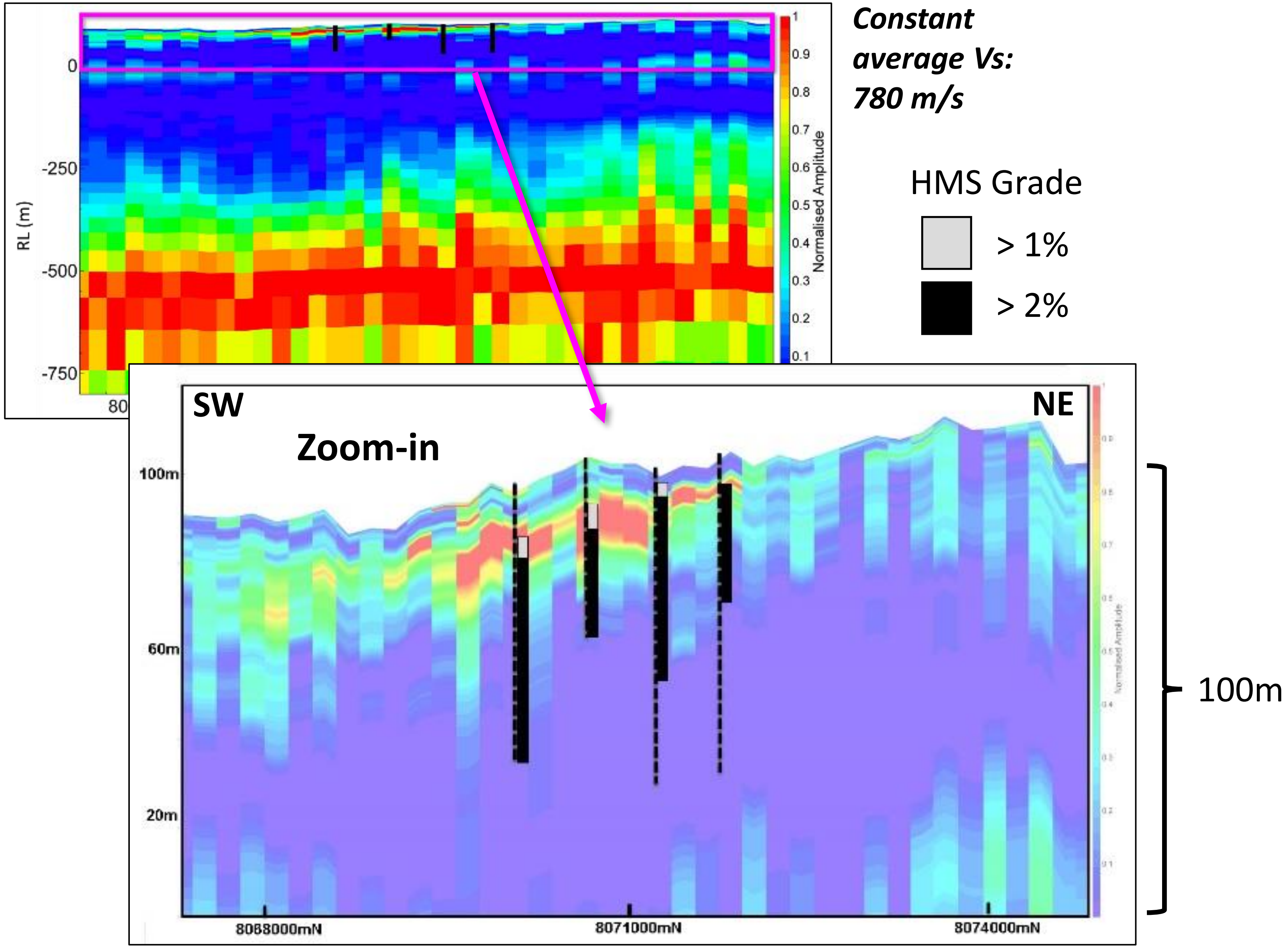
» HVSR Results

- ❑ Acoustic basement occurs at around 650m depth, likely representing indurated Mesozoic sandstone-limestone, with shallow responses related to lithological changes within softer beds above.

- ❑ Shallow profile below of the top 80-100m shows a response correlating to the top of the ilmenite-rich Thunderbird HMS deposit, and was depth converted using a fairly high constant average velocity of 780 m/s in order to match drilling data.

- ❑ The known deposit outcrops in the centre of the profile and dips to the SW (left) as observed in the HVSR cross section.



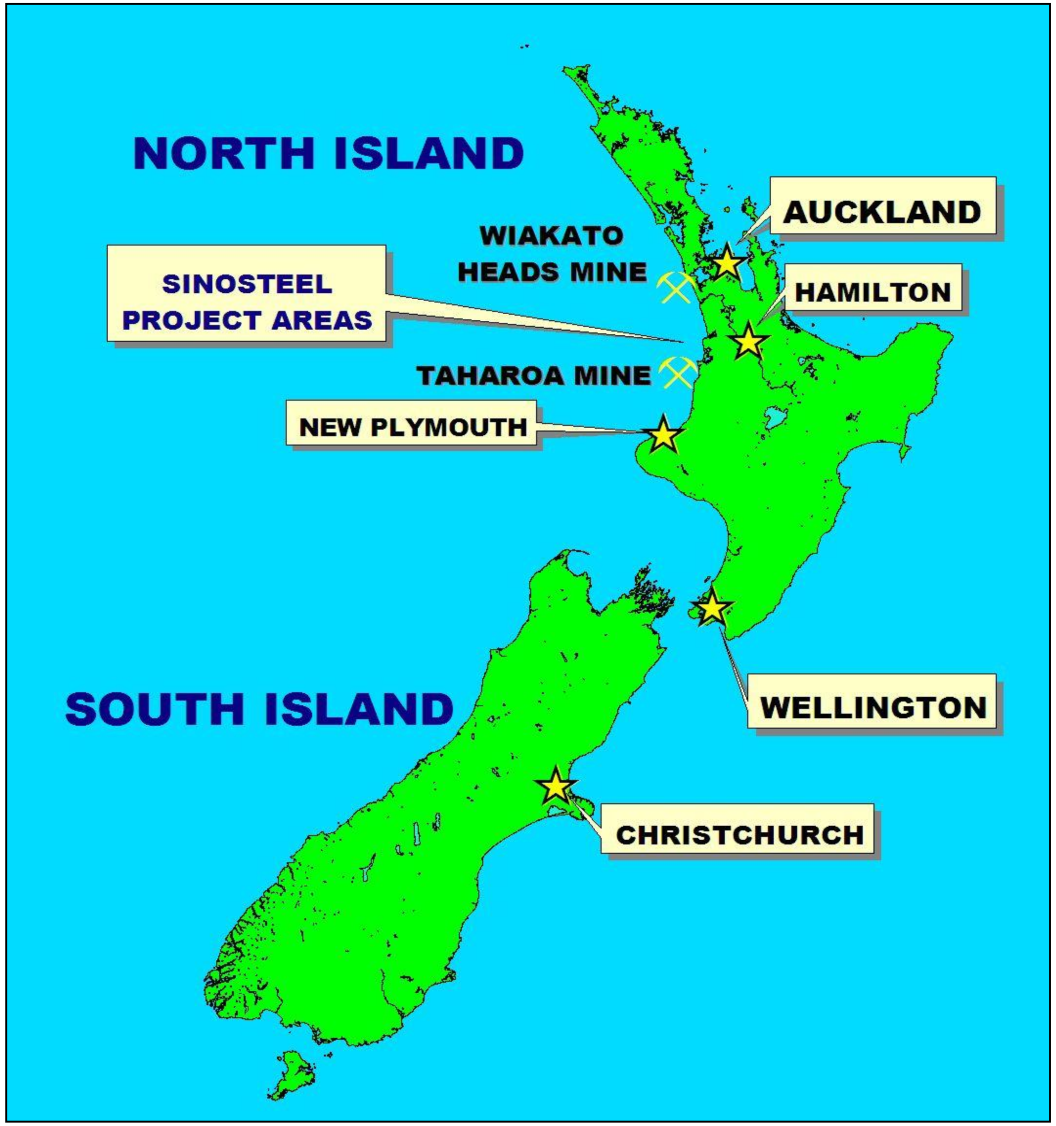
» Case Study 4 > Aotea

Resource Potentials

- Titano-magnetite ironsand deposit located approximately 15 km SW of Raglan, along the west coast of the North Island of New Zealand.

- Sinosteel Australia have defined a JORC resource of 202 Mt of titano-magnetite ironsand in modern and ancient dune deposits.

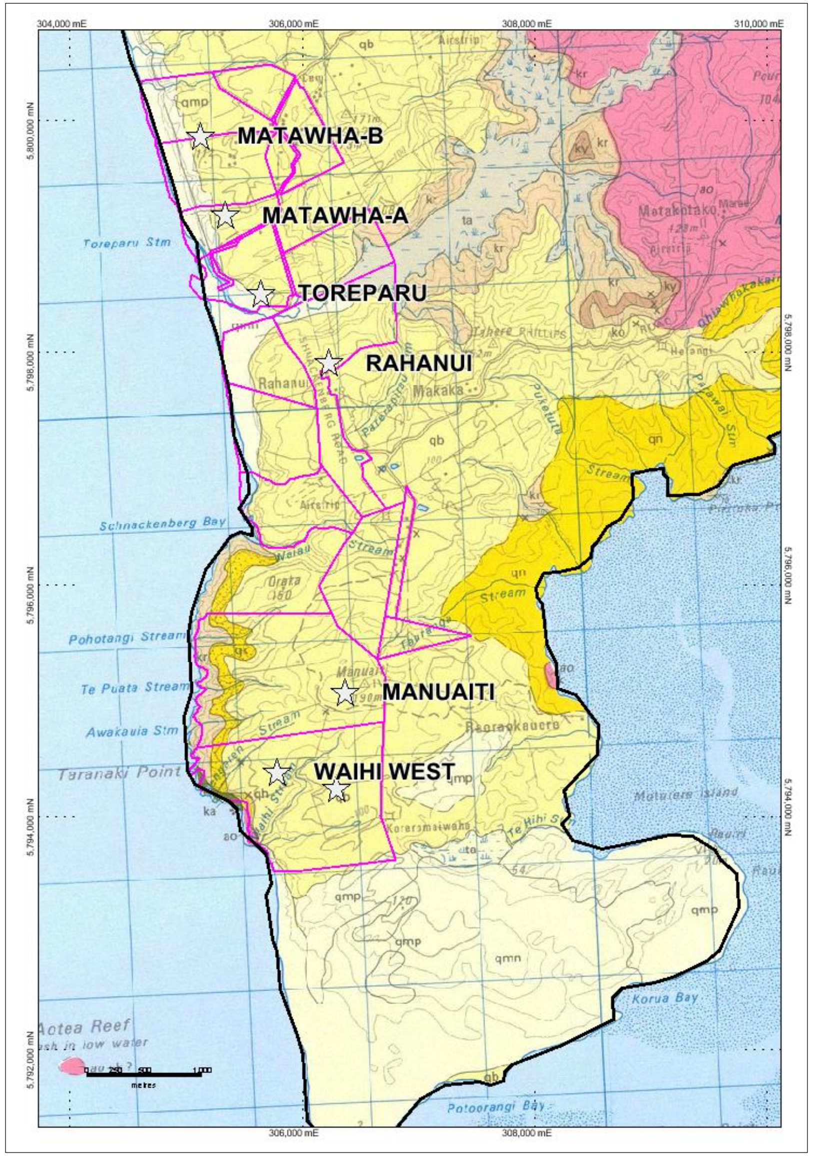

Ruapuke Beach



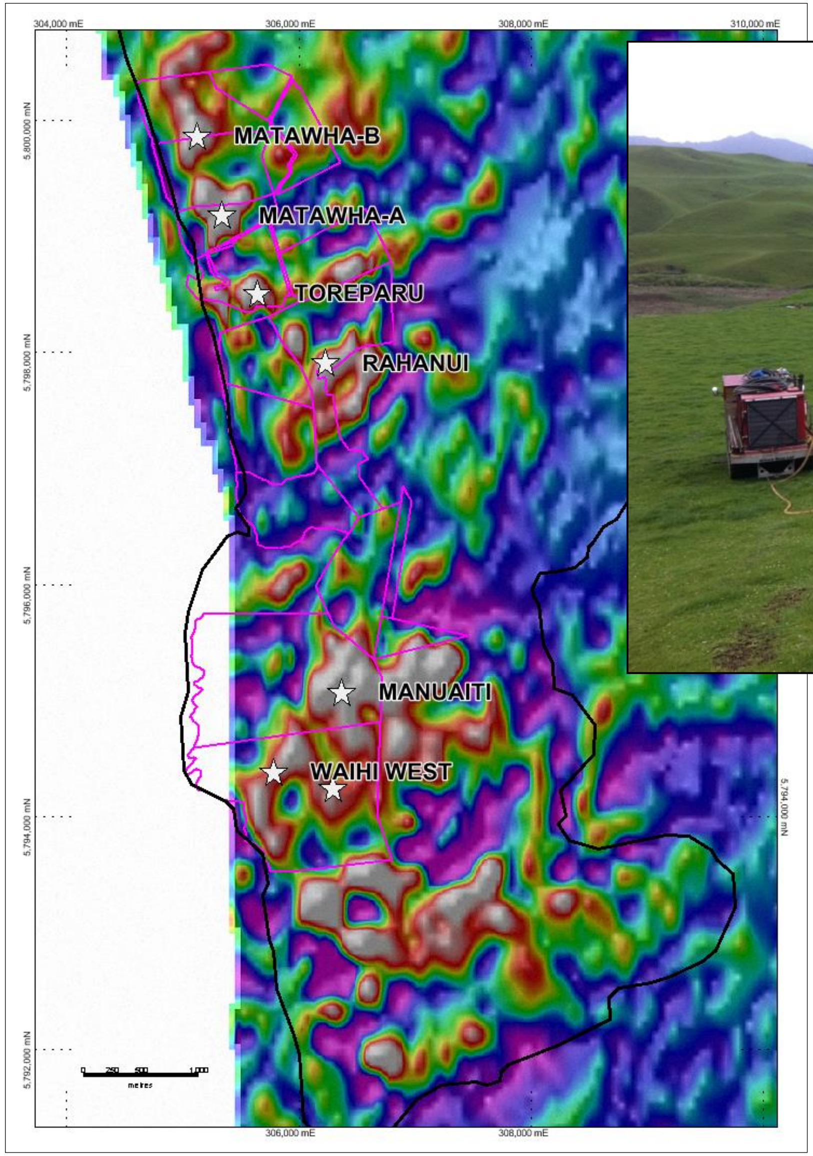
» Airborne Surveys to Desktop Studies to Drilling

Resource Potentials

1:250,000 Scale Geological Mapping



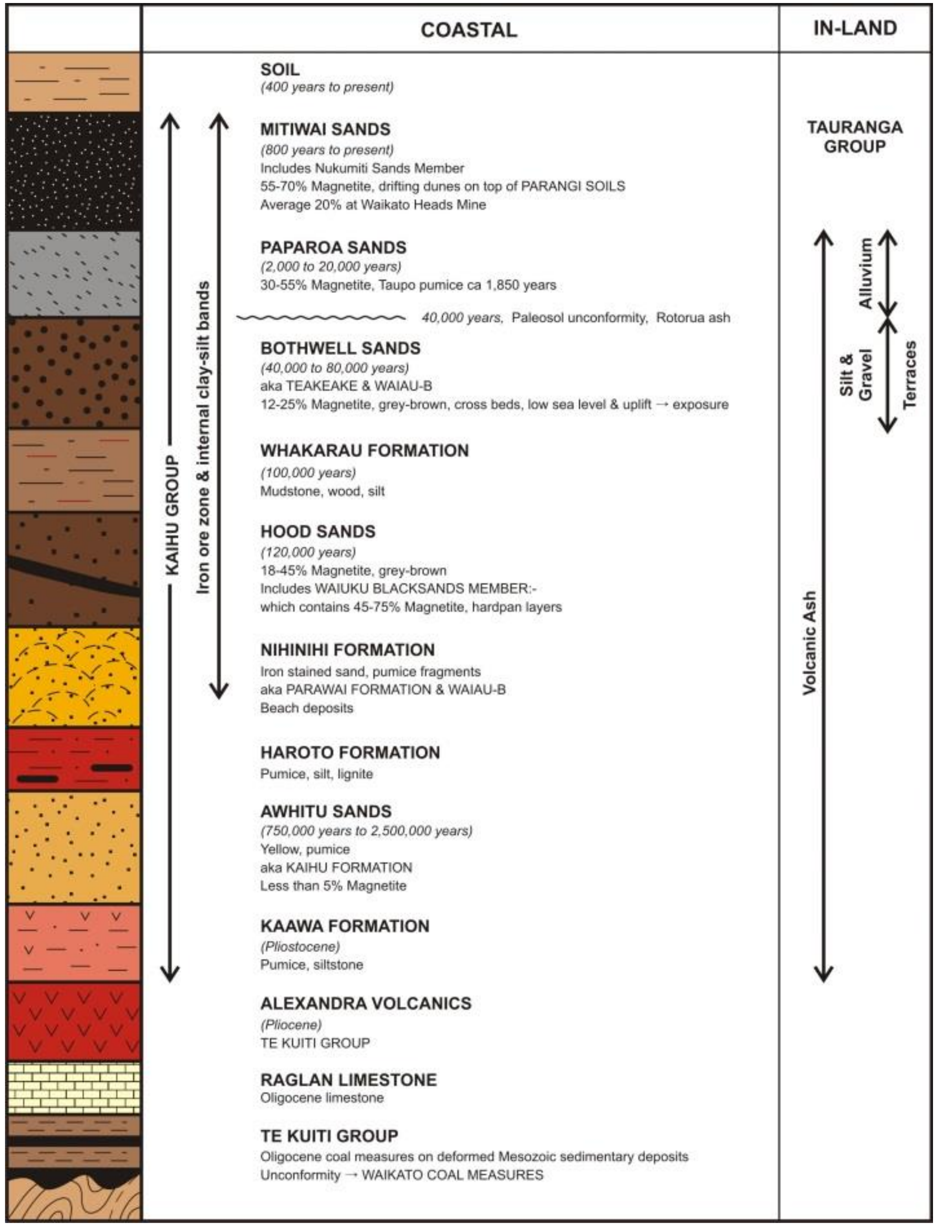
Airborne Magnetics – Rainbow Colour TMIRTP-1VD



» Stratigraphic Section

Cover sequence:

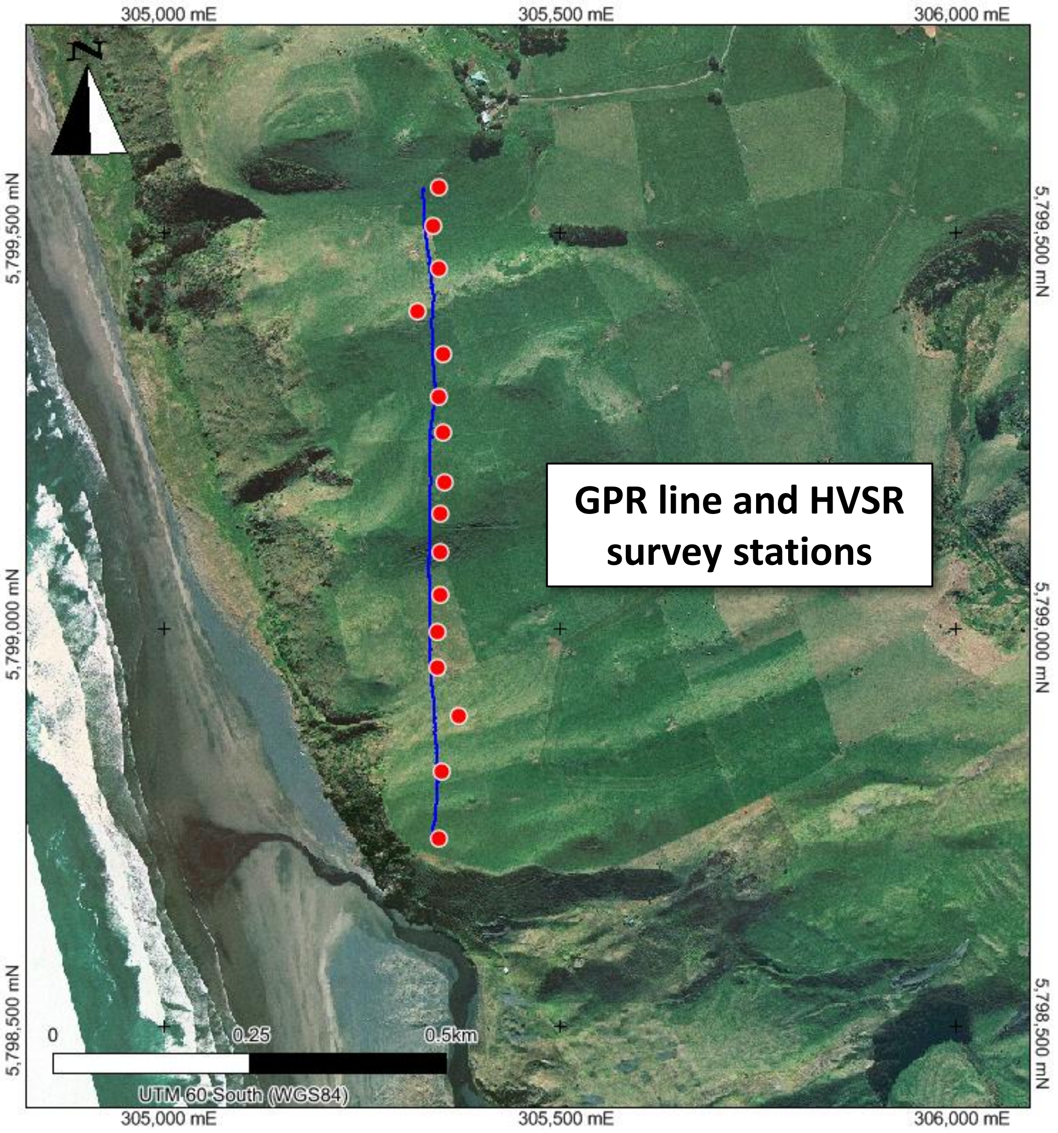
- ❑ Various titano-magnetite bearing sand layers.
- ❑ Typical total thickness of 40m to 60m.
- ❑ Includes puggy clay from weathered volcanic ash events and hard silt layers, very difficult to drill through, and forms internal waste for mining as well as potential to clog concentrating circuit.
- ❑ Sand, silt and clay deposits sit above either limestone or basalt acoustic bedrock.



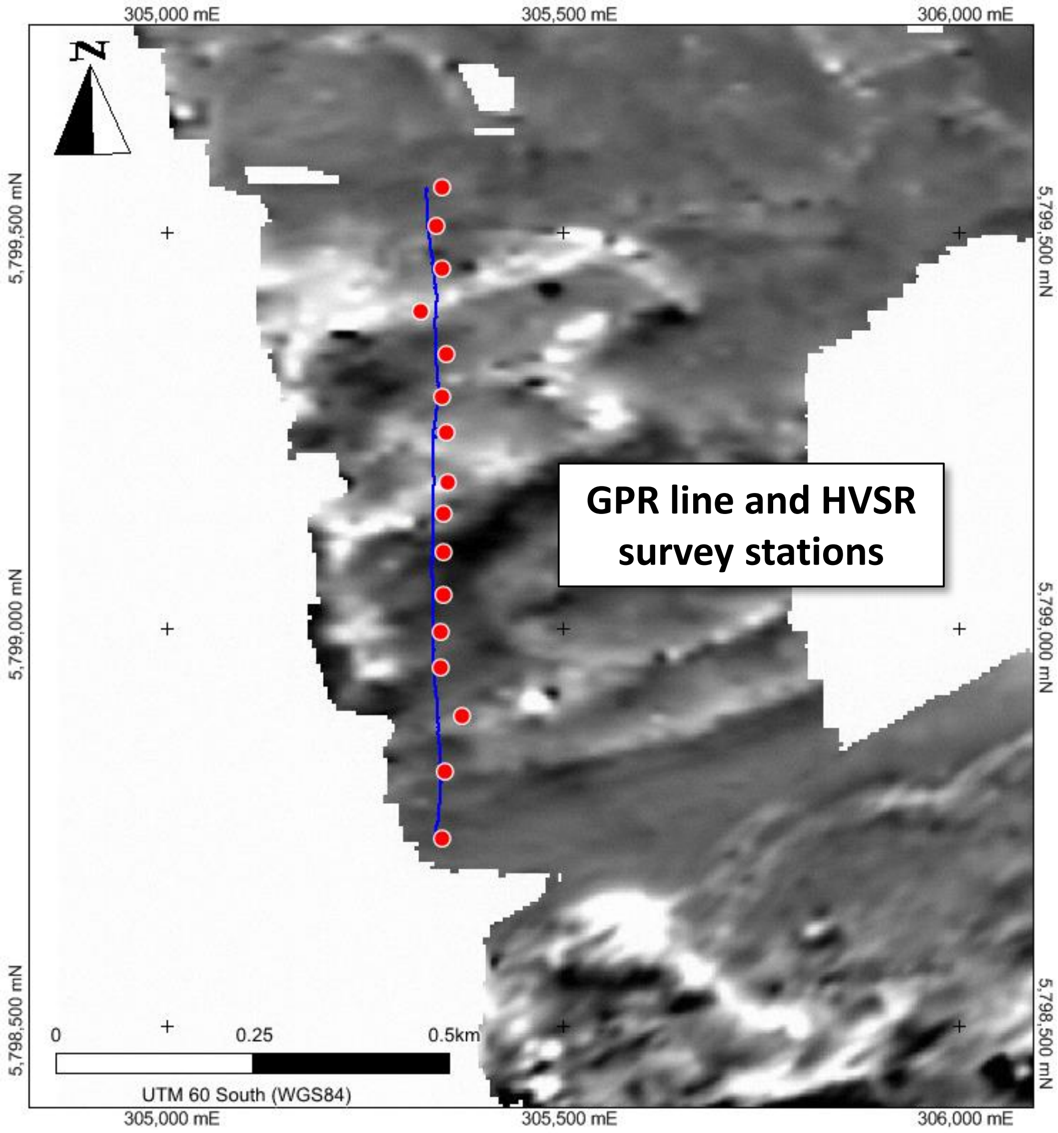
» Ground Magnetics, GPR and HVSR

Resource Potentials

Aerial Photograph



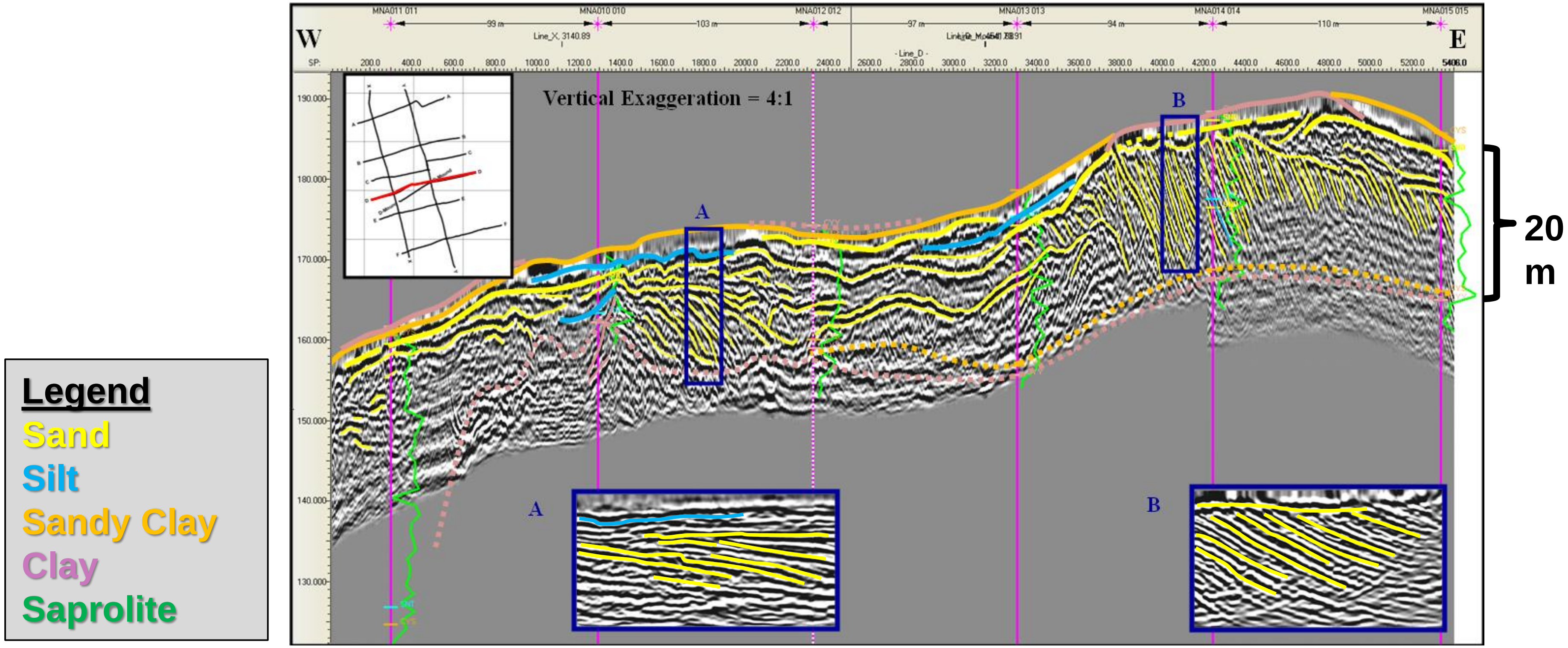
Ground Magnetics – Greyscale TMIRTP-1VD



» GPR

Resource Potentials

- 35 MHz system
- Excellent for defining sand and clay layers, and dune foreset bedding.
- Volcanic ash, now puggy clay layers, obvious as strong reflectors, affects resource/mining.
- Limited to 20m depth of investigation.
- Time consuming, costly, difficult in undulating topography; affected by electrical noise.



Apparent Dip = 10 º

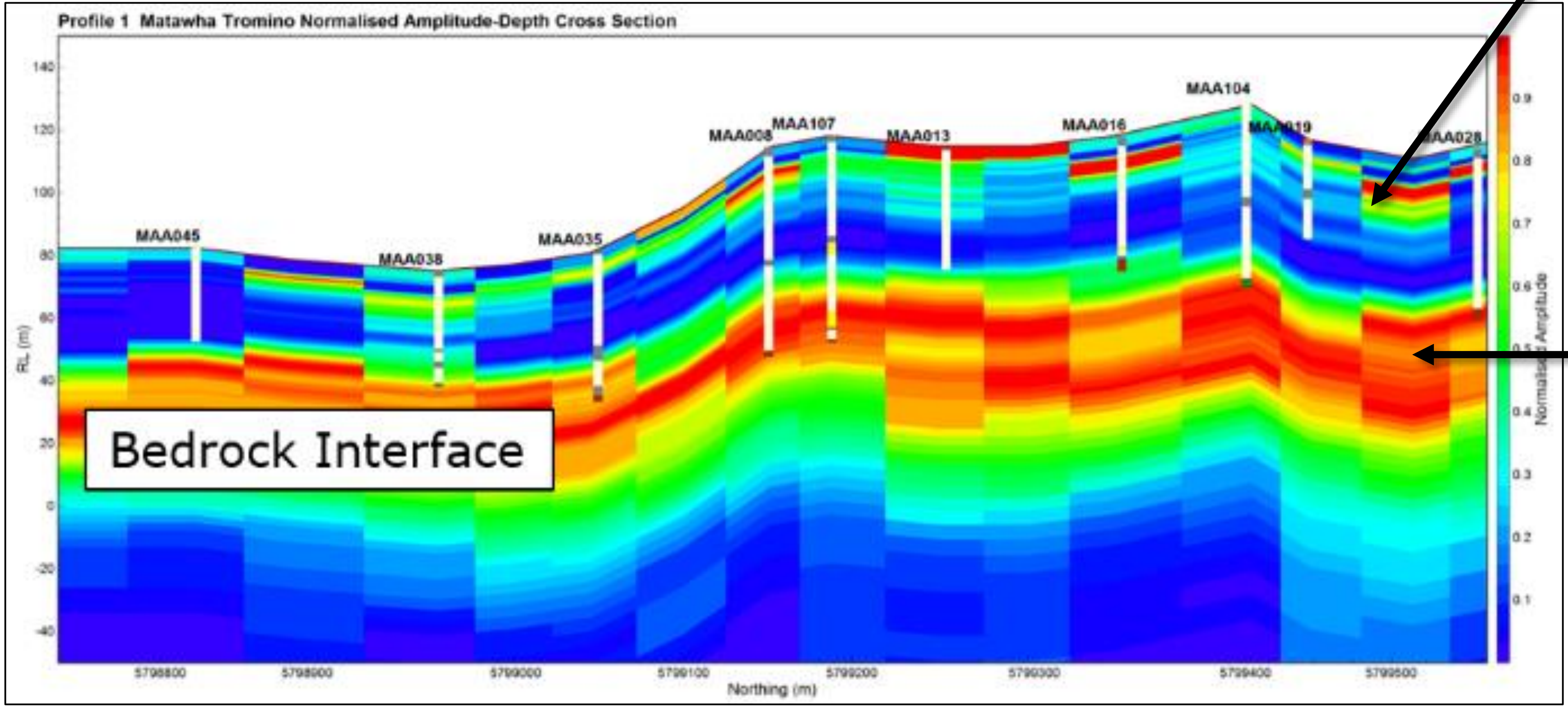
Apparent Dip = 25 º

» HVSR Results

Resource Potentials

- ❑ Data acquired and processed in one day, detects bedrock to 50m or more, works around electrical noise.
- ❑ Great ambient seismic signal, therefore only 16 minute recording time per survey station.

Elevated HVSR responses within the cover sequence related to logged clay pan, silt and ferricrete layers.



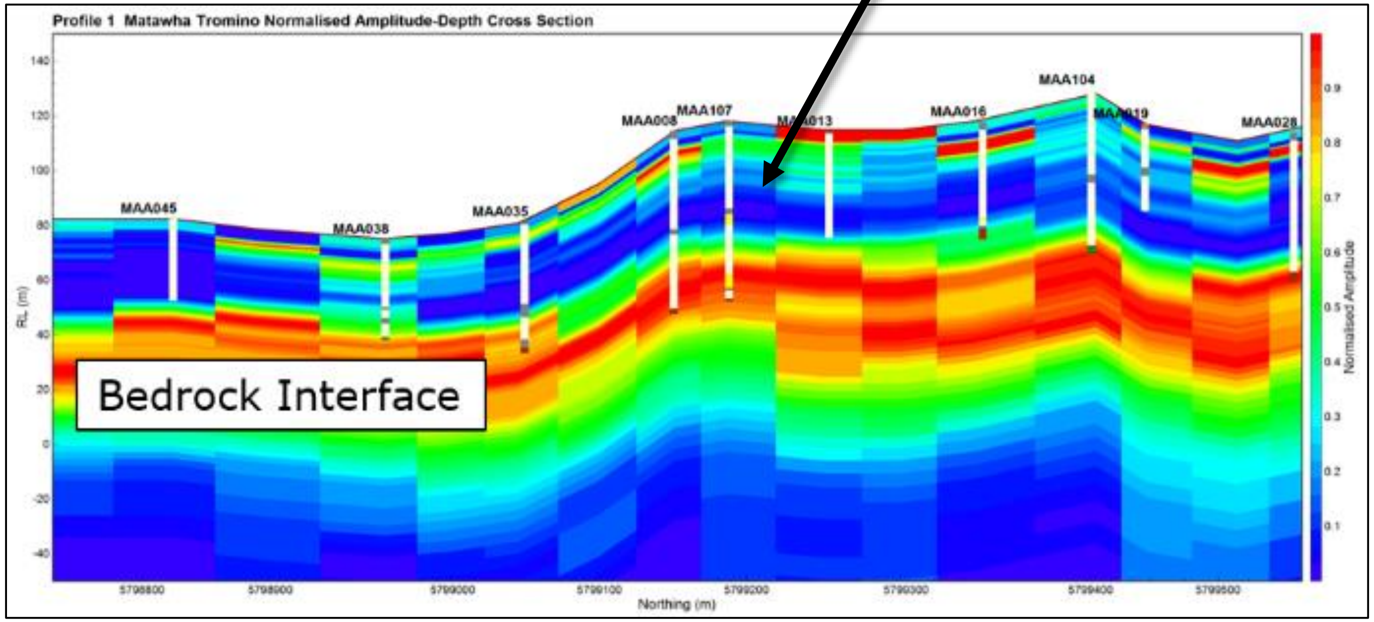
Limestone and basalt bedrock mapped very well.

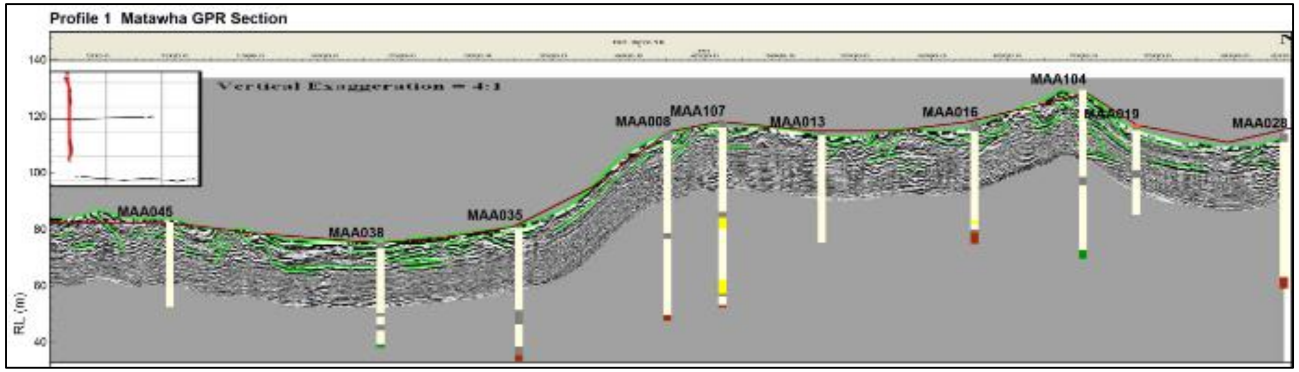
Constant average Vs = 400 m/s

» HVSR vs GPR

Resource Potentials

Total sand cover thickness typically between 40 to 60m

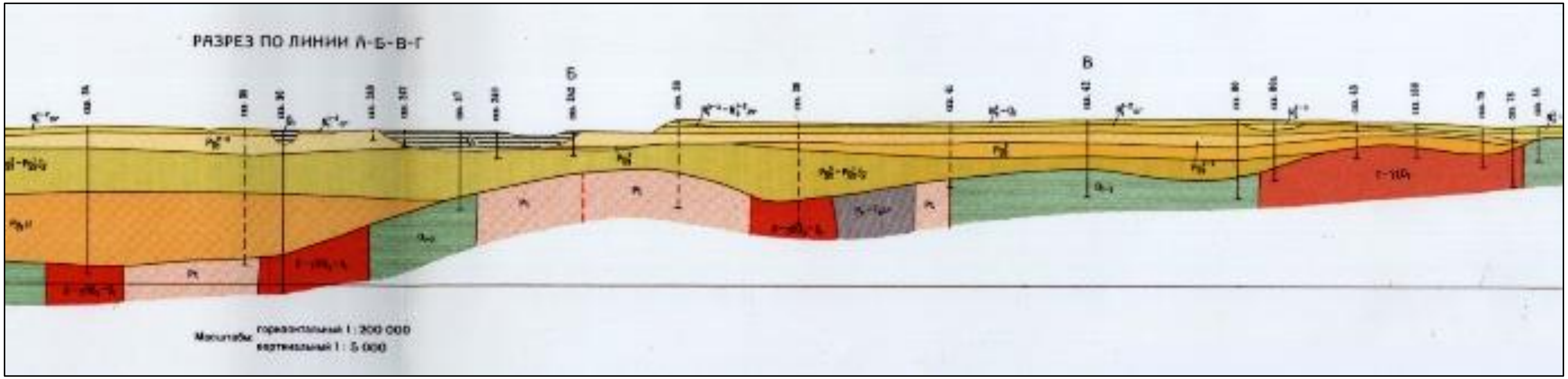




» Case Study 5 > Kazakhstan

Resource Potentials

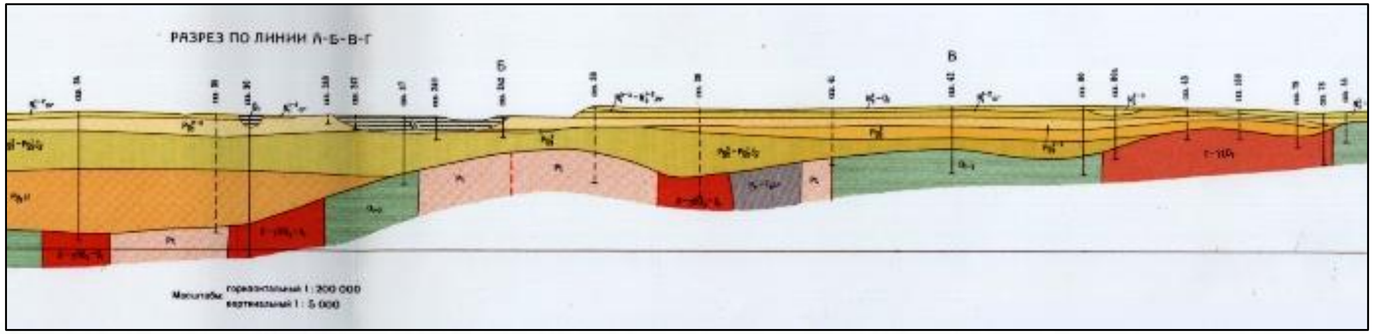
- Oligocene zircon and rutile HMS deposits overlying older Tertiary and Devonian "bedrock" sediments and gneissic rocks located in Northern Kazakhstan, formed as an inland basin.
- A generalised geological cross section for the area is shown below, which demonstrates "layer cake" Oligocene sedimentary deposits above rifted and eroded basement rocks.
- Data acquisition carried out by Iluka Resources staff and data sent back to Resource Potentials for data processing and HVSR cross section modelling.

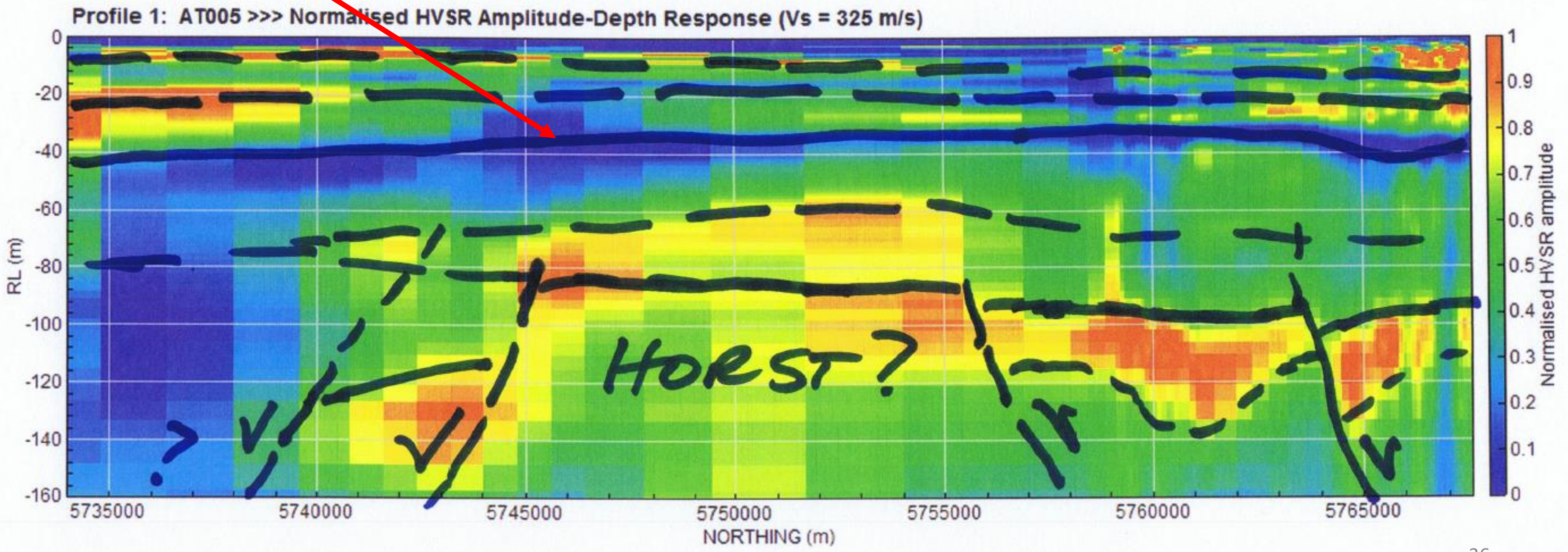


» HVSR Interpretation

Resource Potentials

HMS deposit sits above soft clay band producing a HVSR low due to velocity inversion



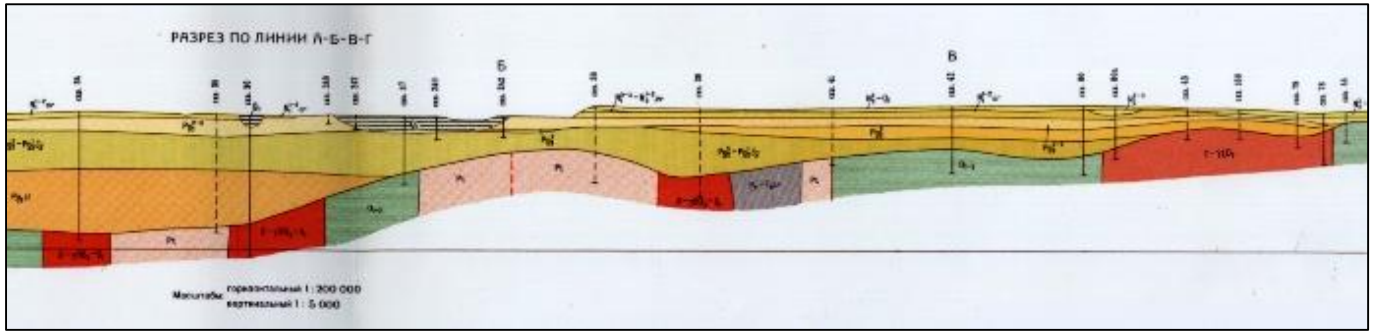


» HVSR Zoom-in on Part of a Very Long Survey Line

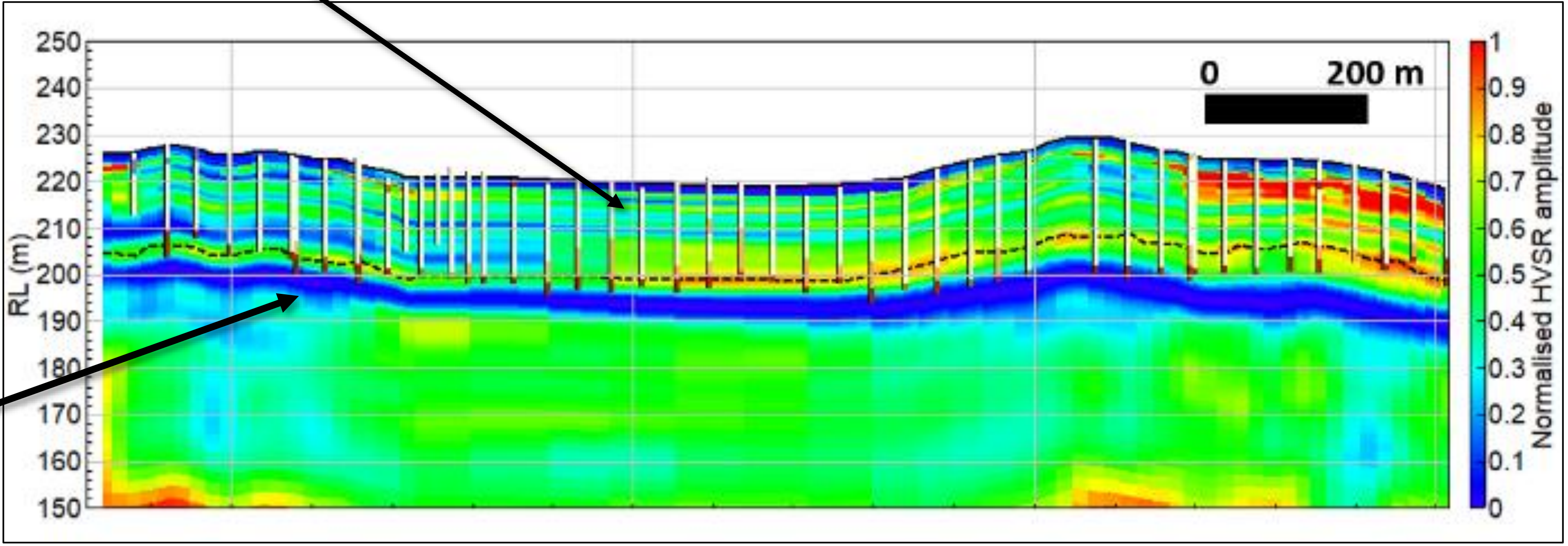
Resource Potentials

HVSR cross section shows layer cake stratigraphy within the cover sequence, which agrees with drilling data and geological cross sections, but extends further down to show basement topography. Passive seismic with drilling could have reduced the number of required drillholes.

Geological cross section from the area showing layer cake stratigraphy:



Zoom in to a shallow part of the normalised HVSR cross section:

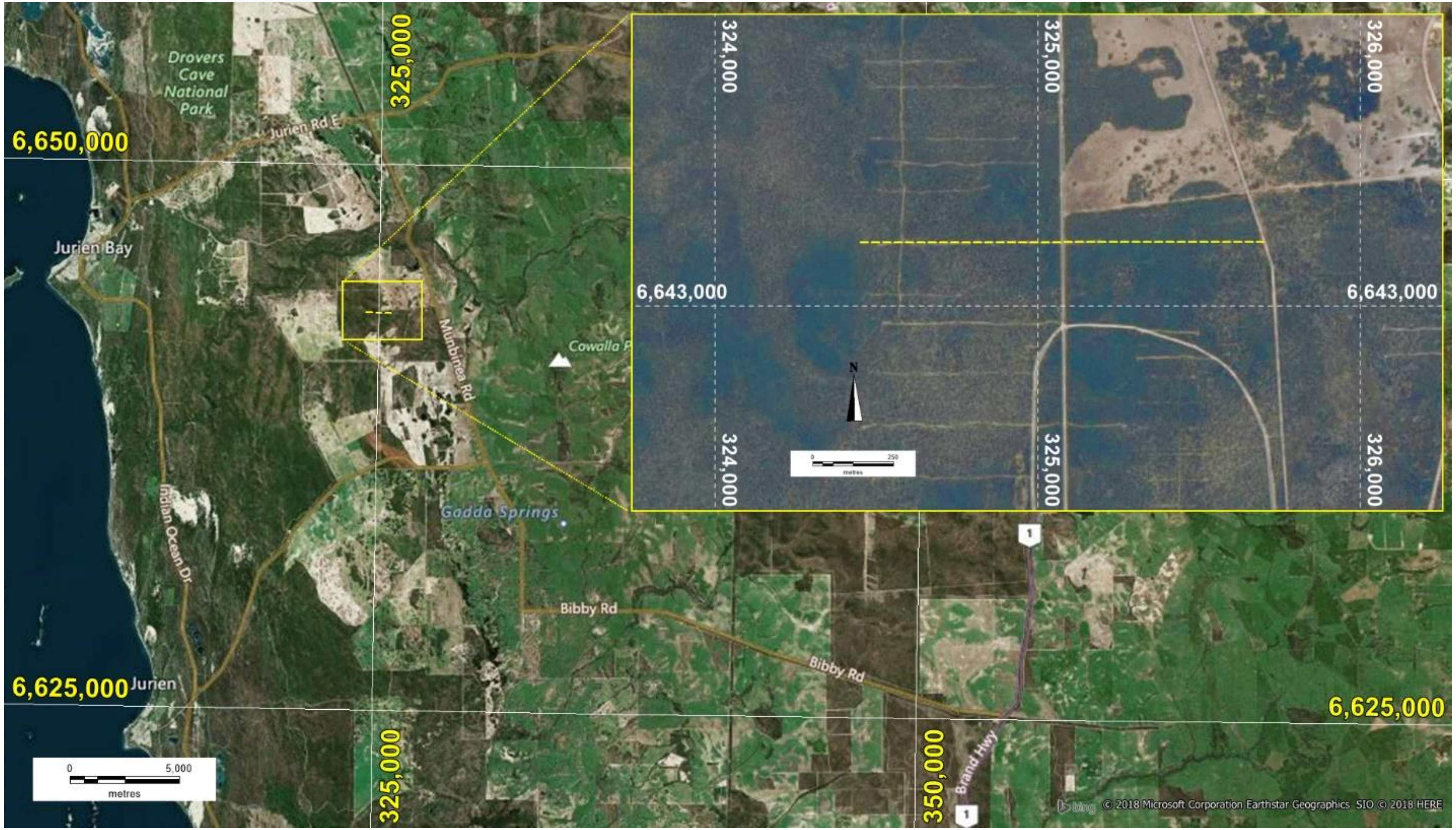


The Chegan clay unit intersected the near end of drillholes (brown) provides an anomalous HVSR low response – marker horizon. Velocity inversion from clay band could also be produced in a shallow coal basin to track coal seams.

Constant average Vs = 250 m/s

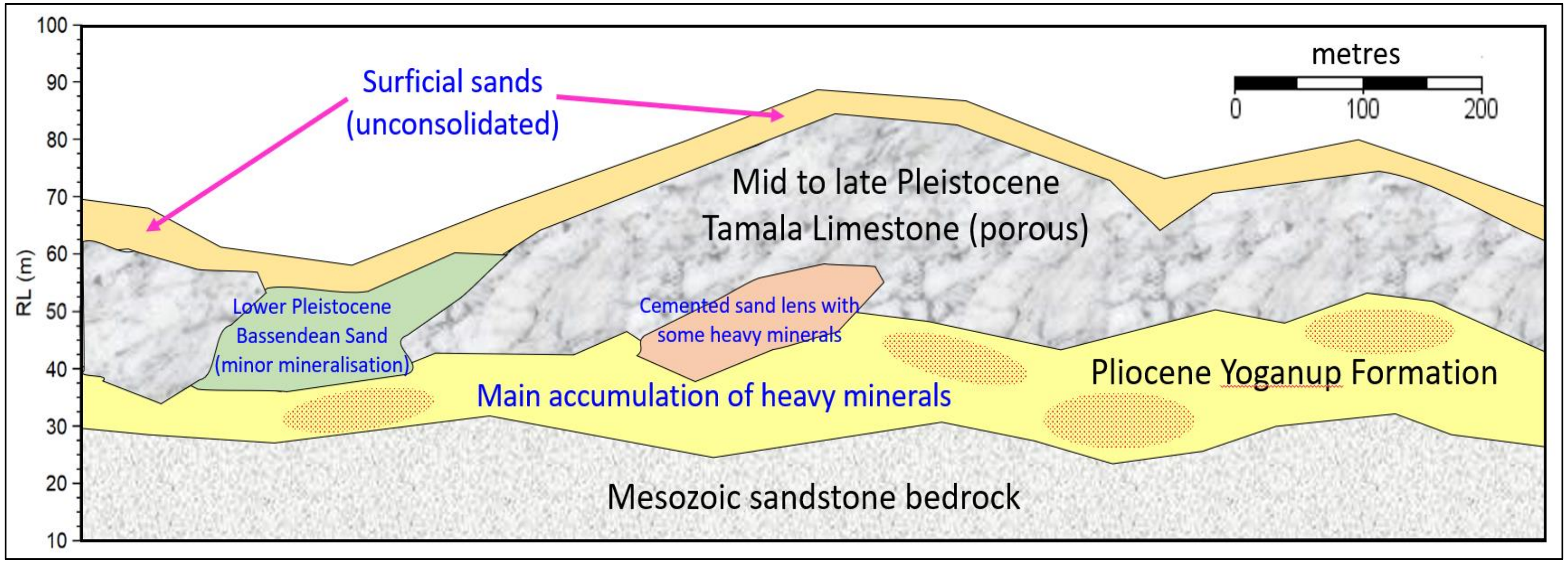
» Case Study 6 > Jurien

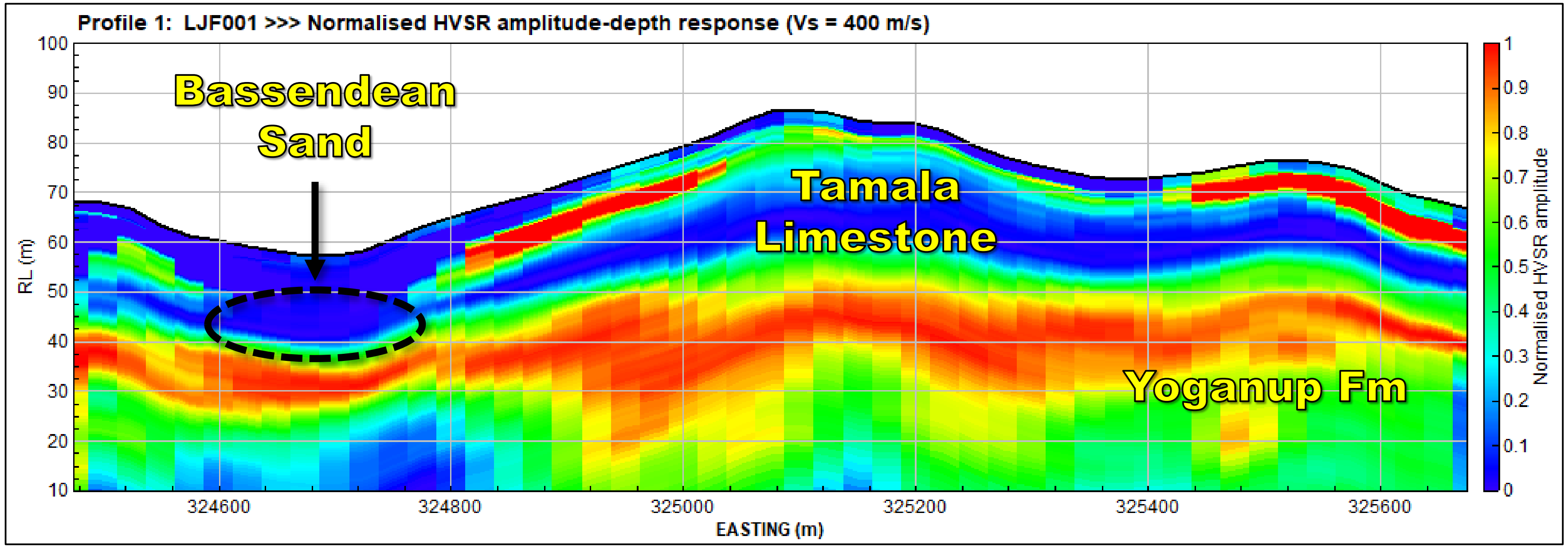
Resource Potentials



» Geology and HVSR Results

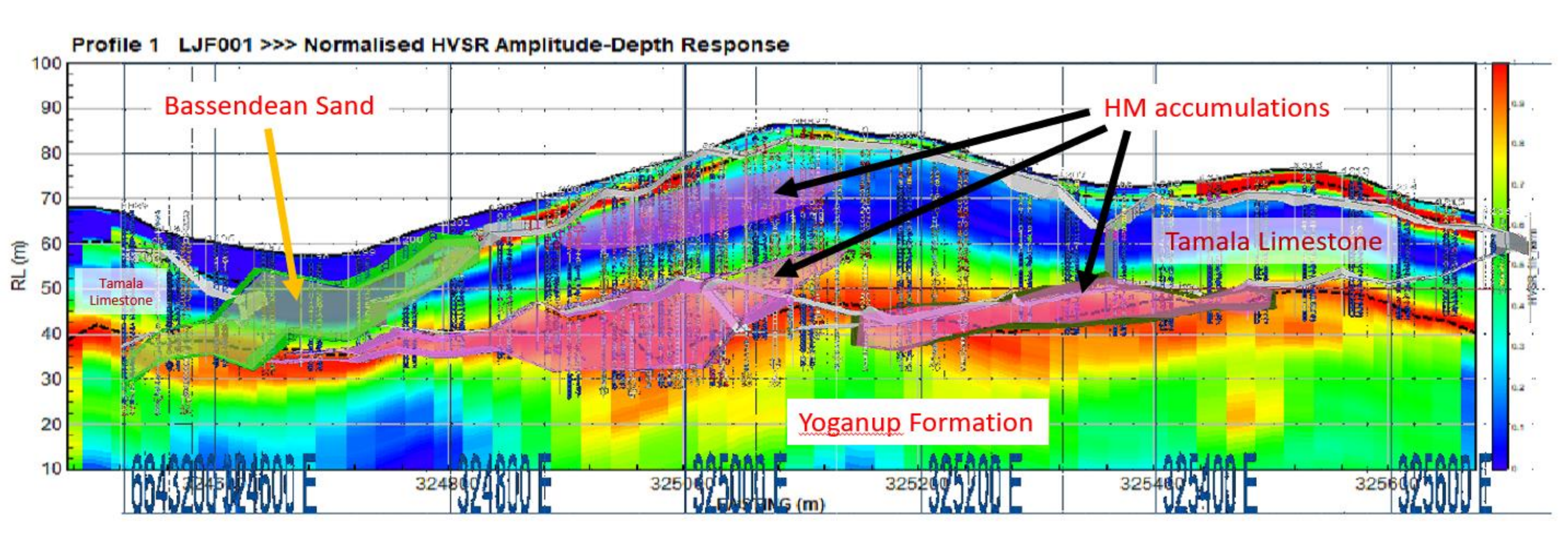
Resource Potentials





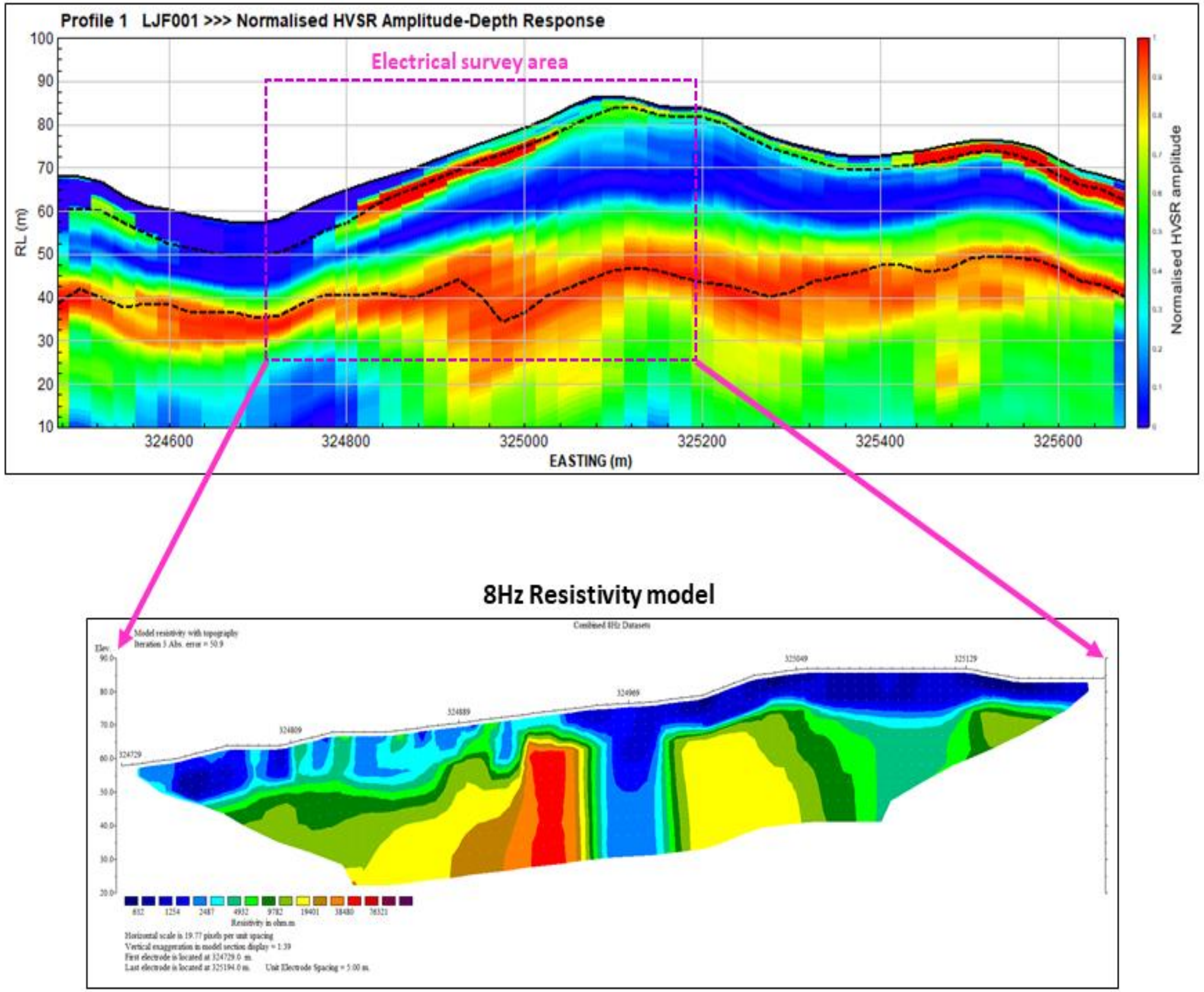
» HVSR vs Geology 3D Surfaces

Resource Potentials



» HVSR vs Electrical Resistivity Tomography (ERT)

Resource Potentials



» Applications

Resource Potentials

The passive seismic HVSR method may be utilised in various applications in HMS exploration and deposit studies, such as:

- Rapidly providing information on **layer continuity within HMS deposits,** which can be used to infer the continuity of horizontal versus *en echelon* bedding.
- Defining **bedrock topography** variations, which may control the distribution of HMS within overlying sand deposits, e.g. Sonoran.
- Estimating the **total thickness** of HMS bearing sands overlying relatively harder sediments or bedrock, e.g. Sonoran and Aotea.
- **Direct mapping of HMS bearing horizons** having higher density and faster seismic velocity compared to surrounding sands, e.g. Thunderbird and Ginkgo.
- Mapping of **marker horizons**, which can be used to infer the thickness of overlying HMS bearing sands, e.g. Kazakhstan.

» Acknowledgements

Resource Potentials

- ❑ Iluka Resources – Sonoran and Kazakhstan
- ❑ Sheffield Resources – Thunderbird
- ❑ Cristal Mining – Ginkgo
- ❑ Sinosteel Australia – Aotea
- ❑ Tronox – Jurien

Latest model Tromino seismometer:

Please come to meet the team at the Resource Potentials booth