Resource Potentials
Mineral Exploration Technologies

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AIG – Workshop
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Passive seismic surveying background, methods and HVSR case studies

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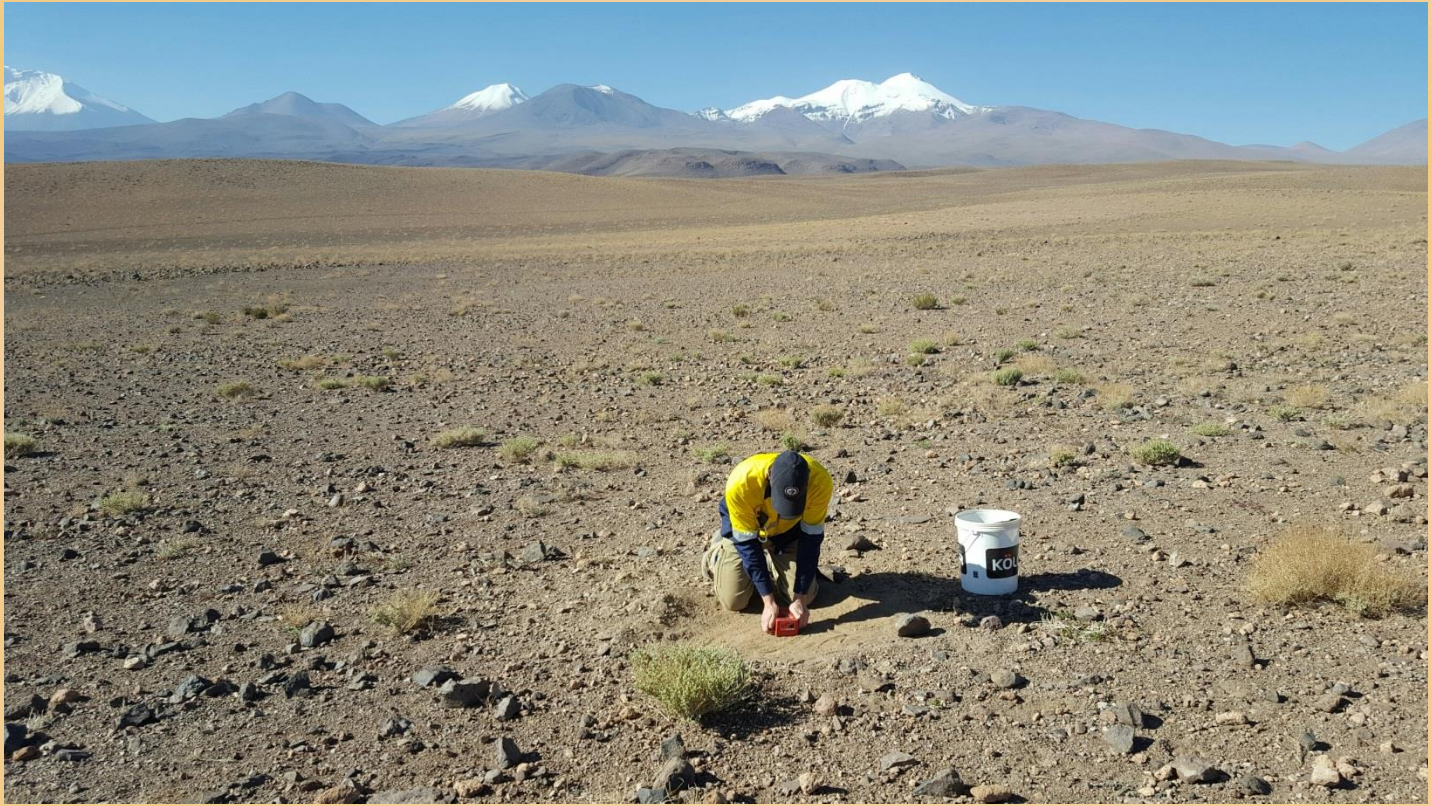
Thank you for attending and presenting!!



Preface - overcoming skepticism

- Passive seismic is not new, but rapid and ”easy” passive seismic is; just that it is limited to cover mapping of soft deposits over hard bedrock using the “HVSR” method – main emphasis of the workshop.
- Most useful geophysical exploration tool to come out in the last decade.
- Also the most boring survey method since magnetotellurics.
- Simple, easy theory, and non-geoscientists can operate and process data.
- For me it was a big risk, have invested a lot in R&D and equipment over the last 3 years, thankfully showing huge promise...
- Trial surveys as proving grounds for tech testing, developing SOPs, generating fixes, developing new ways to process and visualise data, comparison to drilling and other geophysical survey results, small companies great for feedback and interaction compared to the majors.

Preface – embraced more by geologists

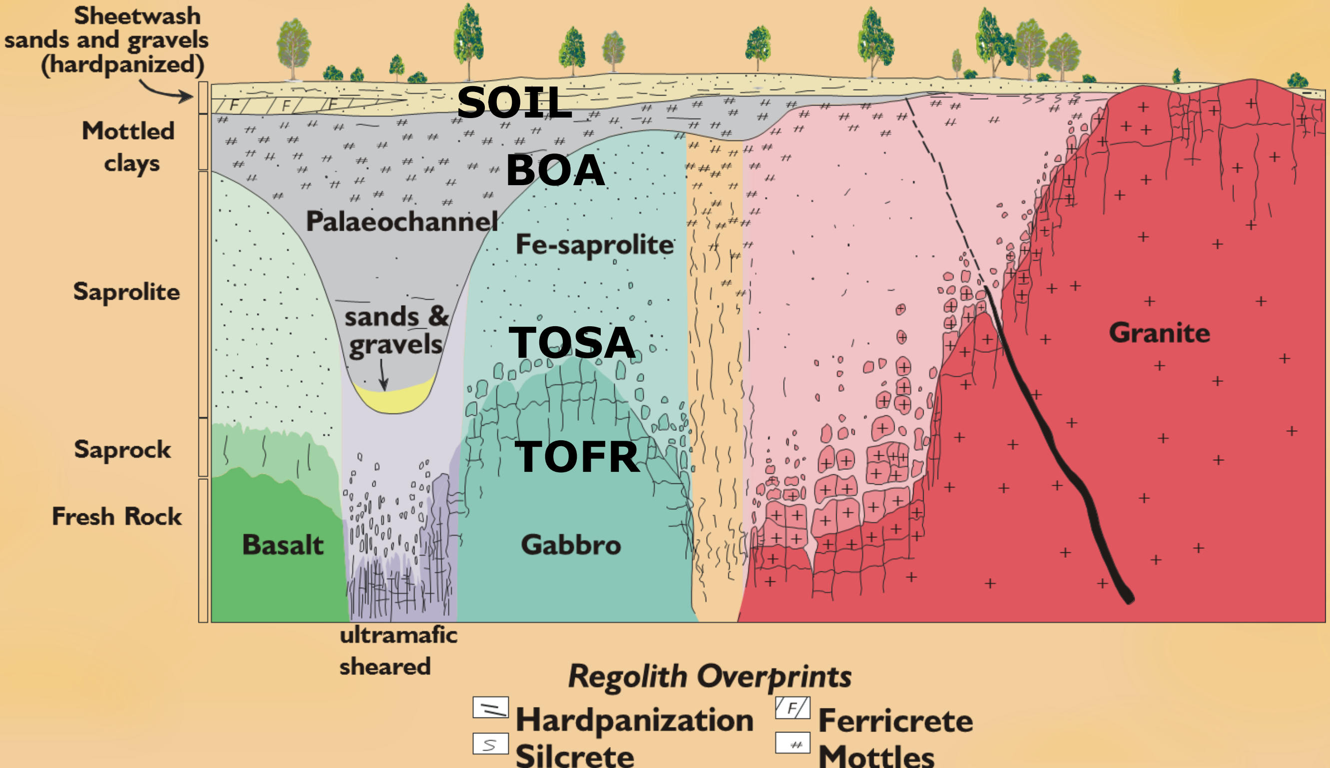
- Making improvements to hardware and software with manufacturer; e.g. internal noise from GPS receiver, took years to figure it out and make changes.
- Noisy data caused by: geological conditions, poor operation (Respot staff are best, but expensive), survey repeats about 10% - but most often get same results, therefore real….
- Results tend to be mixed, sometimes great, sometimes seemly hopeless, sometimes unexpected, but always something useful in the data when squeezed properly…
- Mostly train clients to get their own data, hire or buy instruments and software
- At least there is low cost and logistical risk for doing trial surveys before considering production surveying.

Why Passive Seismic?

- Passive seismic surveying has been developed for geotechnical, environmental and engineering studies, and is now expanding into the mineral exploration space.
- Exploration geophysicists are often asked **"How thick is the regolith cover?"**
- Layer of subsurface geophysical information which can provide robust results at low cost
- Works in highly conductive or resistive ground, and in seismically and electrically noisy built up areas
- Direct paleochannel detection for: alluvial minerals, sulphate-of-potash, lacustrine Li clays and brines, paleochannel U deposits, channel iron deposits, etc
- Other soft sediment hosted mineral deposits: HMS, ironsands, placer Au and gems, coal, etc.
- Passive seismic surveying for depth of cover mapping will likely become a common tool for mineral exploration companies.

Regolith Cover Mapping – type and thickness

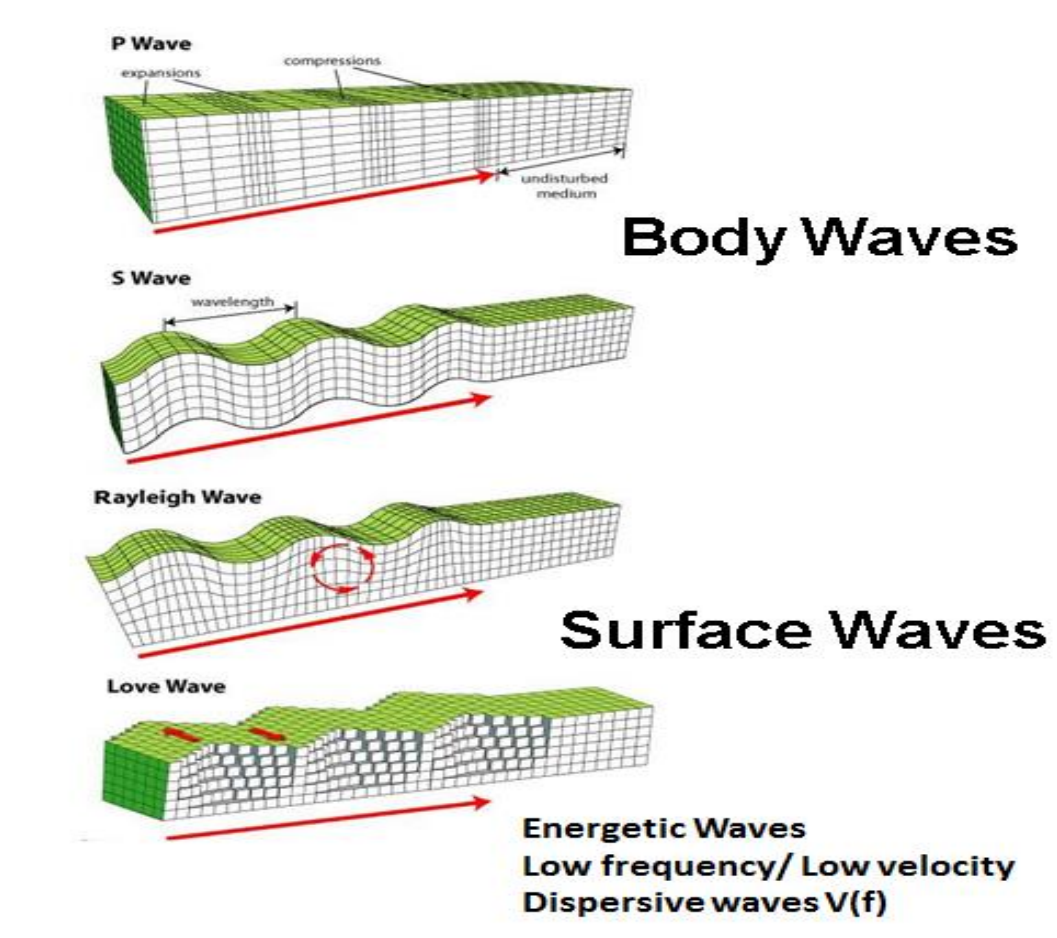
Main application for TOFR depth mapping and targeting; use with drilling information for calibration and interpretation, along with other geophysical methods



Seismic Waves

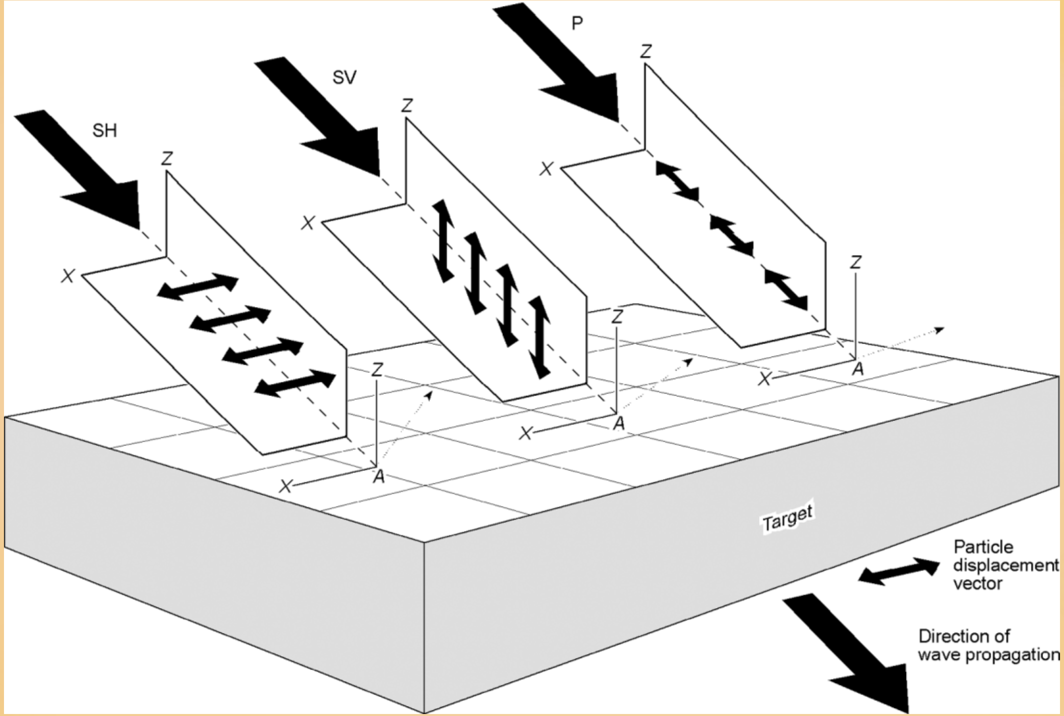
Conventional seismic surveys ⇨

Passive Seismic surveys ⇨



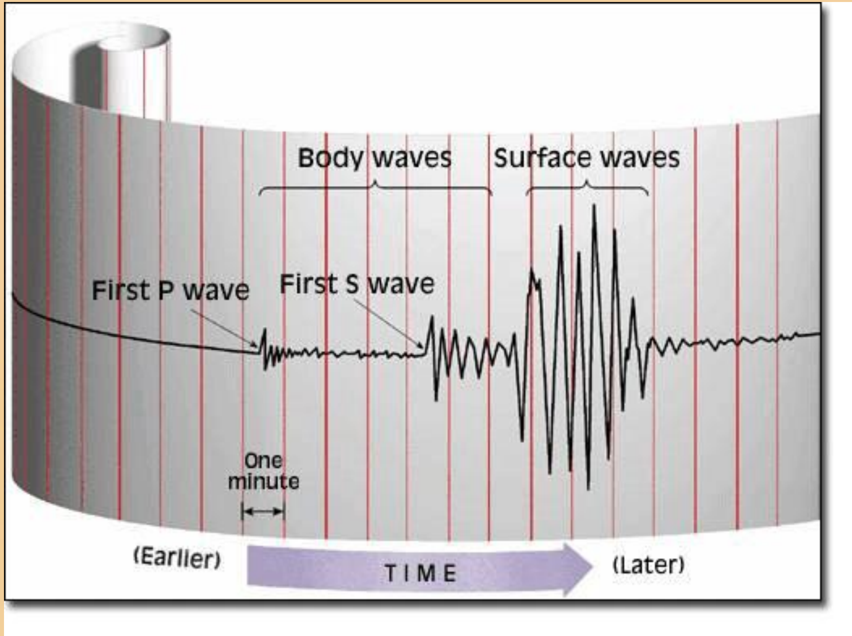
Shallow Passive Seismic

S-waves polarised in the horizontal plane are classified as SH waves.

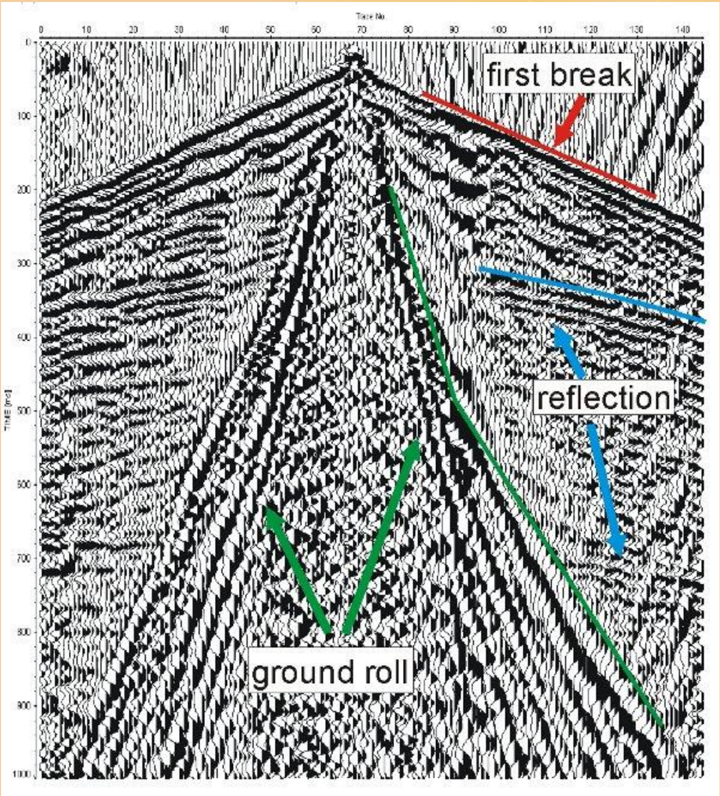


Surface Waves

Surface waves are confined to S-wave velocity, slower, longer wavelength, and higher amplitude. More destructive!

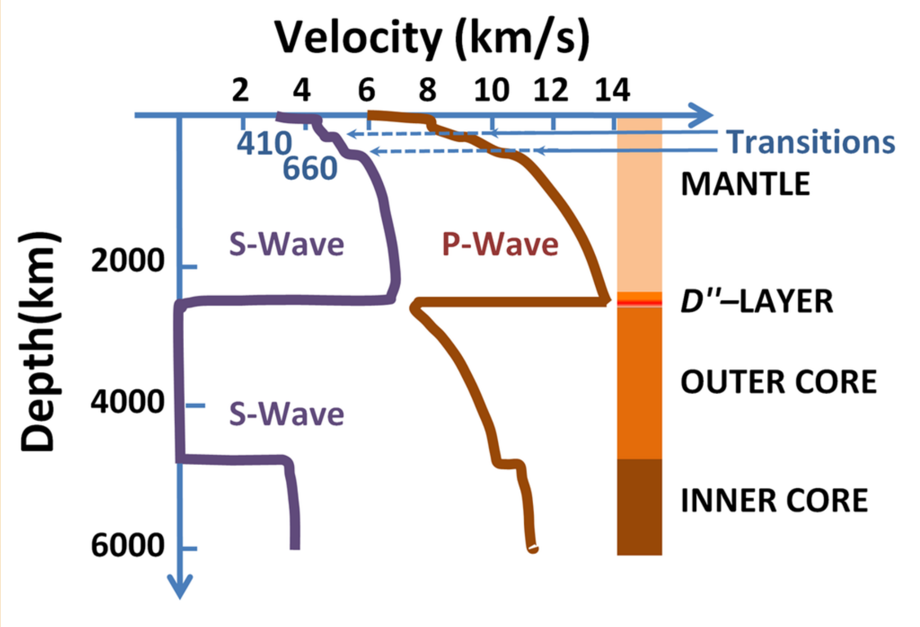


Unwanted noise in conventional active land reflection or refraction surveys: “ground roll”

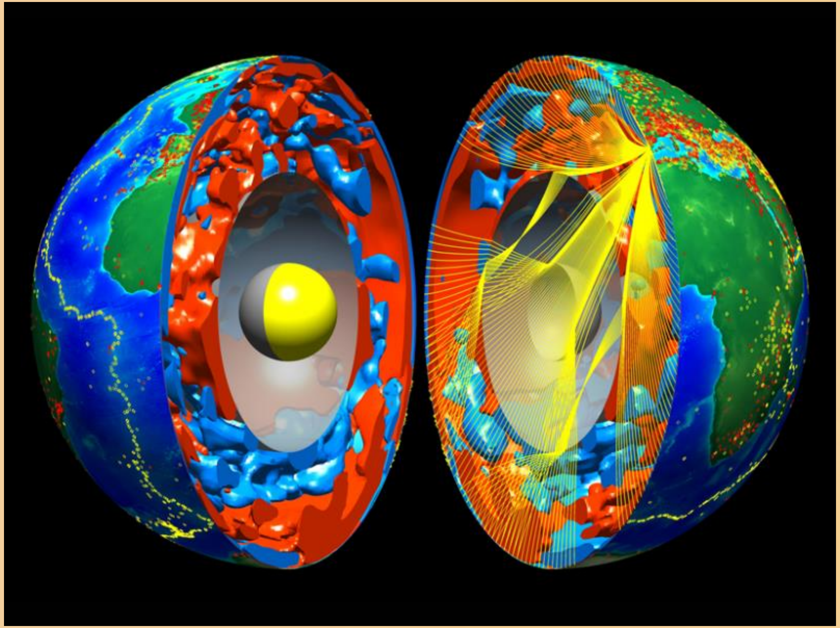


Not Deep Passive Seismic Tomography

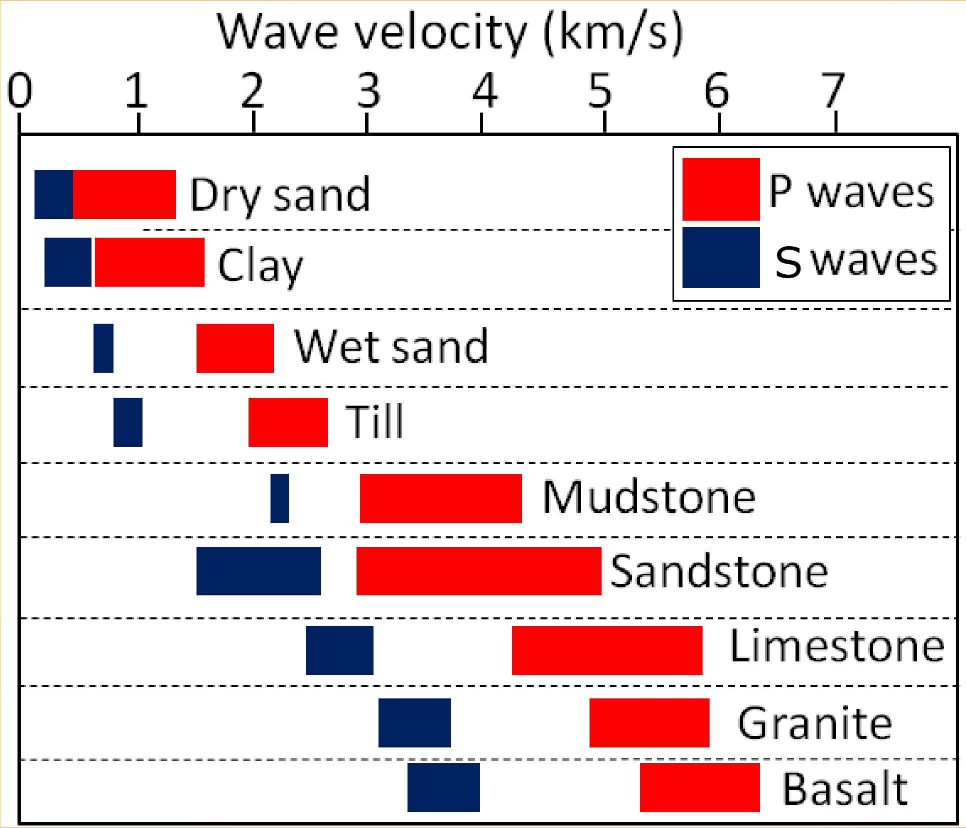
Shear or S-waves less than half velocity of Primary or P-waves, and no S-waves in liquids (requires elastic media)



Body waves used for mapping fast vs slow crust and mantle zones



Shear or S-waves



“Passive” seismic

- Passive seismic is very different from reflection and refraction seismic surveying which requires a controlled source, multiple channels and is very slow, computer intensive and expensive
- Not really “Passive” - for seismic to work there needs to be an energy source somewhere, therefore often referred to as Ambient, Static or Natural seismic surveying
- Microseisms (0.1-1 Hz) are produced by natural phenomena, such as ocean waves hitting the coast, wind and vegetation (fetch), storms, and deeper micro-seismic events (faults, volcanic, geothermal, etc) and fracking
- Microtremors (1-60 Hz) are more likely near surface anthropogenic, such as vehicles, trains, earthworks, industry, etc
- All of this “background noise” acts a permanent seismic source

Not a new method...

Bulletin of the Seismological Society of America, Vol. 68, No. 6, pp. 1623–1636 December 1978

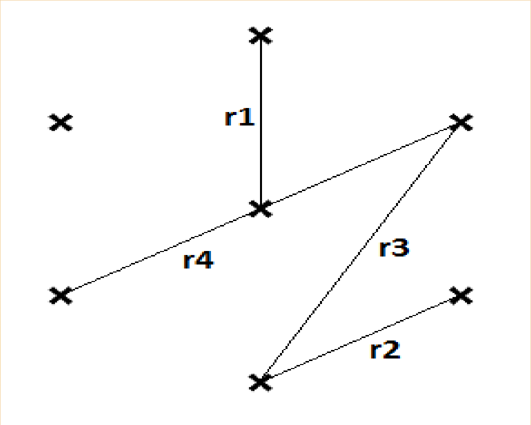
GEOLOGICAL CONTROL ON THE THREE-COMPONENT SPECTRA OF RAYLEIGH-WAVE MICROSEISMS

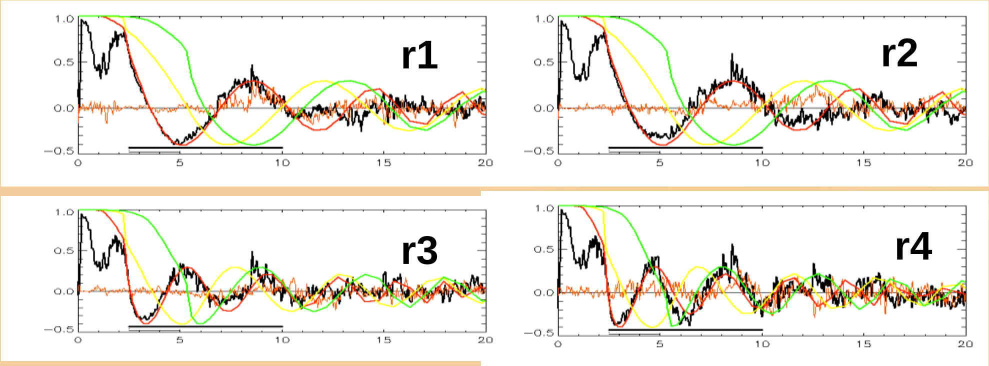
BY MICHAEL W. ASTEN

- Sensor arrays in a geometric pattern: spatial autocorrelation "**SPAC**", >2 seismometers, broadband, good for stratigraphy and layers within shallow bedrock, but very slow and lots of equipment
- Single sensor: H/V spectral ratio "**HVSR**", single reading using 1 portable seismometer, good for bedrock depth, "quick and dirty"

SPAC Array Techniques

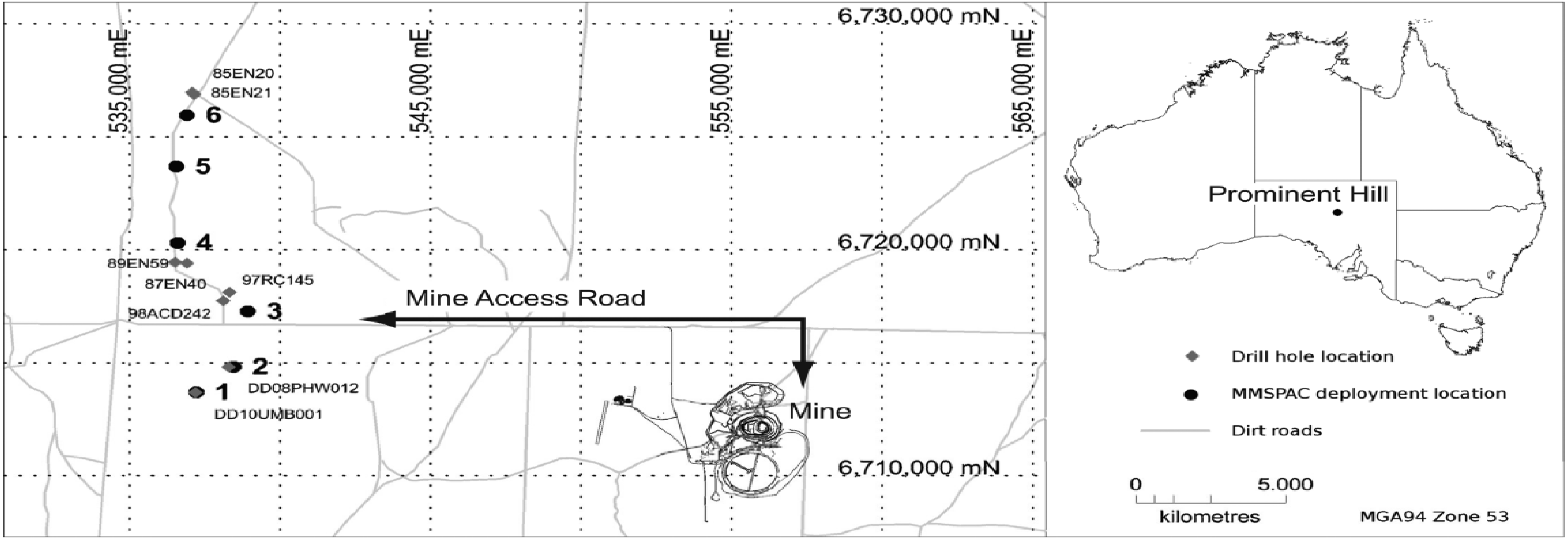
- Cross correlation / coherency
- Circular arrays
- Independent of wavefield directionality
- Lateral surface wave dispersion
- Estimates shear-wave velocity vs depth
- Sensor separation → wavelength sensitivity





(From Smith, 2016)

REGOLITH THICKNESS ESTIMATION AT PROMINENT HILL



(from Smith et al, GEOPHYSICS, VOL. 78, NO. 5 (SEPTEMBER-OCTOBER 2013); P. B227–B242)

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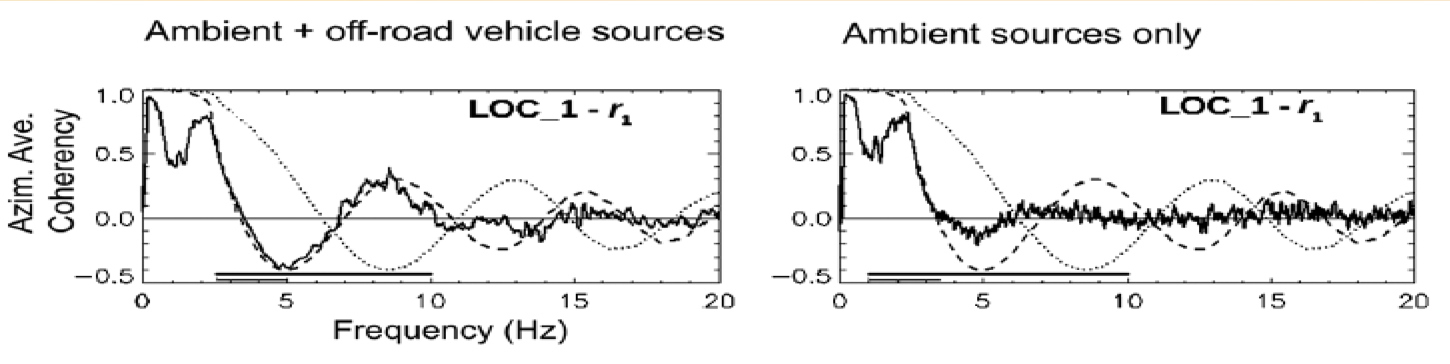

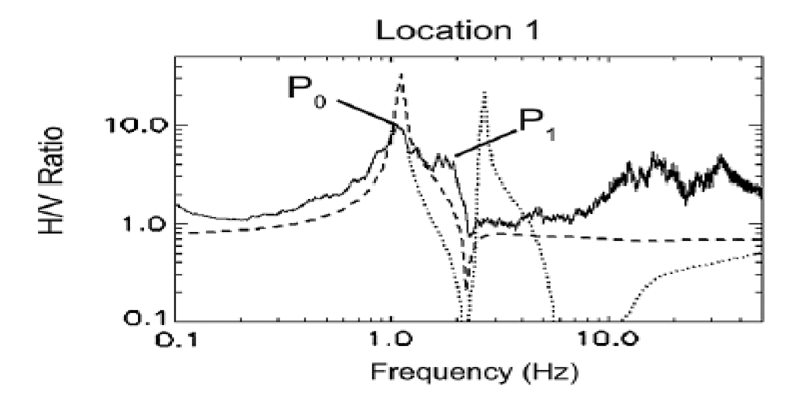

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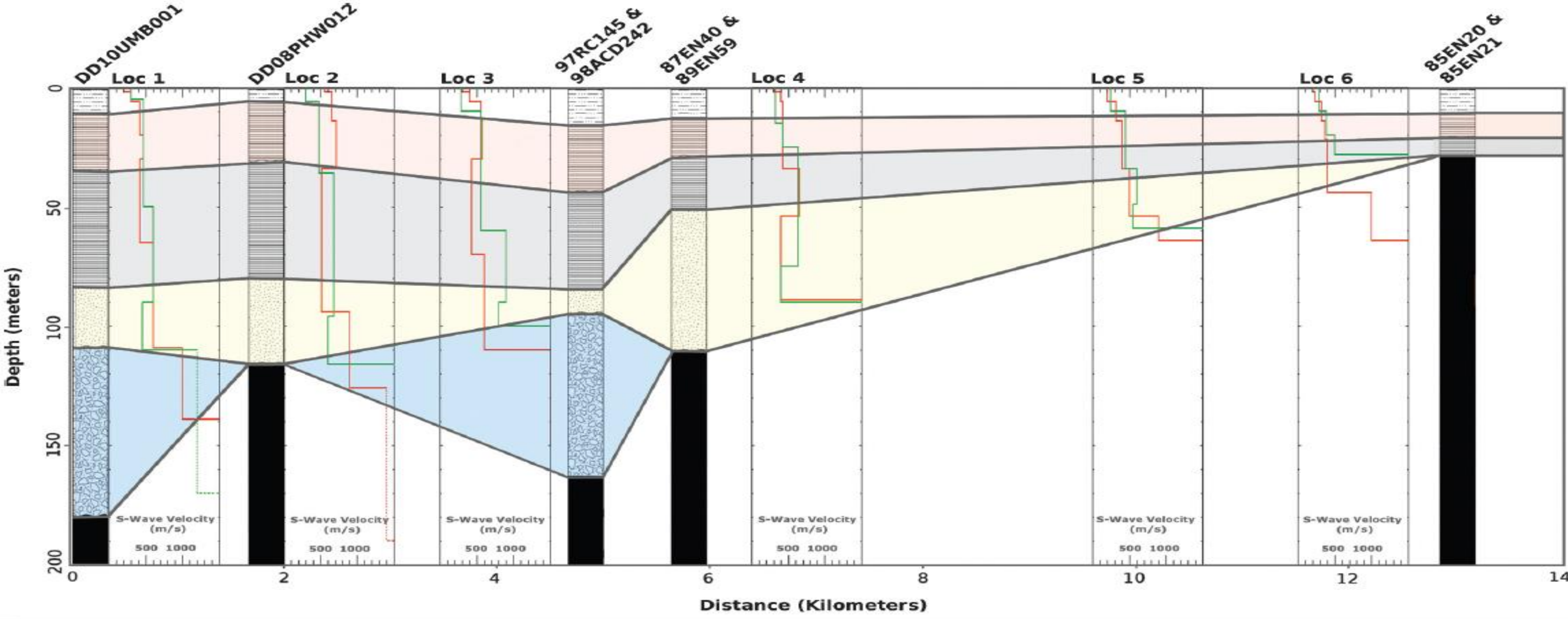
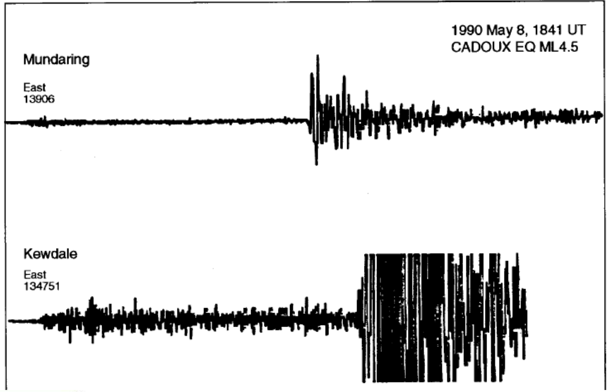


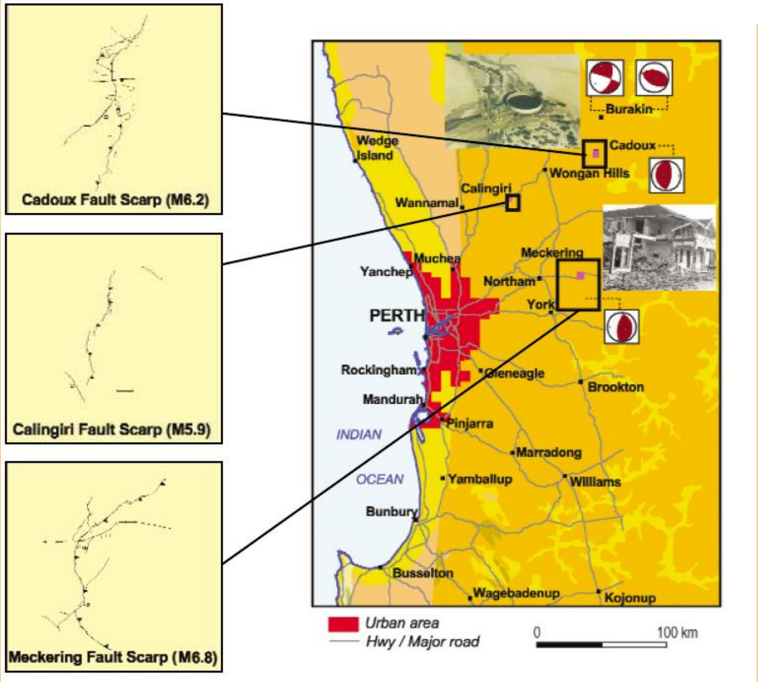
(from Smith et al, GEOPHYSICS, VOL. 78, NO. 5
(SEPTEMBER-OCTOBER 2013); P. B227–B242)

HVSR Shallow

Passive Seismic

- Sensitive seismometers ("tomographs") which record horizontal (H) and vertical (V) components of ambient seismic energy at a single recording station over a broad frequency range (0.1-2048 Hz) for 10-30 minutes, and then the energy spectrum is processed to calculate the H/V spectral ratio (HVSR) and detect strong peaks in HVSR frequency plots representing layers with different S-wave velocities – form of "seismic amplification" recording





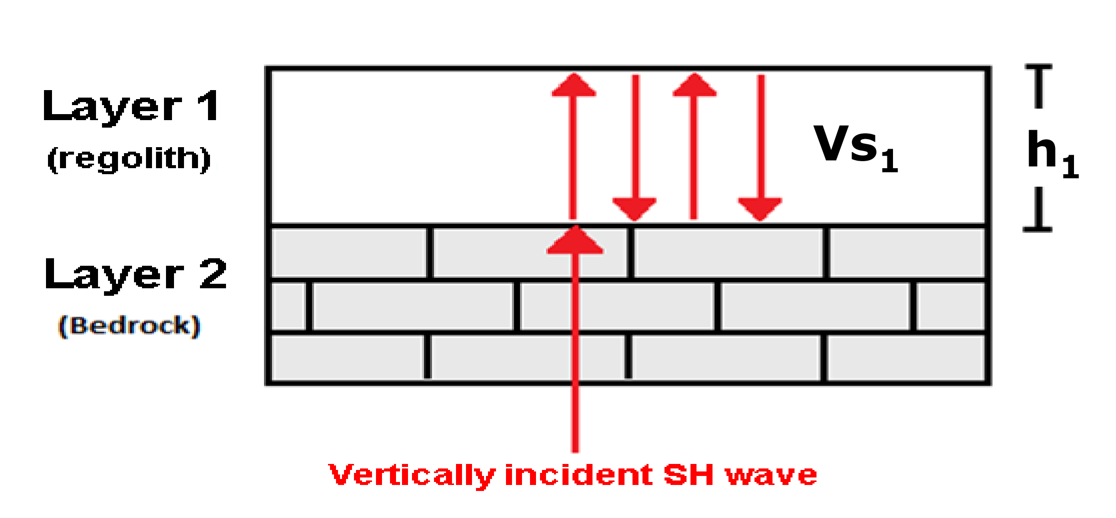
Resonance Conditions

Resonance is due to the trapping of the of the vertically incident SH waves above a strong "acoustic impedance" contrast (AI = Vs x ρ)

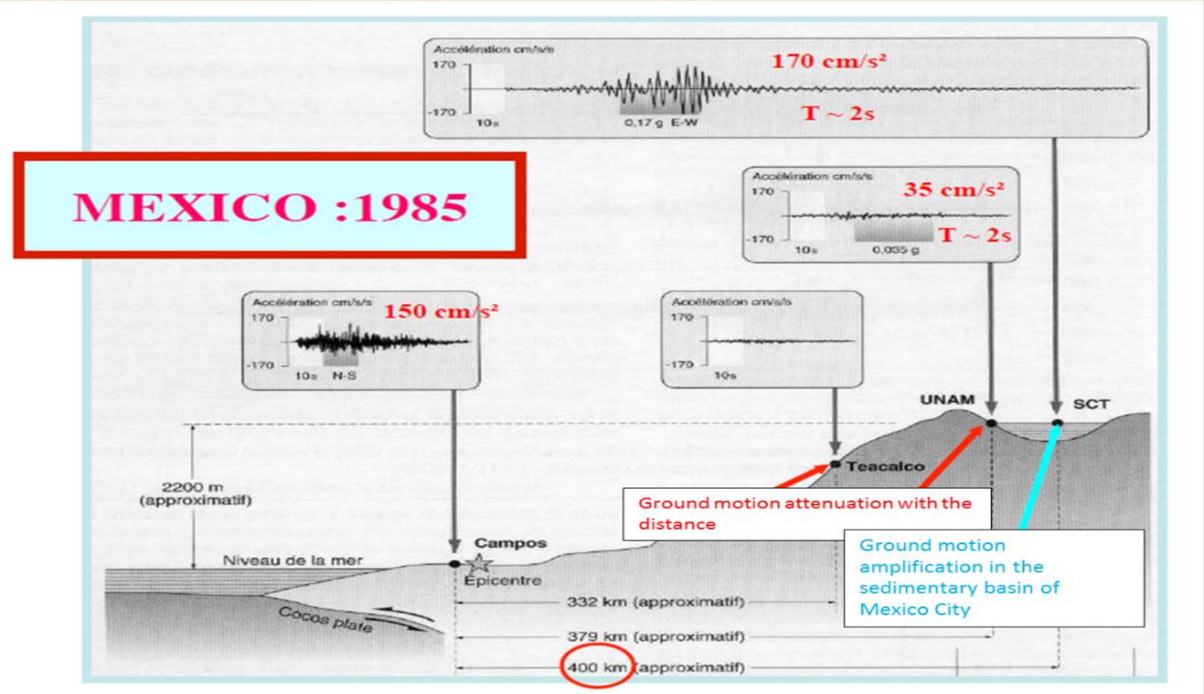
Peak resonance frequency of vertical SH is related to depth by:

$$f_0 = V_{s_1}/(4h_1)$$

"Seismic amplification frequency"



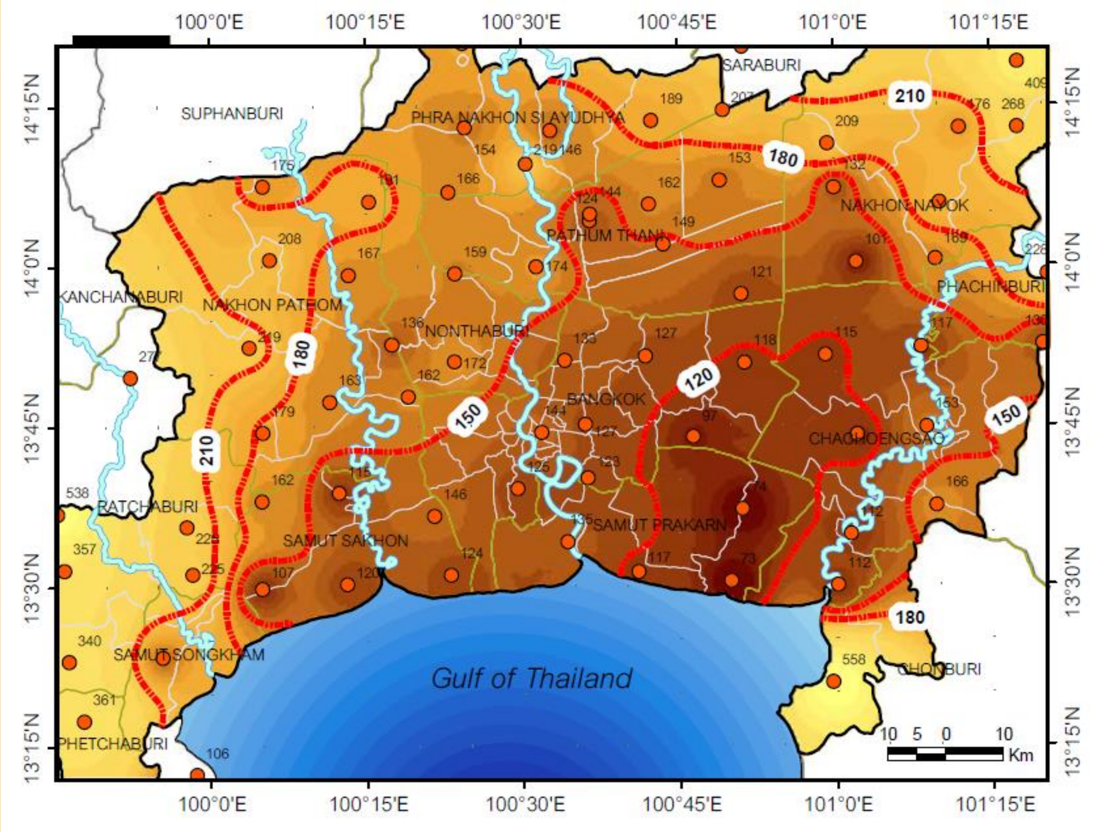
Developed for Seismic Microzonation Mapping



Coast = No damage

Mexico City = All buildings between 10 -20 floors were destroyed

Vs-30 Mapping in Bangkok, Thailand

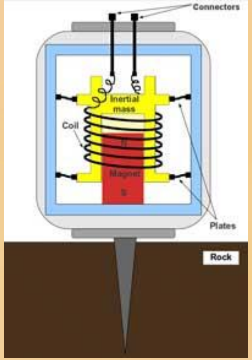


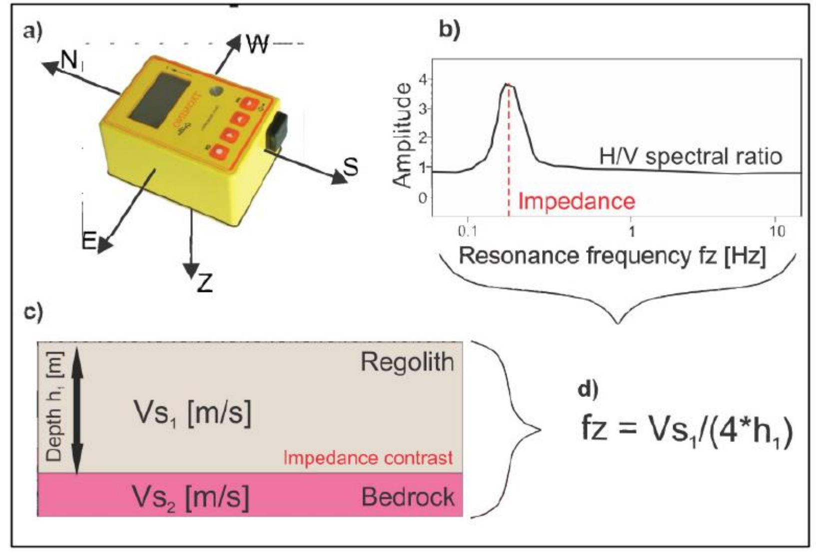
(from Poovaradom and Plalinyot, 2012)

HVSR Passive Seismic Method

- Use 3 component velocimeters
- "HVSR" normalises the power and produces frequency peaks (f) from resonance above strong impedance contrast layers (S-wave velocity x density)
- Depth of layer (h) can be estimated using: f = Vs / 4 h

Typical geophone only measures V (vertical)





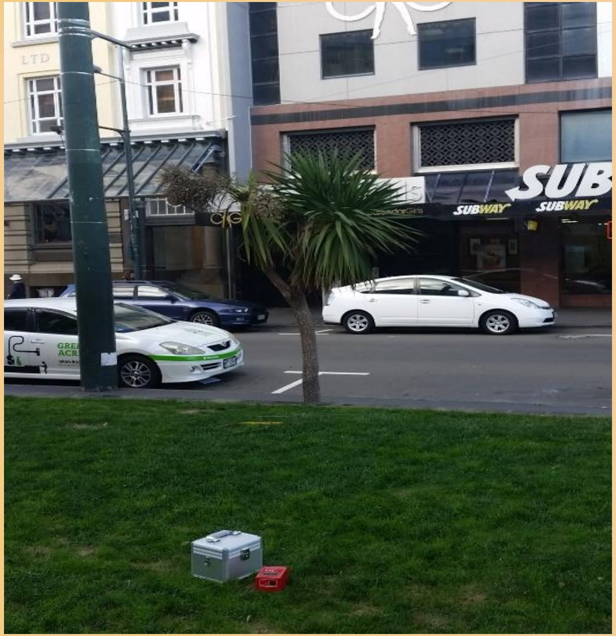
Tromino seismometer

- Tromino is new and innovative in its miniaturised and self contained design to be widely used by geoscientists and engineers
- Tromino has an internal battery (2x AA), memory and GPS – highly portable
- Also contains accelerometers, radio triggering and synchronisation for active seismic (MASW, REMI), recording in arrays, and engineering applications
- Comes with Grilla software for data download, processing and modelling
- Longer period seismometers have much sensitivity and better resolution at low frequencies (<0.1 Hz), but are not as ‘portable’ or easy to use, requires time to stabilise (Trominos record right away), and they require much longer recording times – sometimes overnight

Guralp system configuration

VS

Works in Cities and Bush



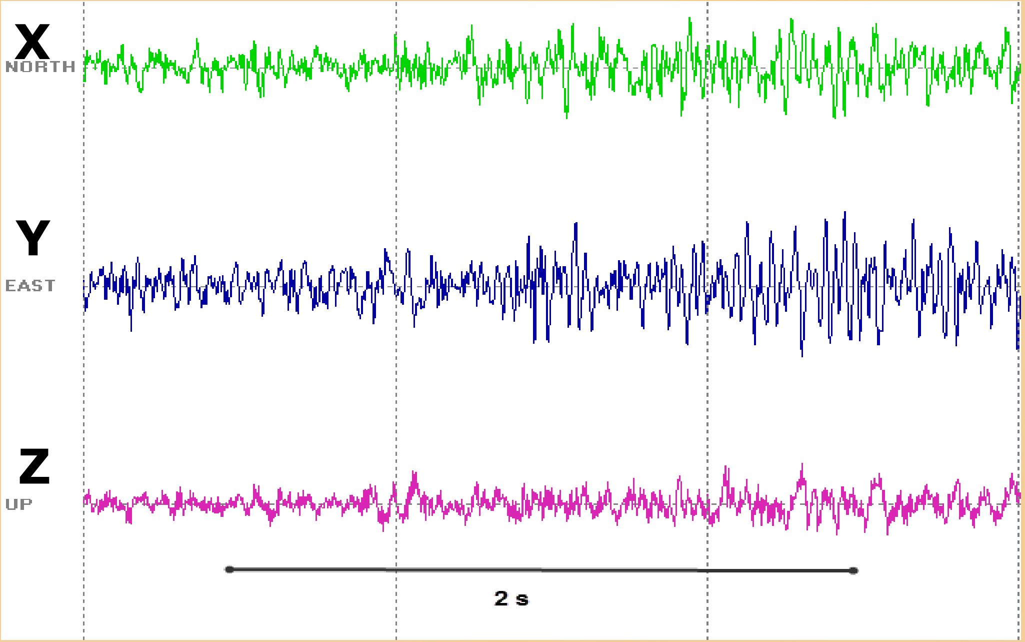
One field technician with 2x instruments can collect 40 stations per day

HVSR passive seismic pitfalls

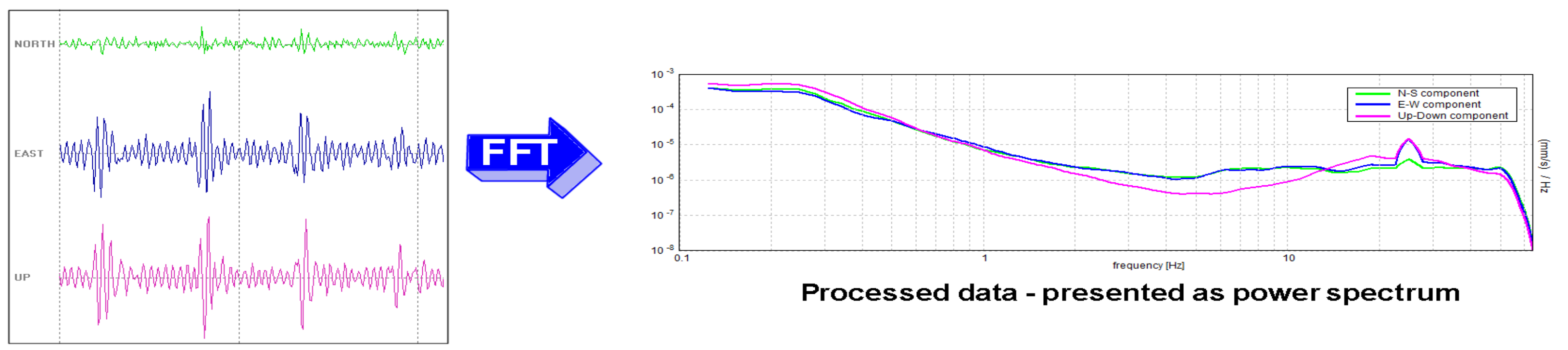
- Required strong bedrock acoustic impedance contrast of Vs x ρ
- S-waves do not propagate elastically in wet swampy ground
- Will not penetrate below hard, well indurated deposits and bedrock
- Requires borehole calibration for local survey conditions; but can model data, especially with MASW velocity for the first layer, or use empirical velocity assumptions as a first pass, and then calibrate to borehole results later
- Not enough signal (rare): repeat later
- Too much signal or vibration interference from wind, construction, etc: survey at quiet times, dampen wind noise by covering with a bucket
- Poor acquisition: inappropriate instrument settings and careless operation (e.g. poor ground coupling)
- Poor data processing and modelling
- Not ideal for very deep layers (>1km) due to high noise at low f

Tromino at Work

- The Tromino measures and records the horizontal (H) and vertical (V) displacements recorded as 3 separate channels, which are recorded over a broad range of frequencies (0.1 - 64 Hz) over a set time interval (generally 5-30 mins)
- The Tromino seismometer can detect oscillations as small as ±1.5 mm/s and up to ±5 cm/s



Time to Frequency Domain

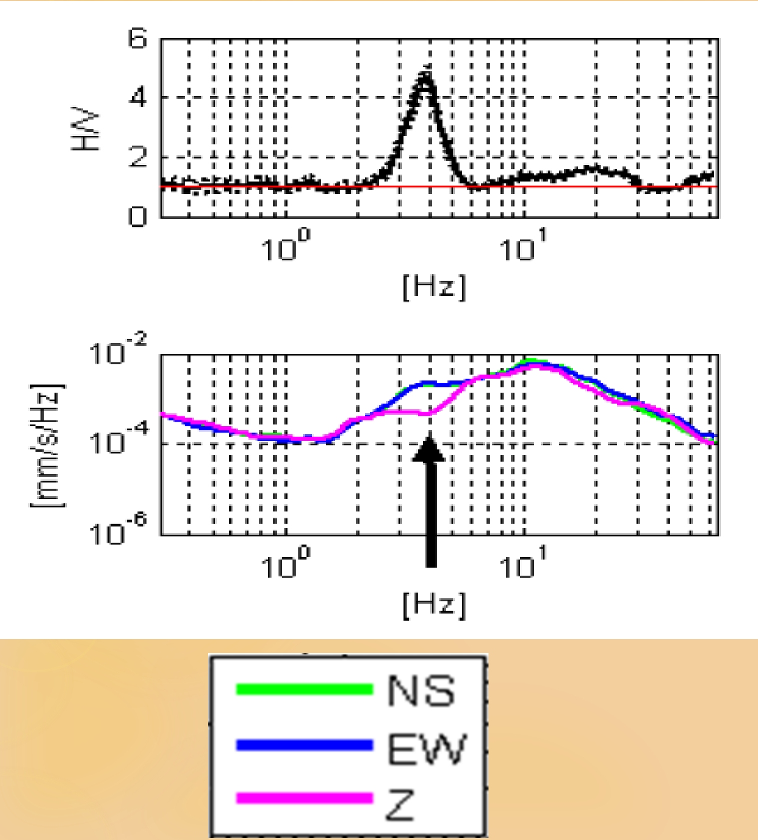


Time-based Tromino reading

Processed data - presented as power spectrum

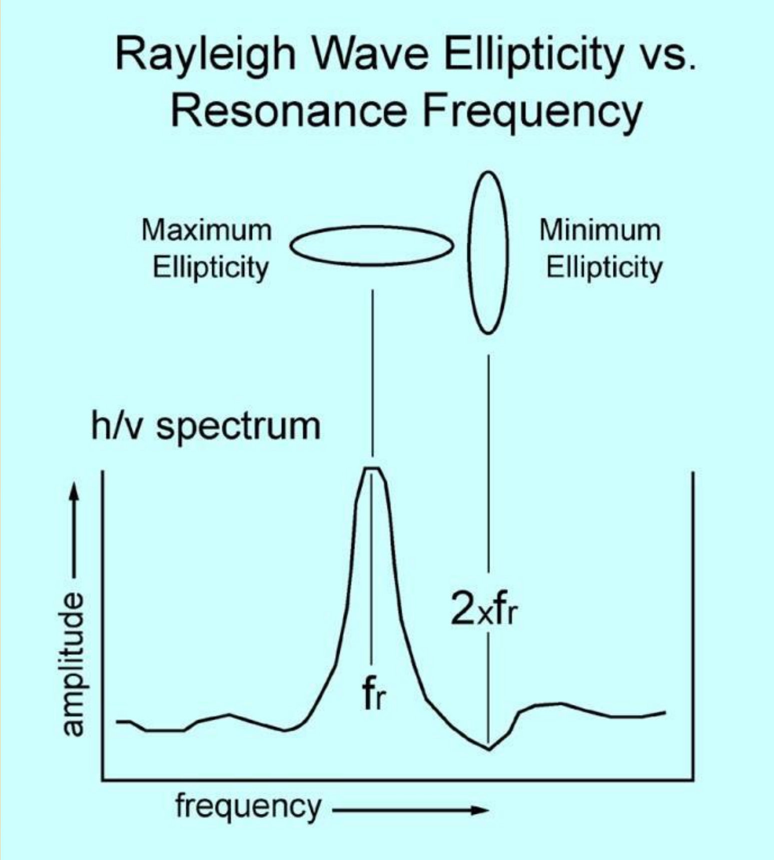
- The time-series data recorded by the Tromino are transformed into frequency spectra by FFT and presented as a power spectrum
- The **H**orizontal components (east-west and north-south) should look very similar, unless there is strong anisotropy in the near surface, and the **V**ertical component will "dip" where resonance occurs from trapping by underlying layers

Peak Frequency Detection



- Trapping / Resonance causes the vertical SH waves to constructively interfere – this appears on power spectra as an “eye” like gap between the component spectral profiles
- When the ratio of the geometrically averaged horizontal components (H) with the vertical component (V) is taken, the resulting HVSR profile shows a peak at the resonant frequency

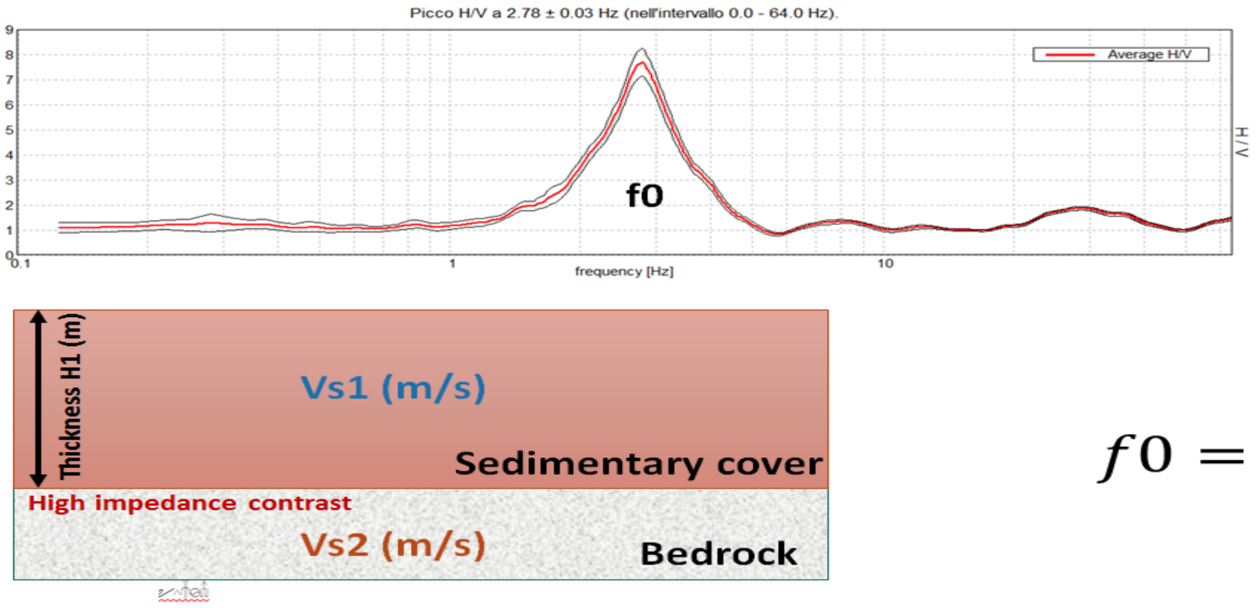
Peak Frequency Detection



- So at the peak f, resonance causes the V component to drop in amplitude relative to the H components at "maximum ellipticity"

Depth Estimation

Taking the H/V spectral ratio will produce a profile with a peak occurring at the resonant frequency for that layer, which is related to the thickness and S-wave velocity.



$$f0 = \frac{Vs1}{4.H1}$$

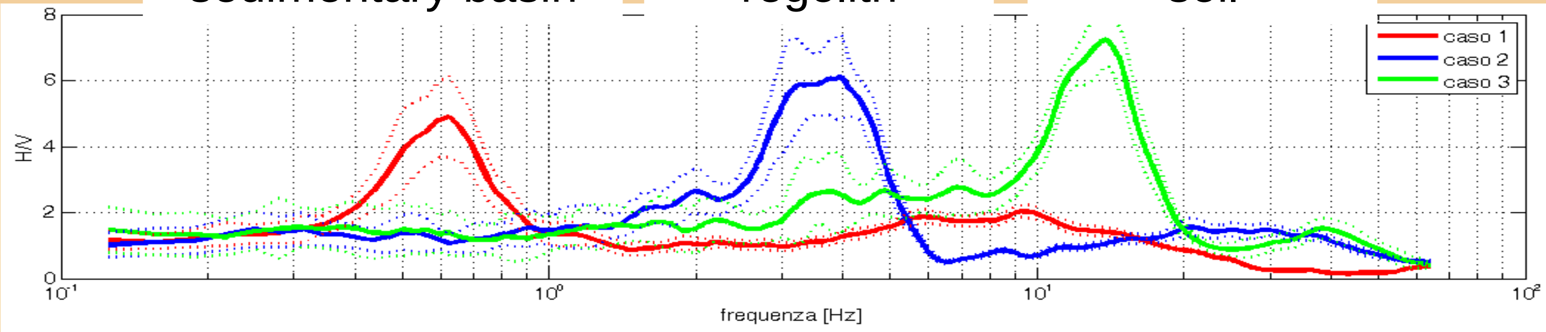
Frequency vs Depth

- Trominos can detect bedrock down to >700 m, and therefore have application for mapping in coal basins, but most surveys are carried out to detect low velocity soil and regolith thickness above 200 m depth
- Deeper bedrock shows up as lower frequency peaks

300 m
sedimentary basin

40 m
regolith

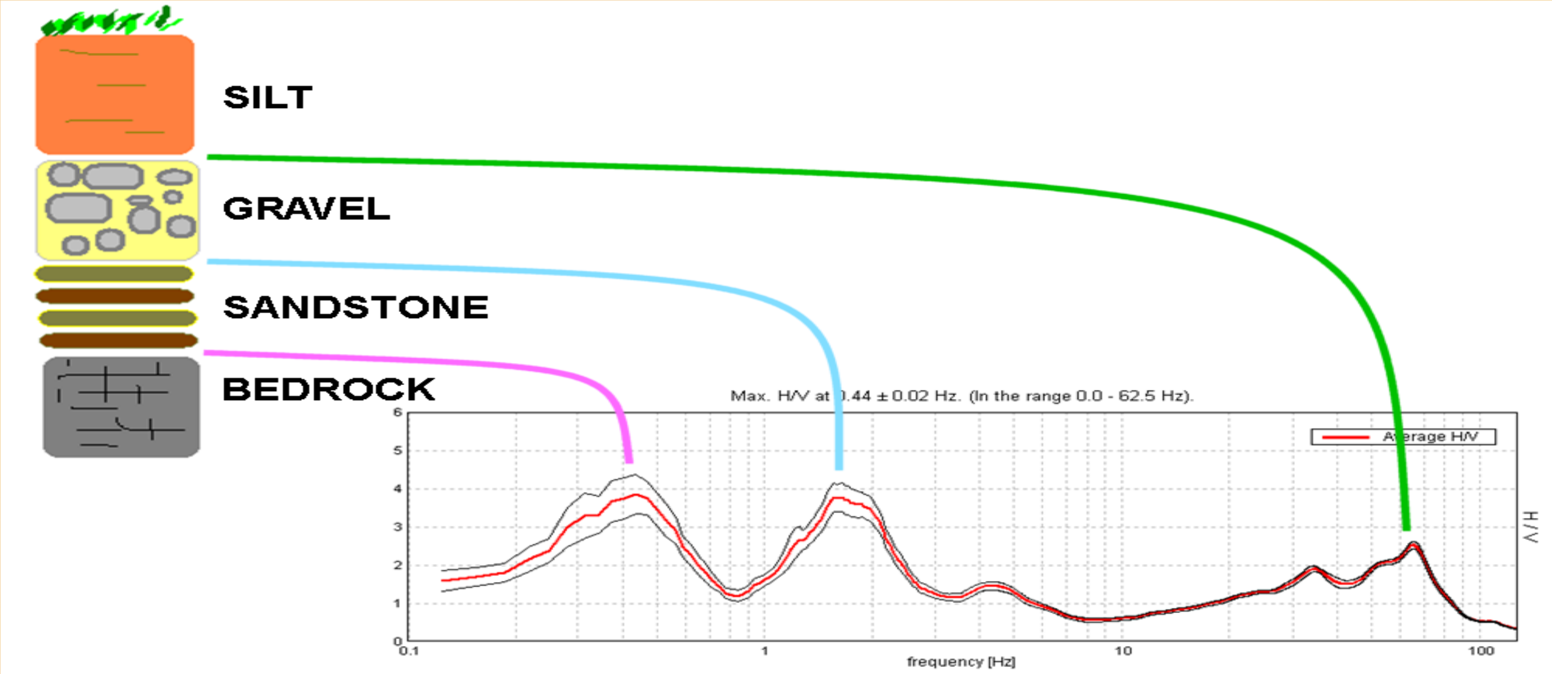
4 m
soil



Deep **Shallow**

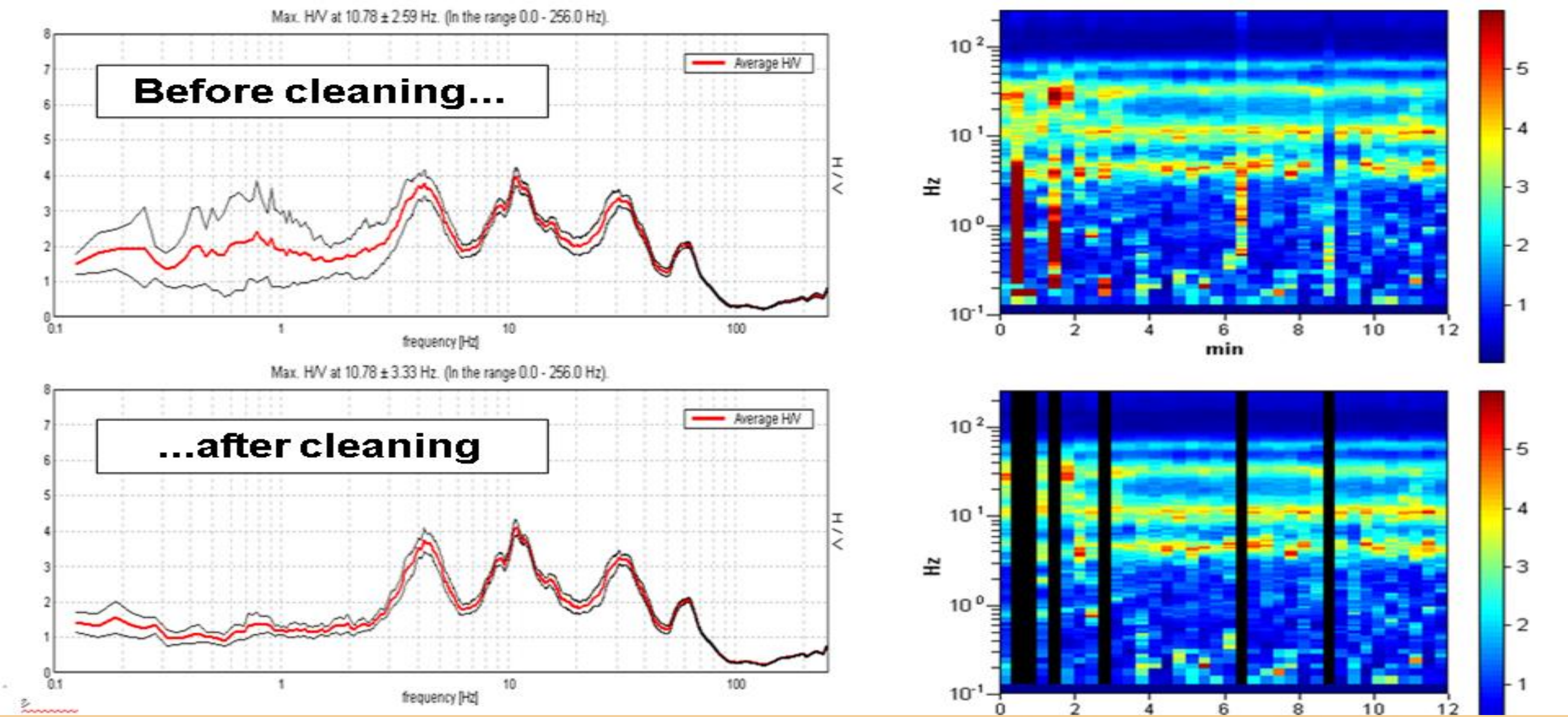
Multiple High Impedance Contrast Layers

Multiple f peaks are possible where there is strong impedance contrast between layers, and a peak will occur at the resonant frequency corresponding to each subsequent layer



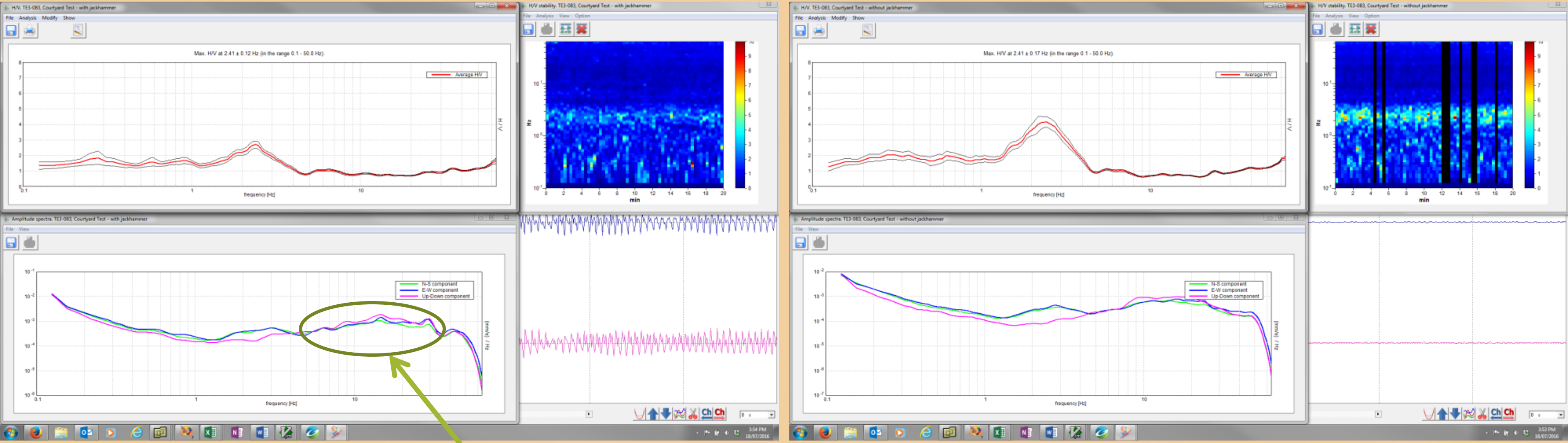
Data Cleaning

The Grilla software package allows the user to "clean" the data to enhance the peak frequencies in the power spectrum.



Rock breaker noise 70m away

- Perth City, Bassendean Sand over Tamala Limestone, recorded through brick pavers
- Same location with rock breaker on and off, same peak *f*
- Noisy signal with rock breaker on, masks main peak *f*, BUT STILL WORKS!

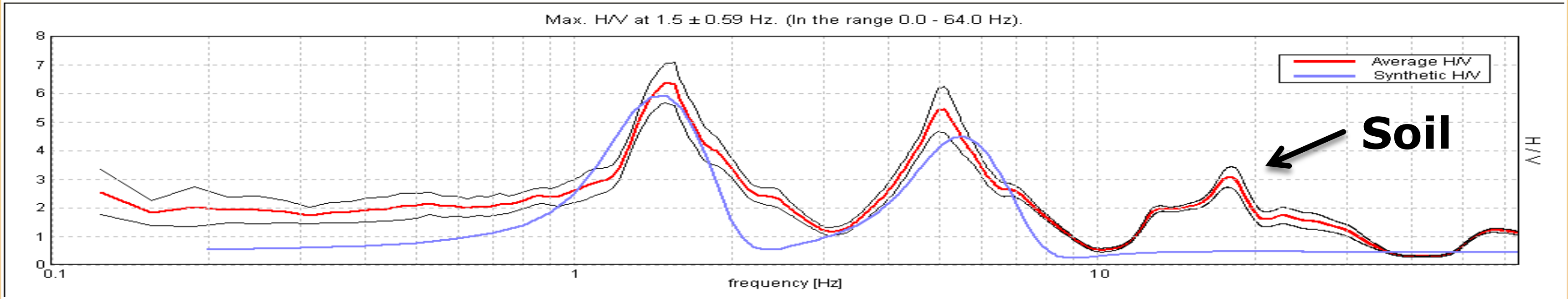


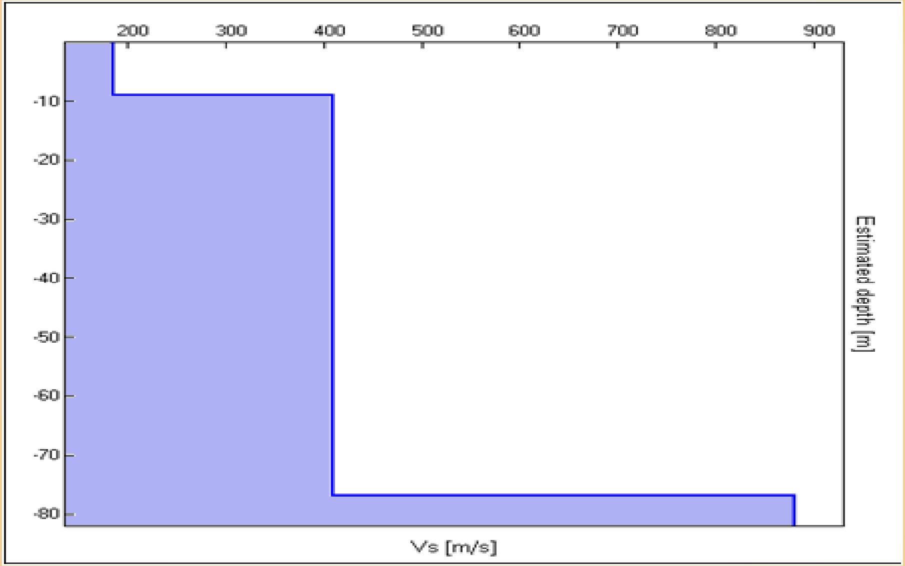
High *f* peaks from rock breaker

1D Vs with Depth Modelling

- A velocity-depth model can be produced for each field recording, and velocity models can be constrained by taking readings at drillhole locations where the depths to geological horizons are known
- Modelling is carried out so that the shape of the velocity model roughly matches the measured H/V amplitude vs frequency profile
- The final result is a depth vs shear wave velocity profile for a particular site, transects or a mapped area
- The calculated depths obtained from the modelling can then be contoured or imaged to show the architecture of the subsurface regolith geometry

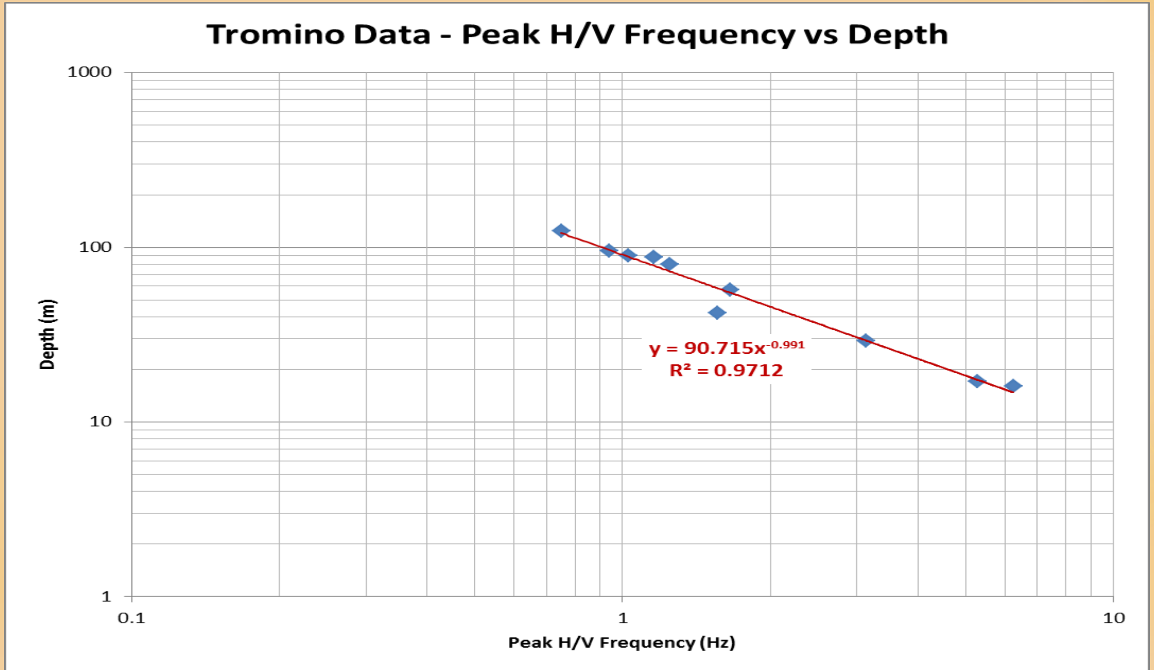
Two Layer 1D Model



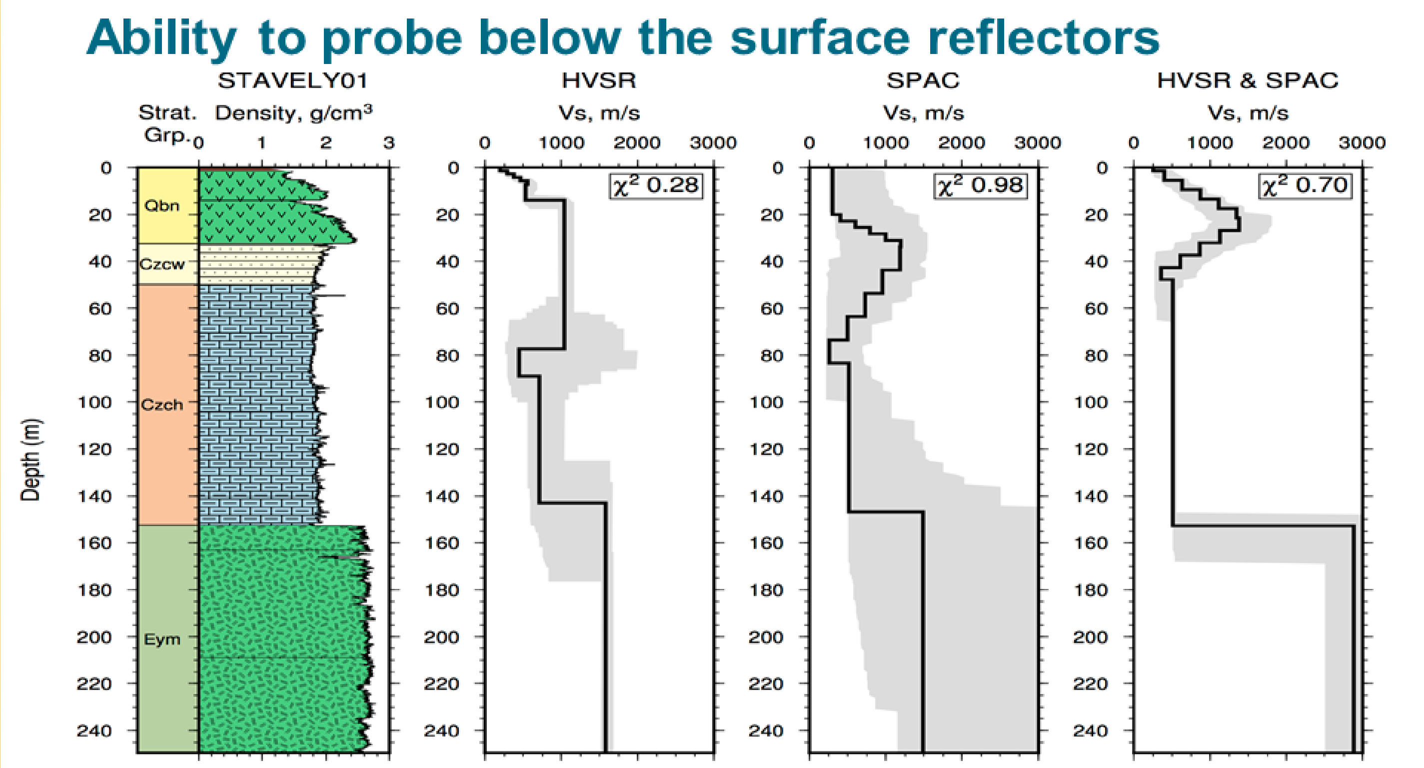


Depth Calculations Using Drill Lith Logs

- Calibration of peak frequency to bedrock depth from drilling lith logs
- Generates a formula for depth estimation away from drillholes when vertical Vs gradient is laterally consistent
- Vertical Vs increase with depth following the equation is usually due to compaction

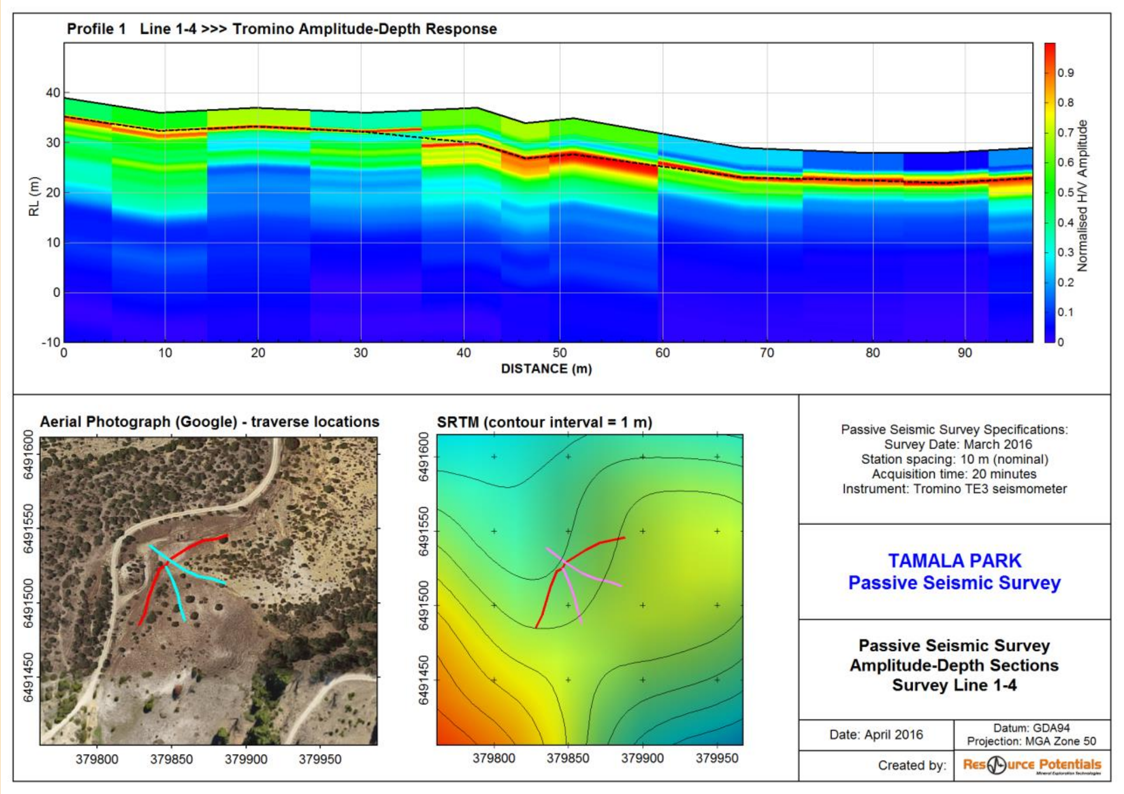


Inversion – from GA using Geopsy



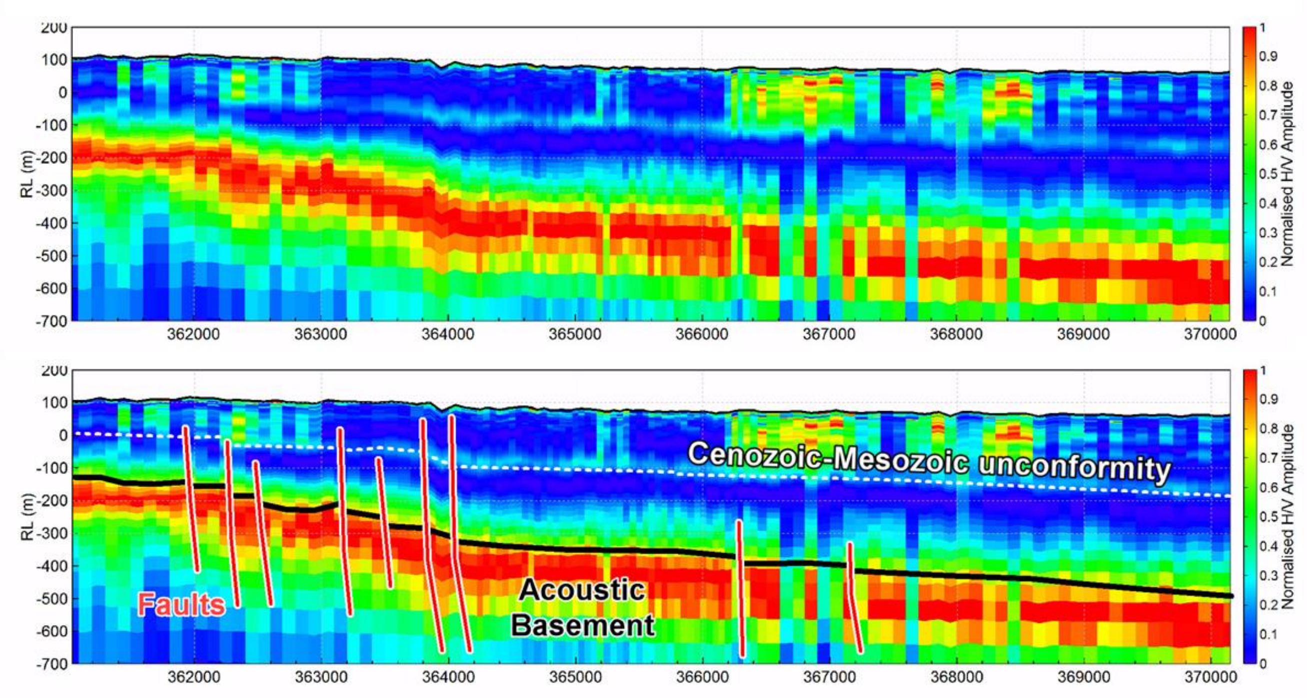
(from Buckerfield et al., 2016)

Sand cover for waste dump planning



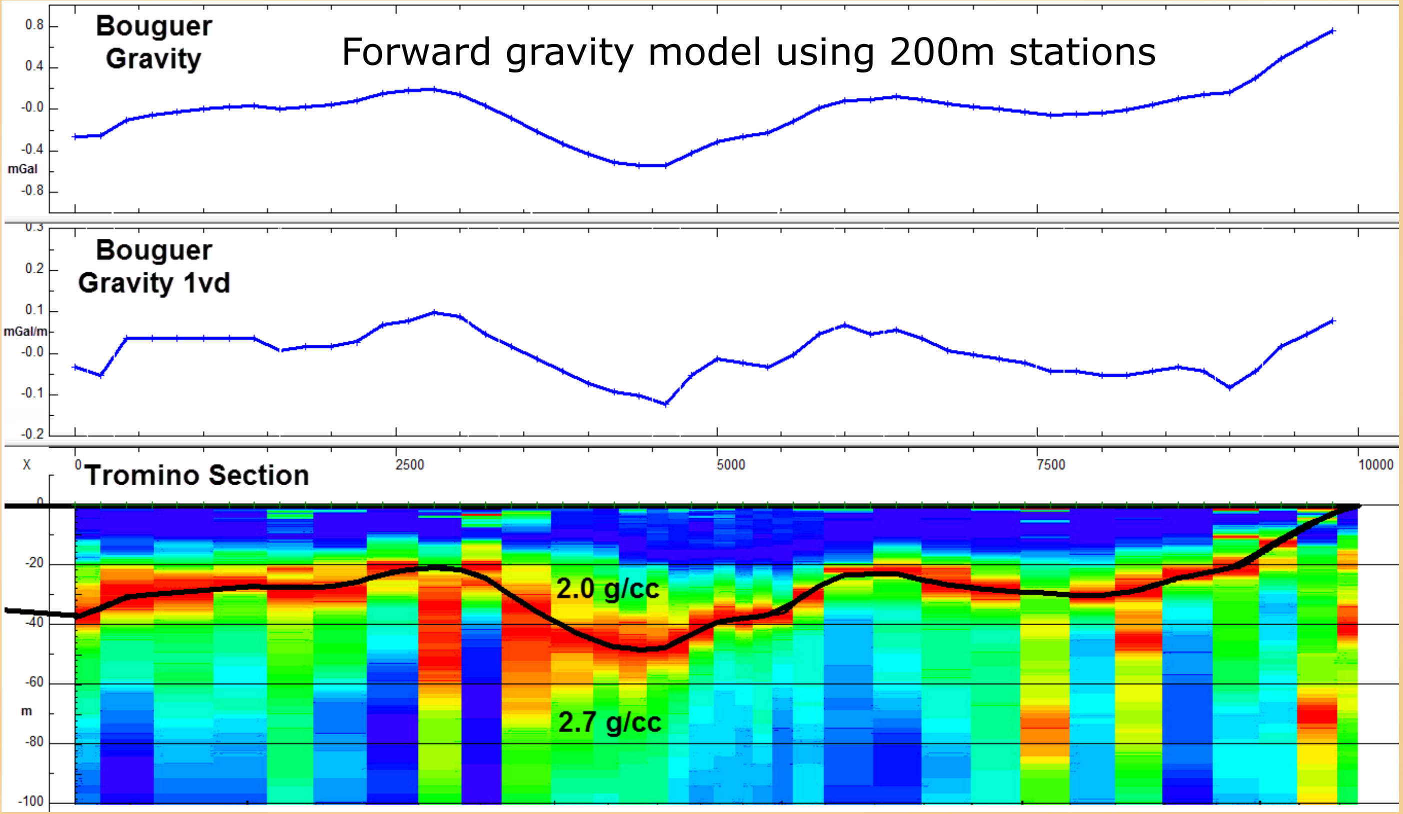
Recent Survey – sedimentary basin

- Survey to detect the base of a intracratonic sedimentary basin filled with Mesozoic-Cainozoic siliciclastic sedimentary deposits
- Intra-sedimentary units and major unconformity detected
- Base of basin detected down to 700m, constrained by seismic reflection and drilling data



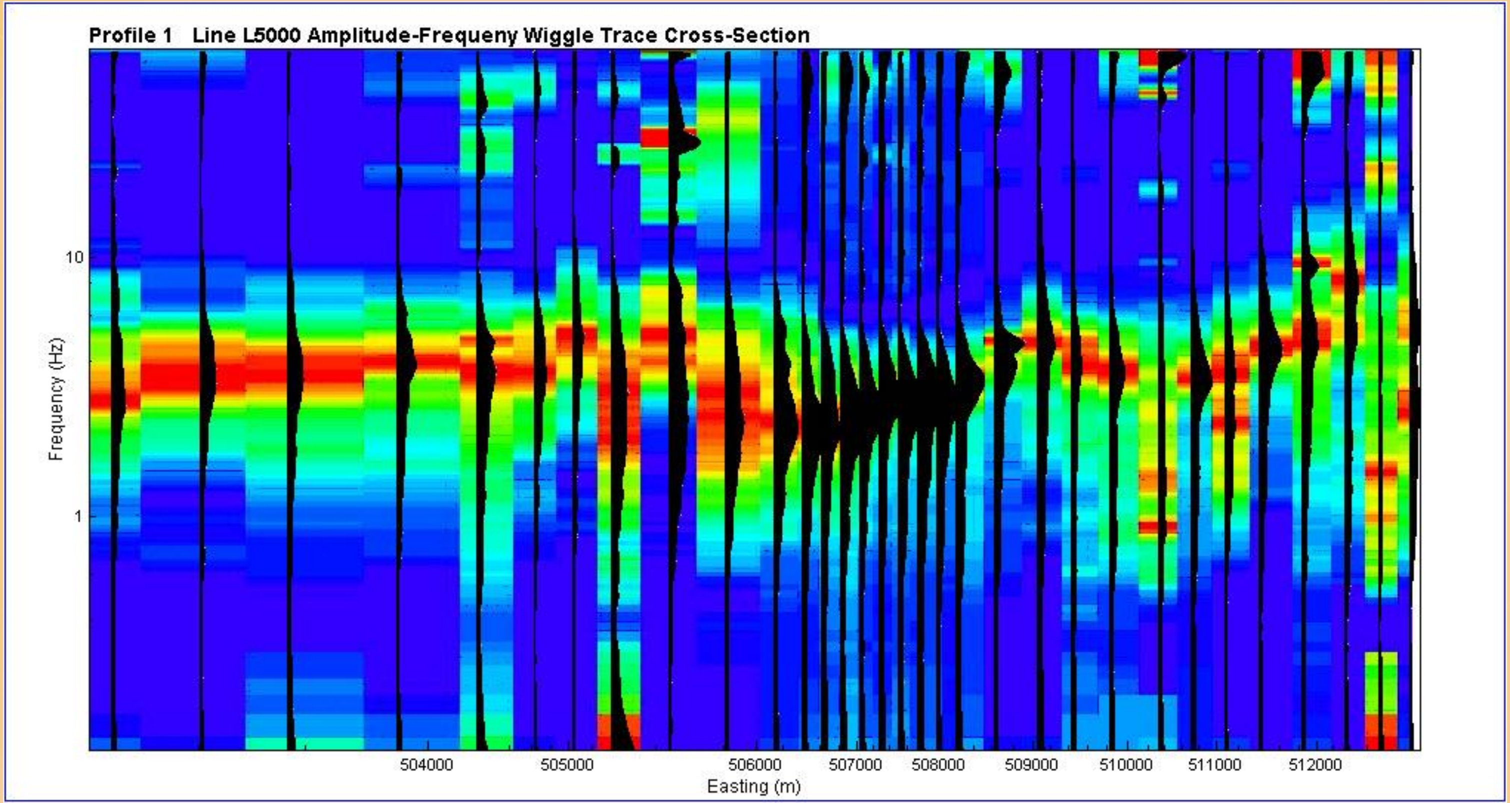
Paleochannel, WA – 400m and 200m spacing

Infill creates better detail, vertical "beam" of resonance can detect dipping features, unlike seismic reflection and refraction!!



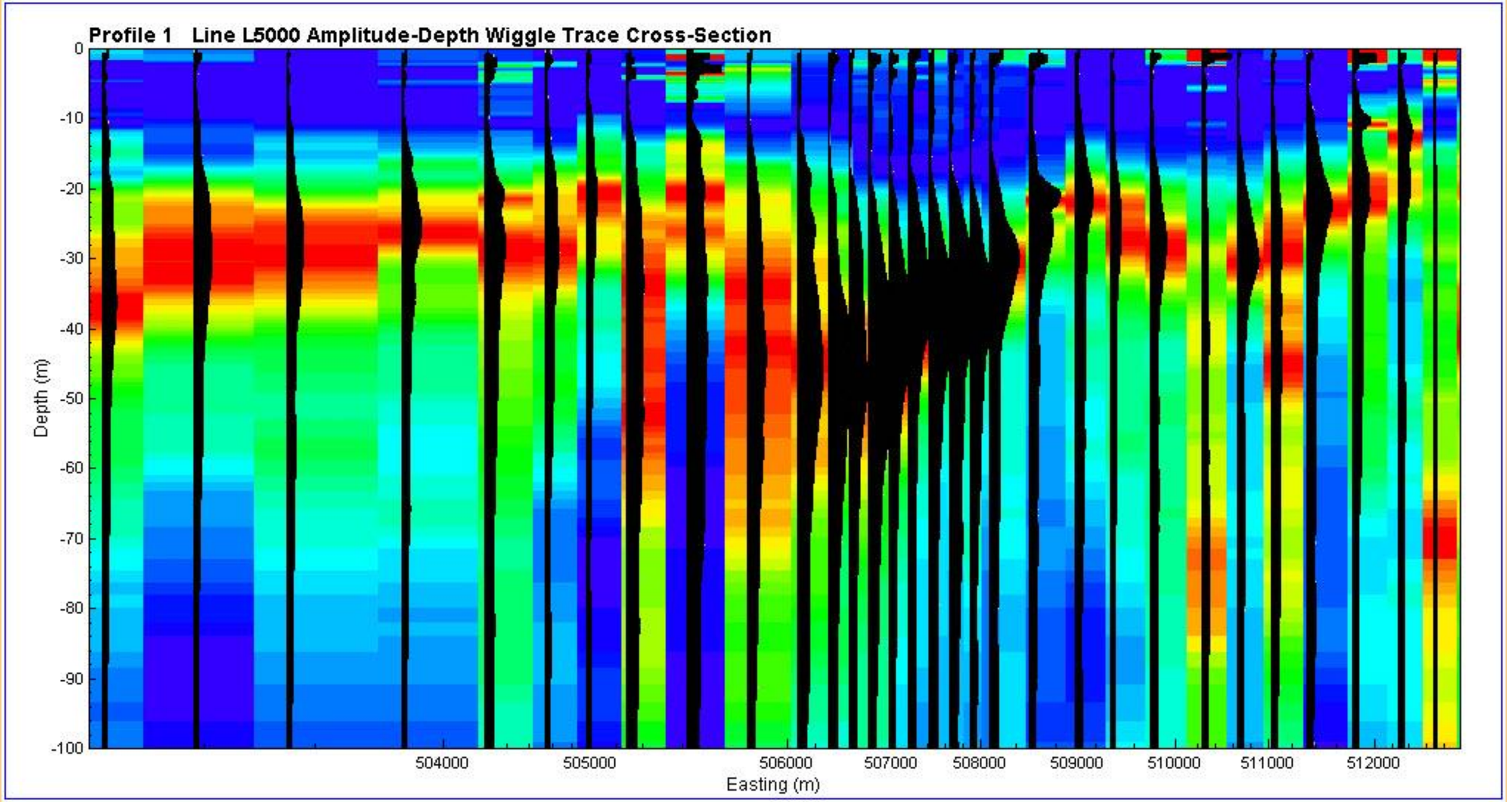
Paleochannel, WA – 400m and 200m spacing

Frequency section



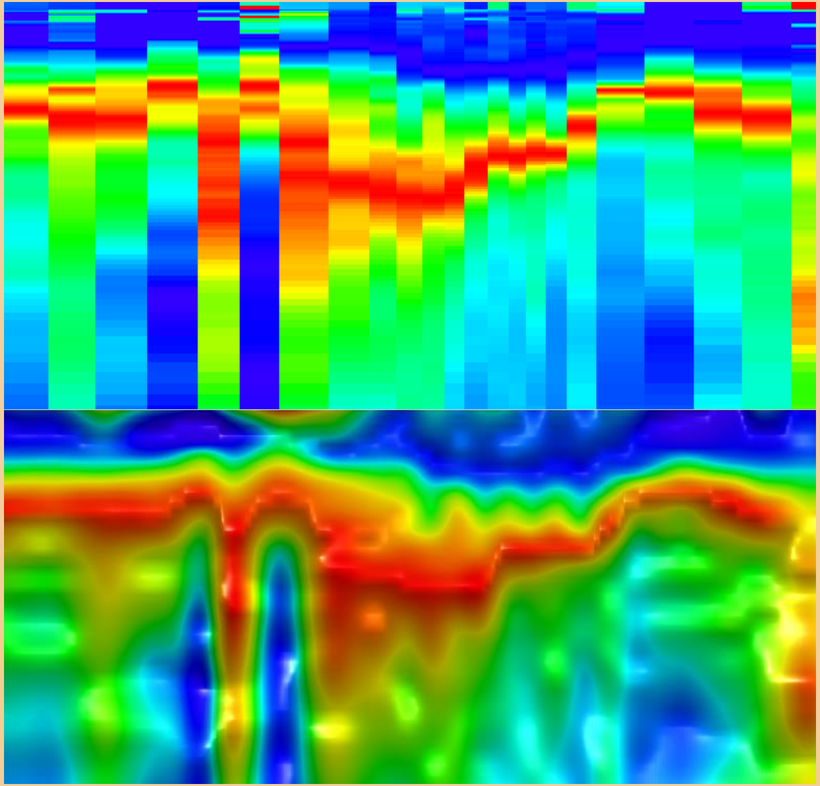
Paleochannel, WA – 400m and 200m spacing

Depth converted cross-section



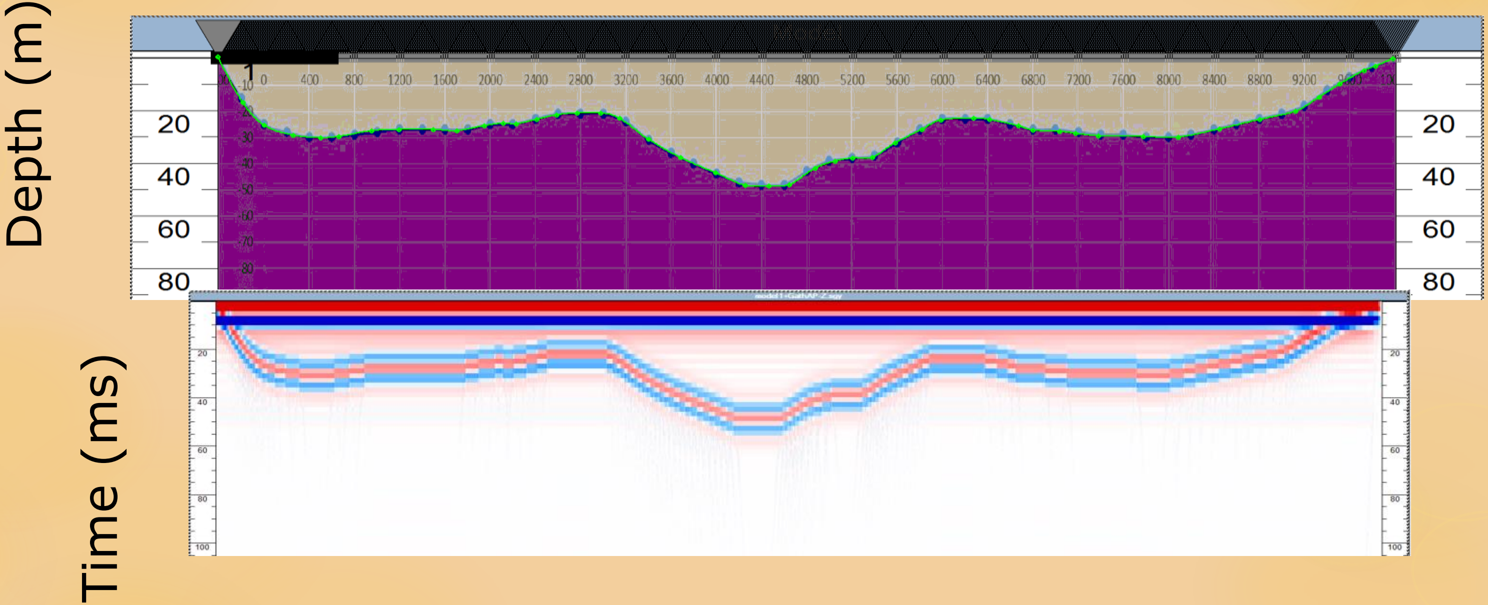
Paleochannel, WA – 400m and 200m spacing

Normalised amplitude readings compared to gridded image sections



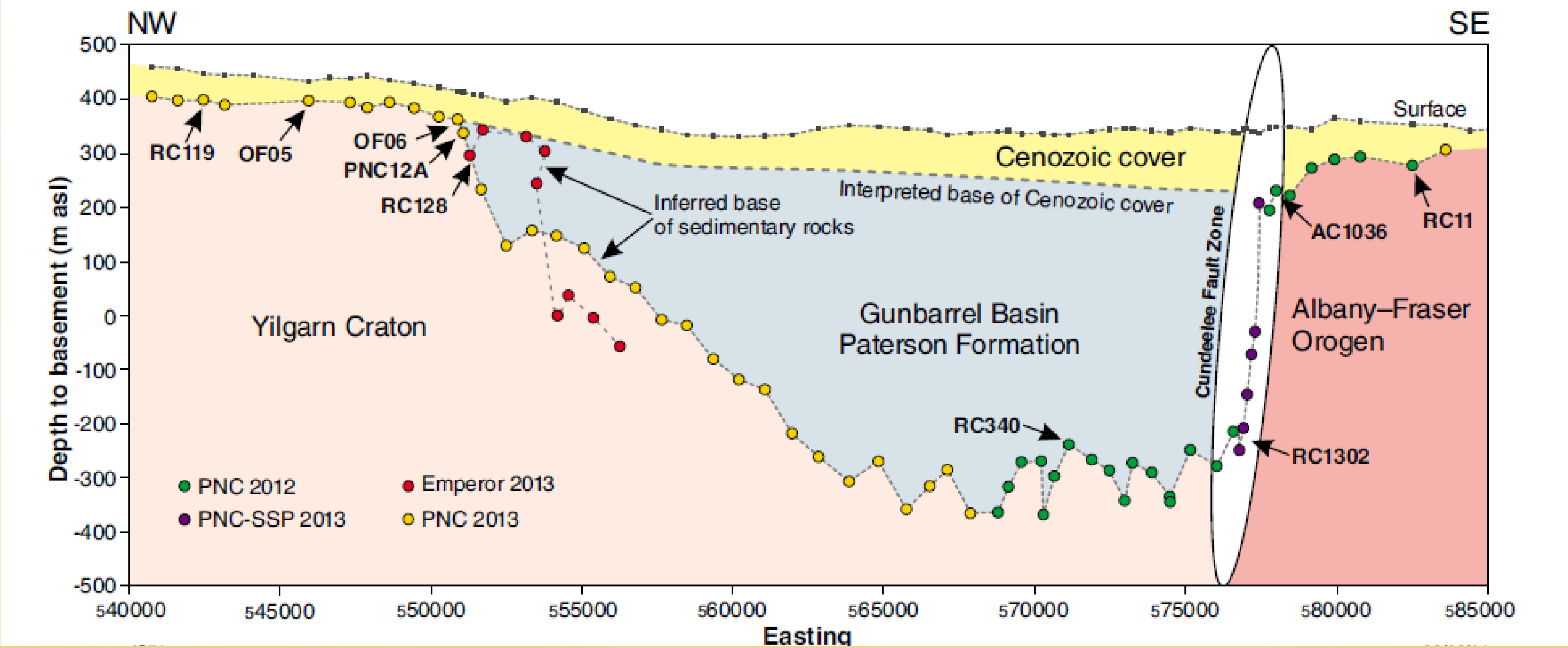
Paleochannel, WA – Refection model

- Zero-Offset Seismic Section (noise free modelling of stacked section)
- Raw idealized shot 80 Hz Ricker
- 5m CDP



GSWA Mulga Rock line, Gunbarrel Basin

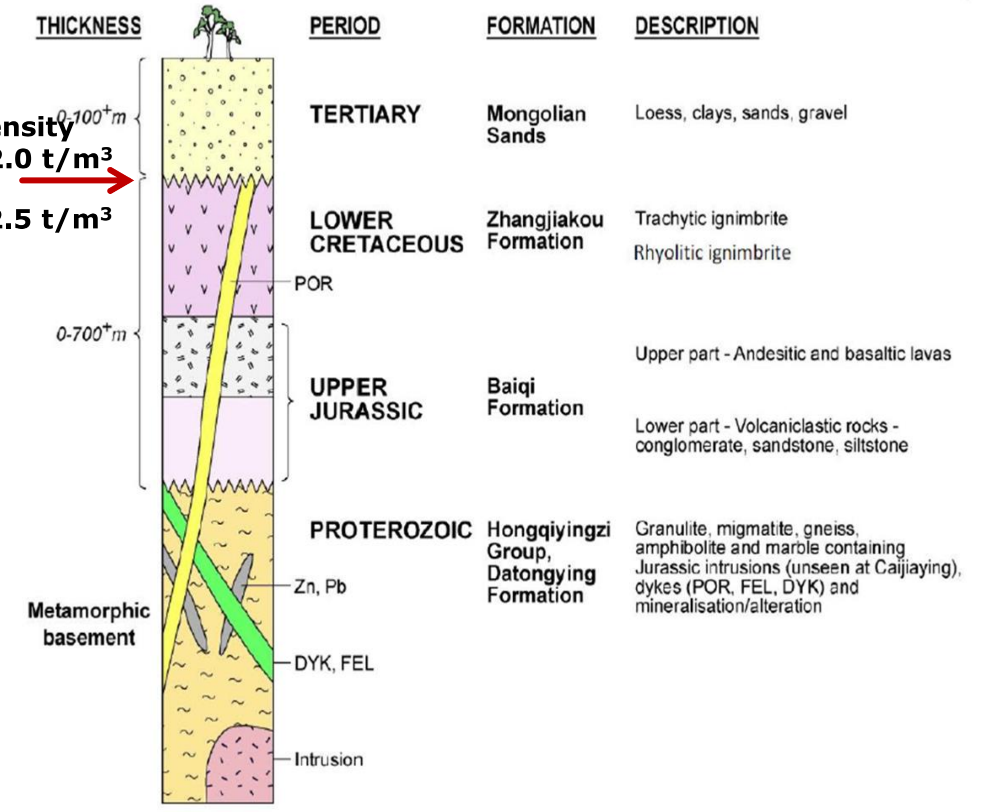
- Cundelee Fault surface detected

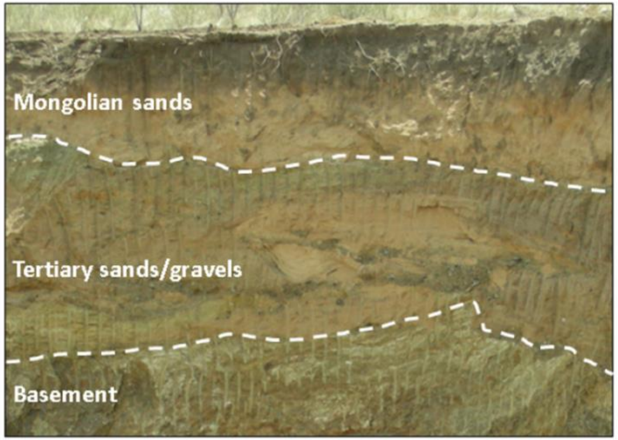


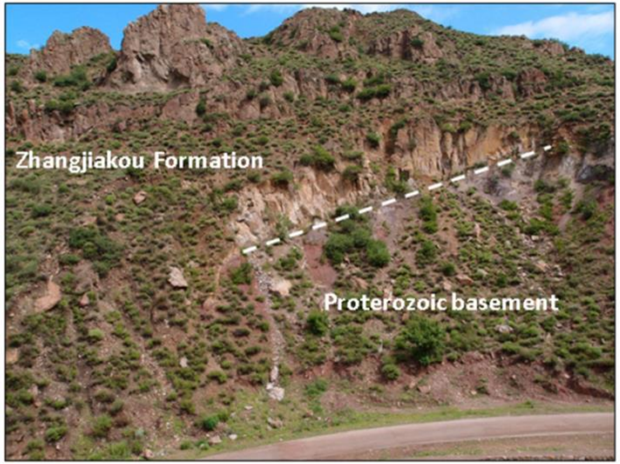
(from Scheib, GSWA Record 2014/9)

Loess, alluvial and fluvial thickness N China

Density
<2.0 t/m³
>2.5 t/m³

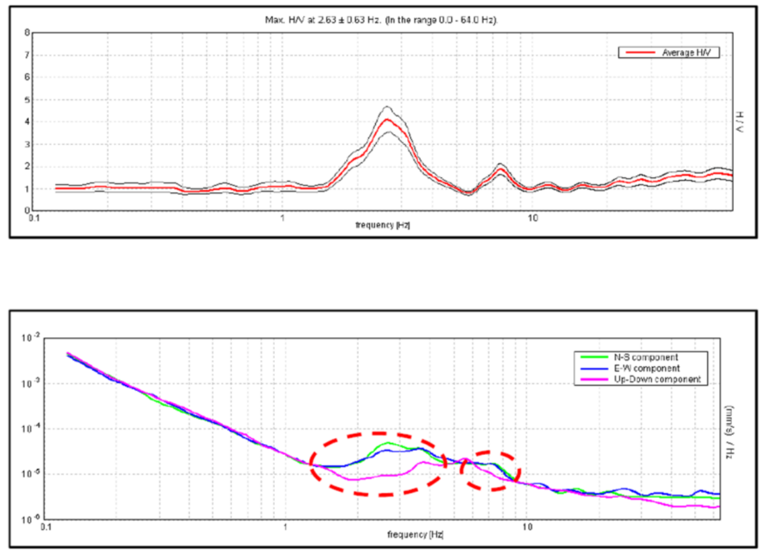


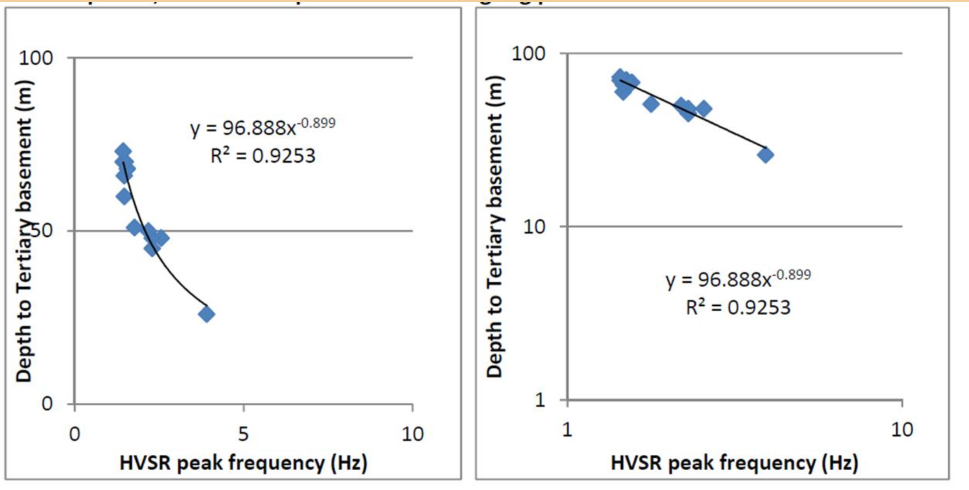




Tromino Zero model – matched drilling!

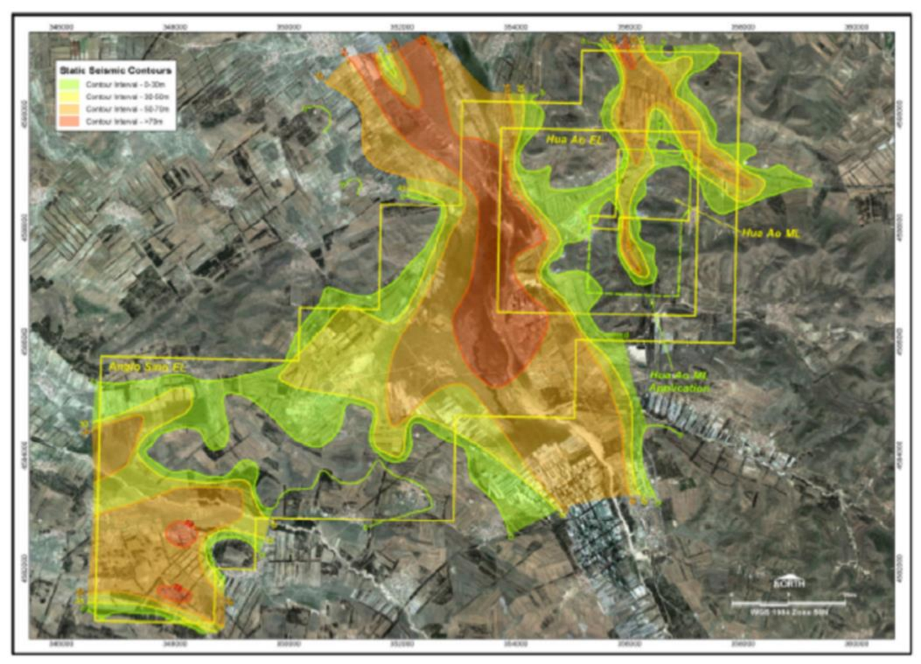
Visually logged bedrock interface depth vs peak frequency





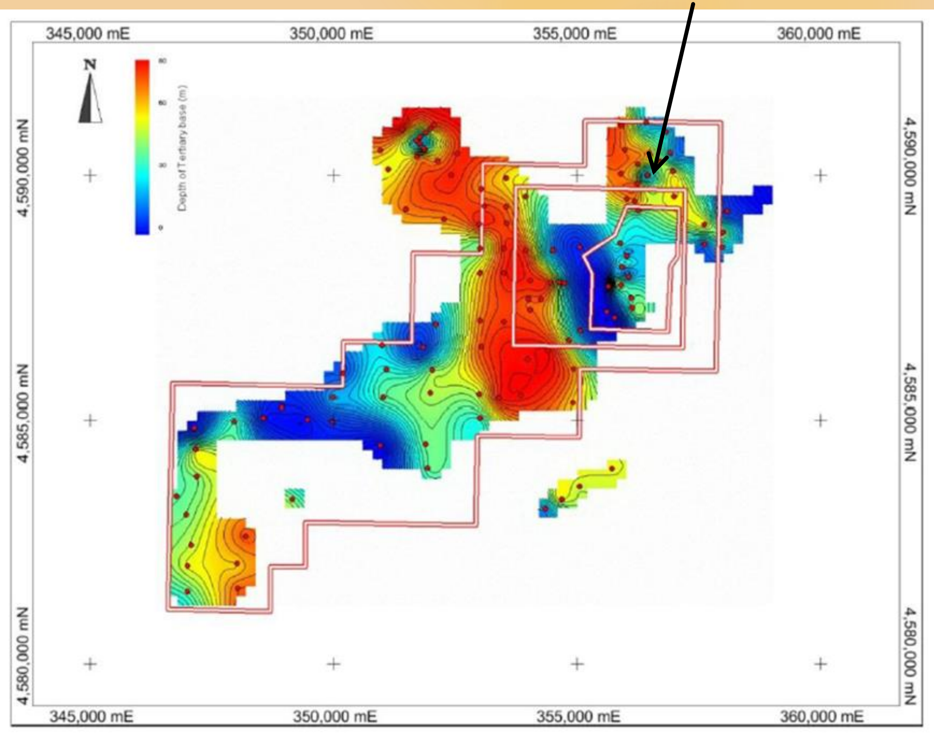
Cover thickness map – wide stations

Hand contour

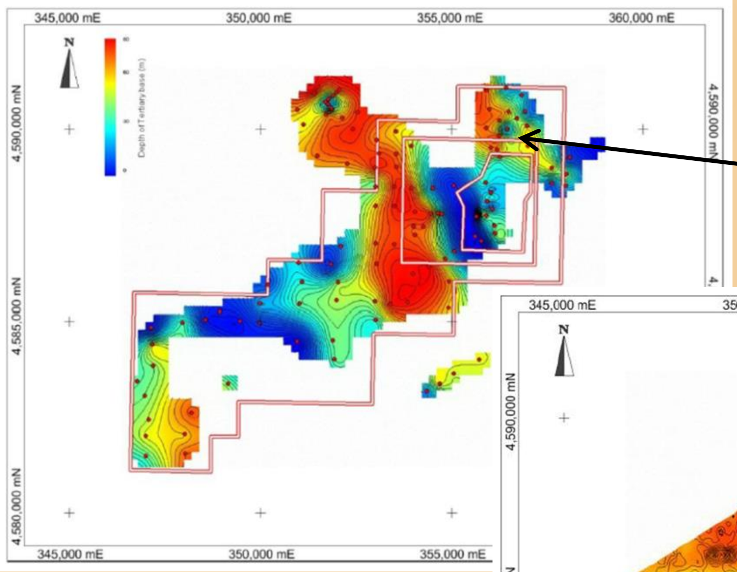


Computer contour

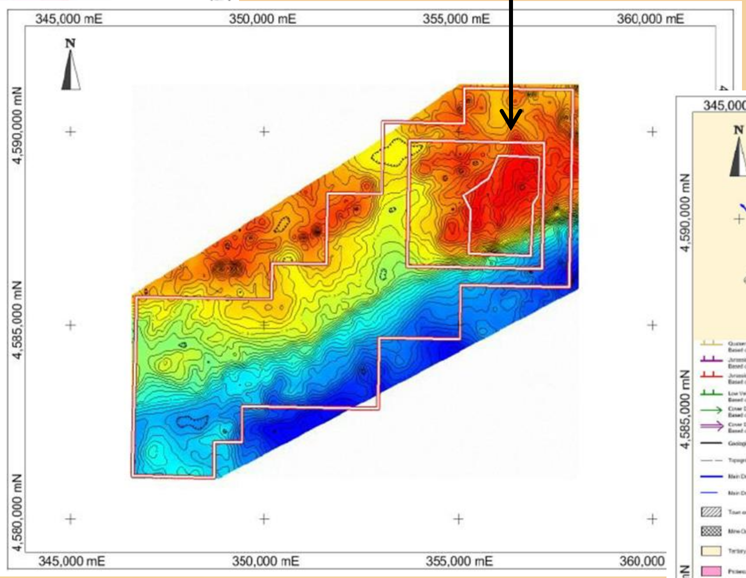
Bad reading?



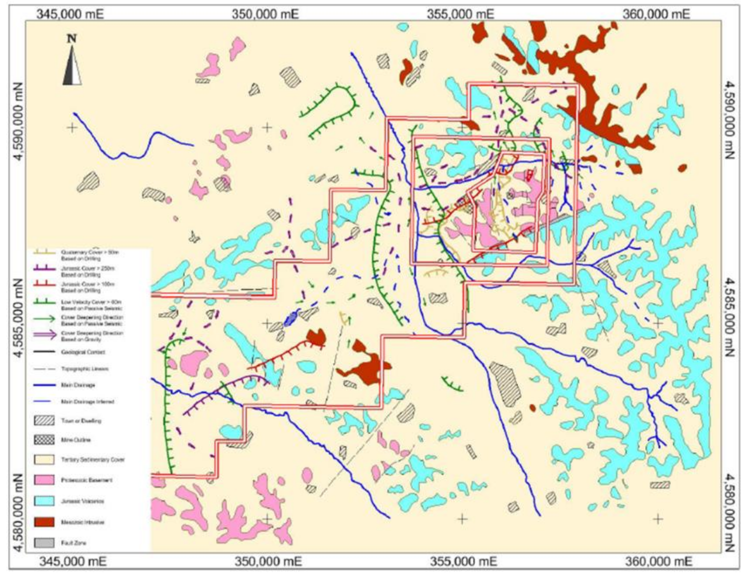
Agrees with outcrop and gravity data



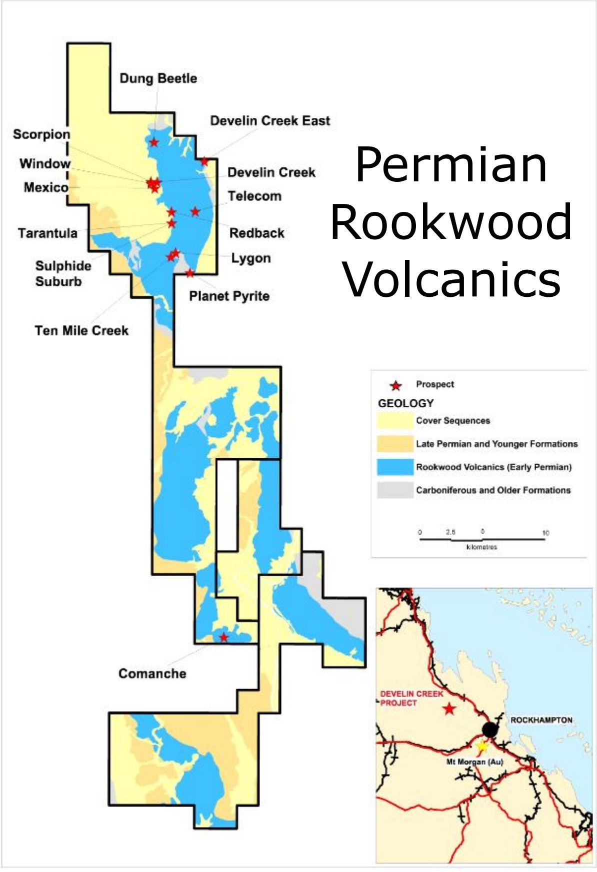
Basement high



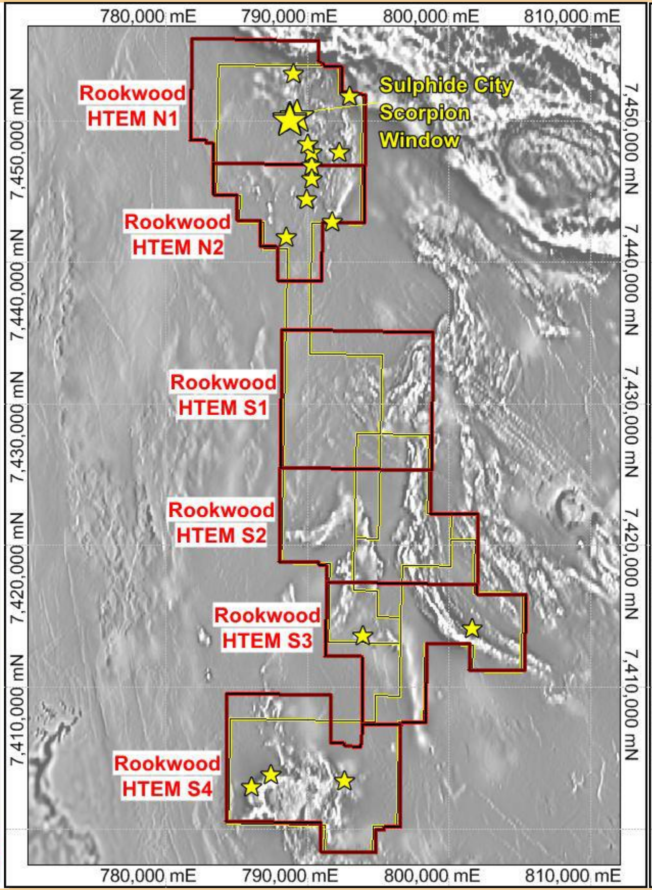
HALLELUIAH, NOW I BELIEVE!



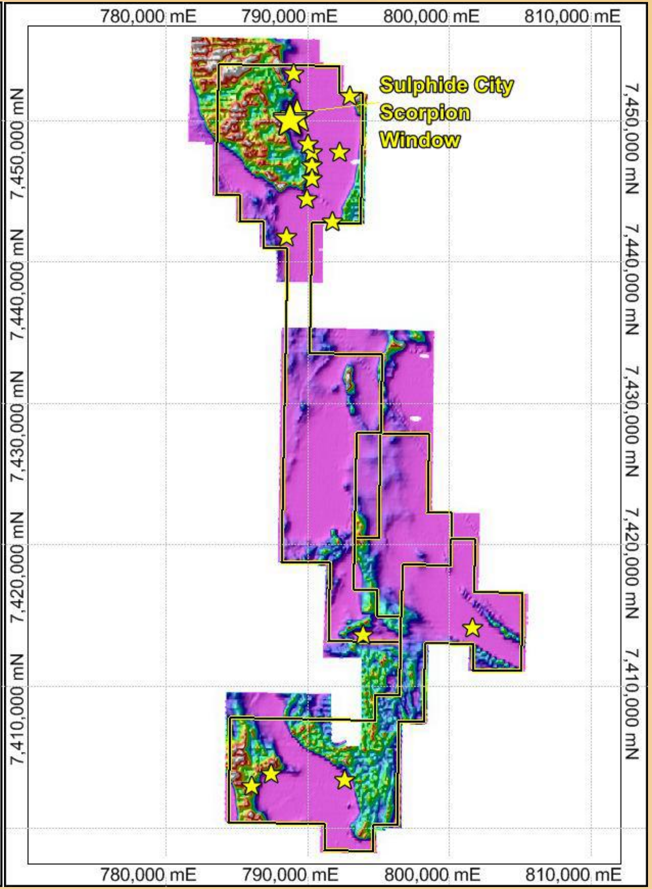
Devlin Creek, QLD: VHMS



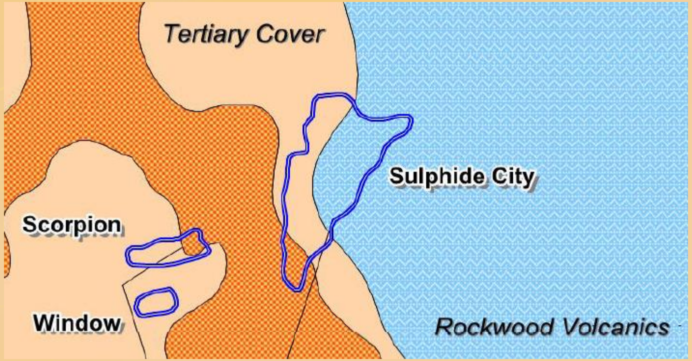
Permian Rookwood Volcanics



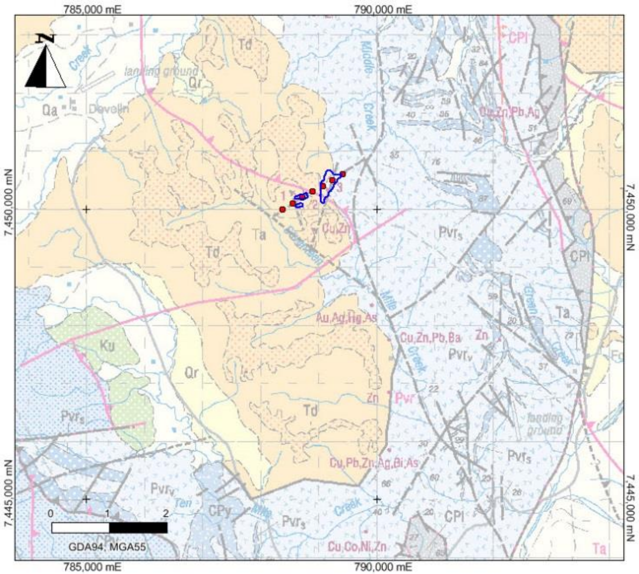
HeliTEM dB/dt Z Ch20

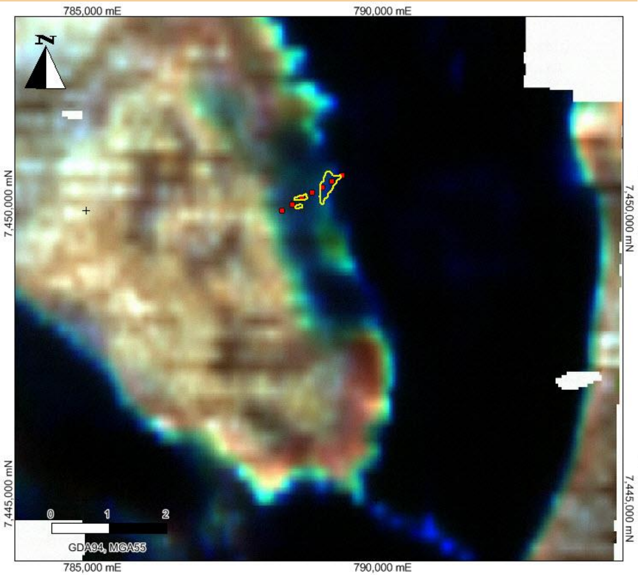


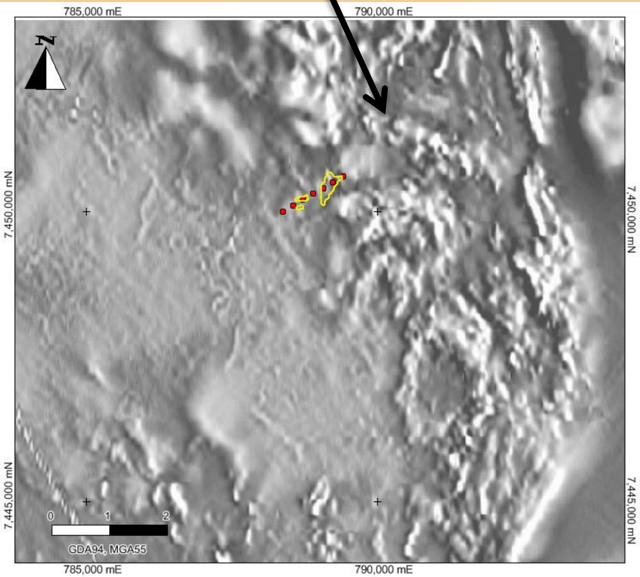
Devlin Creek, QLD: VHMS



Permian Rookwood Volcanics

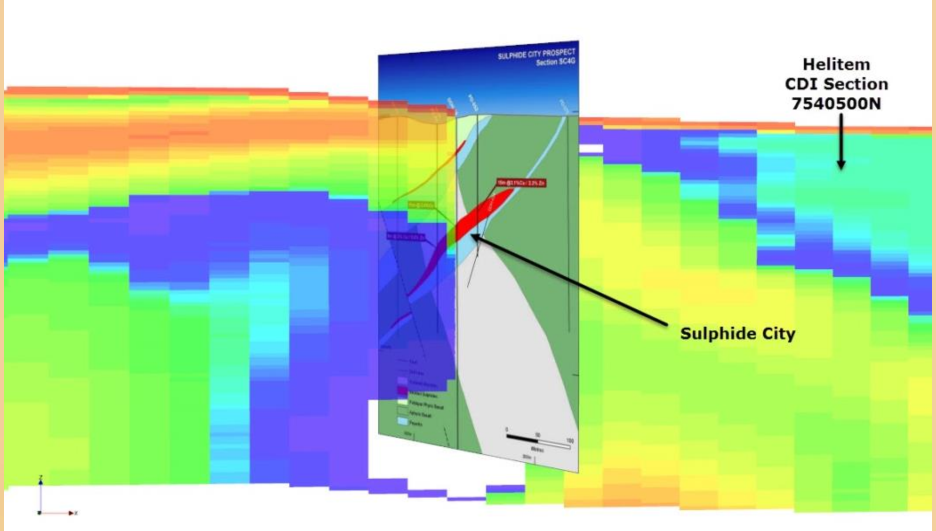


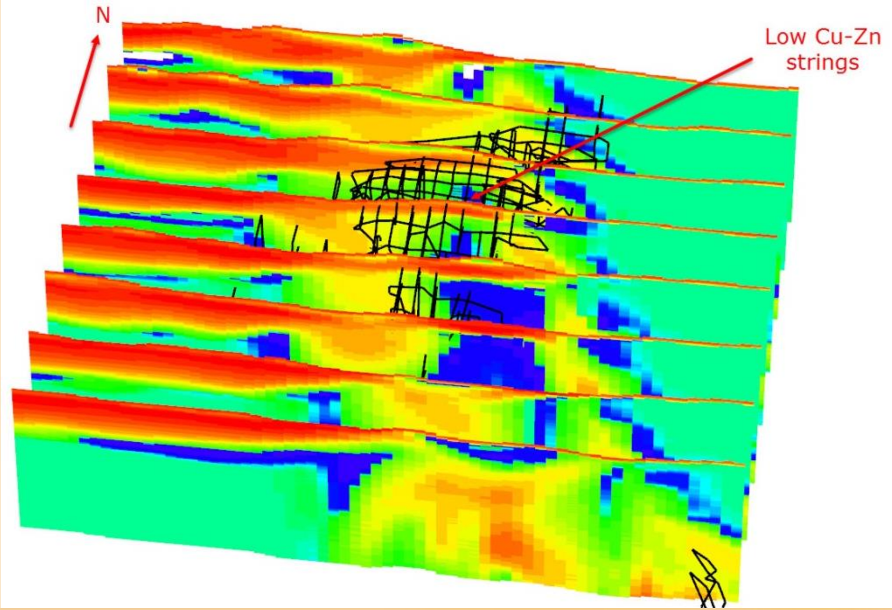




Devlin Creek, QLD: VHMS

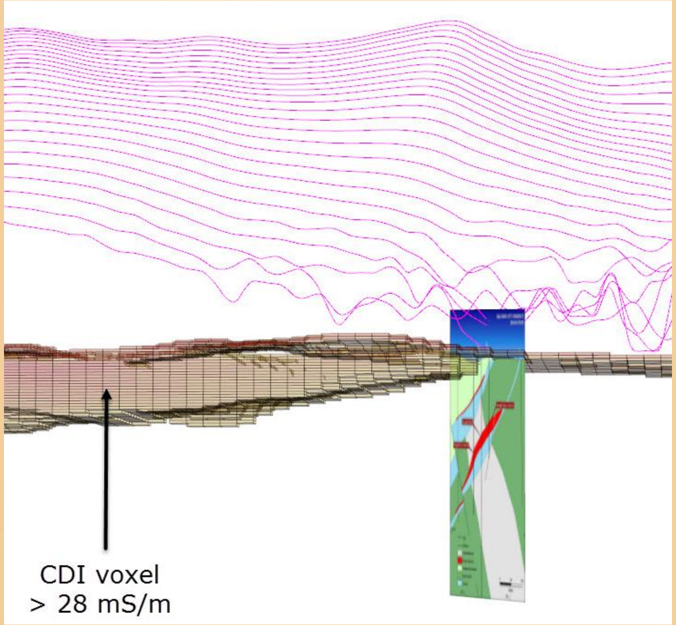
HeliTEM CDI block model

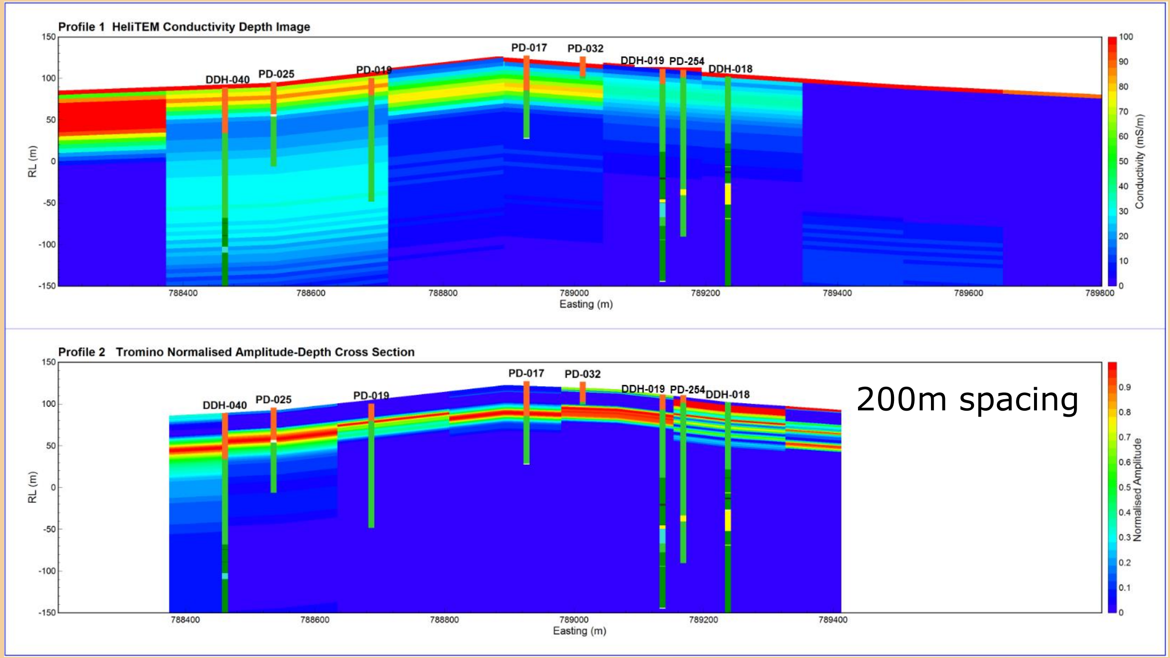




Devlin Creek, QLD: VHMS

Tromino results follow drilling very well, seems to work!





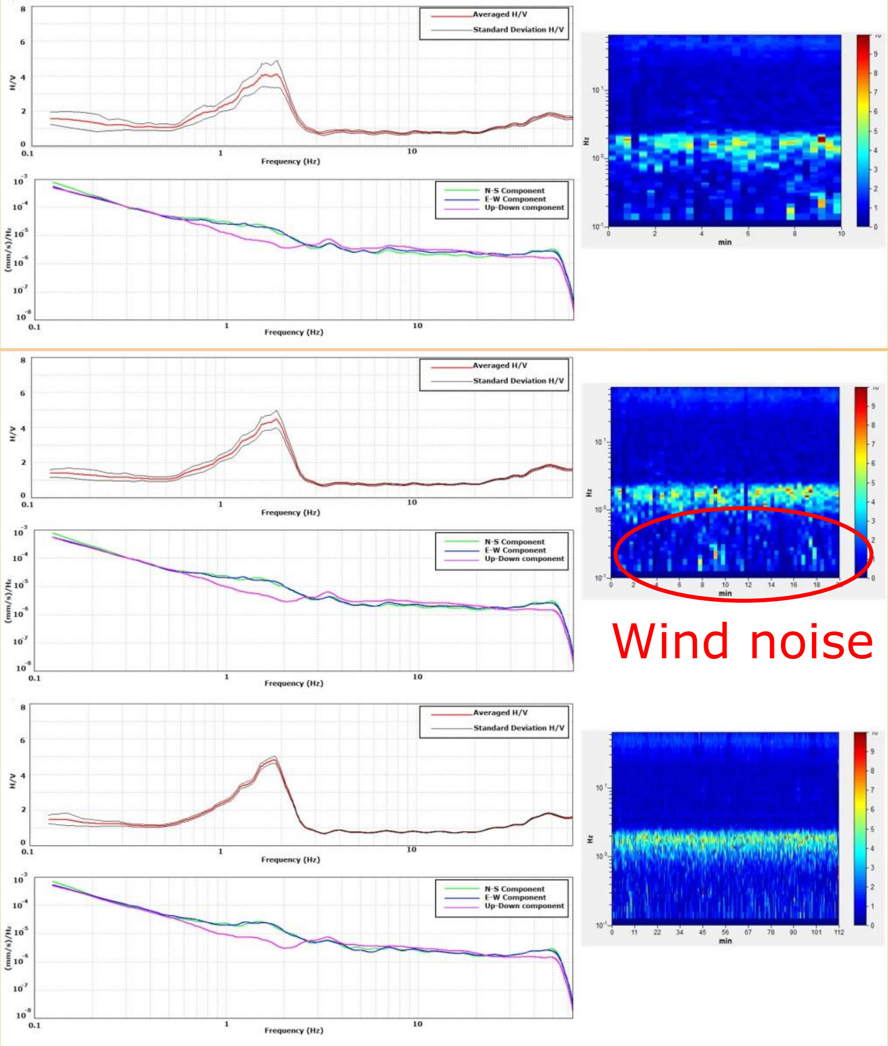
Devlin Creek different recording times

10 min

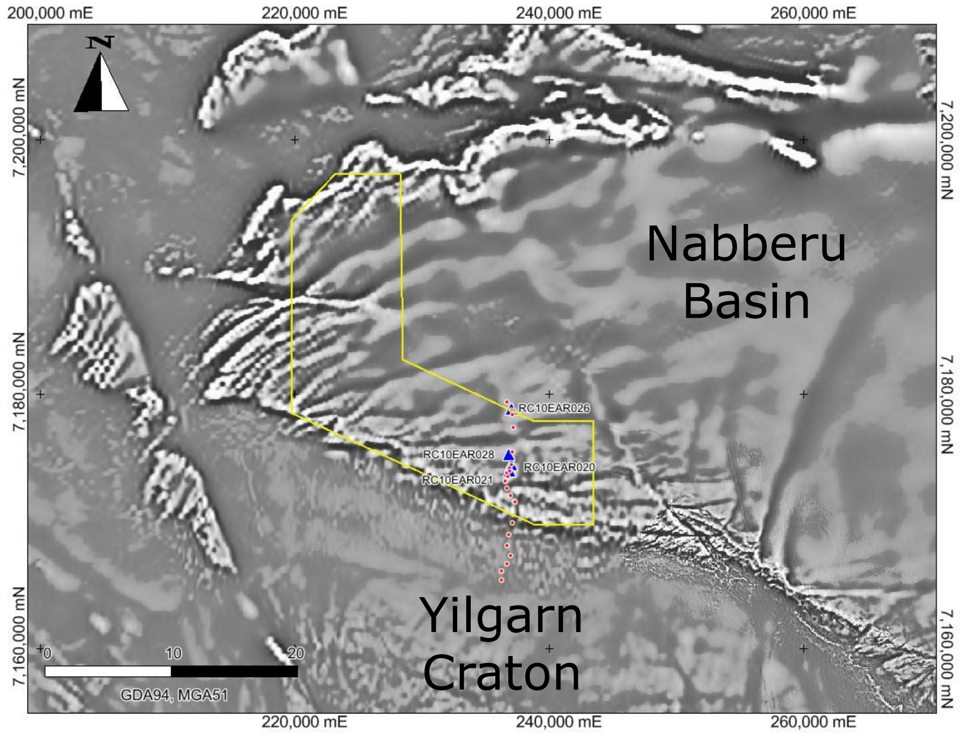
20 min

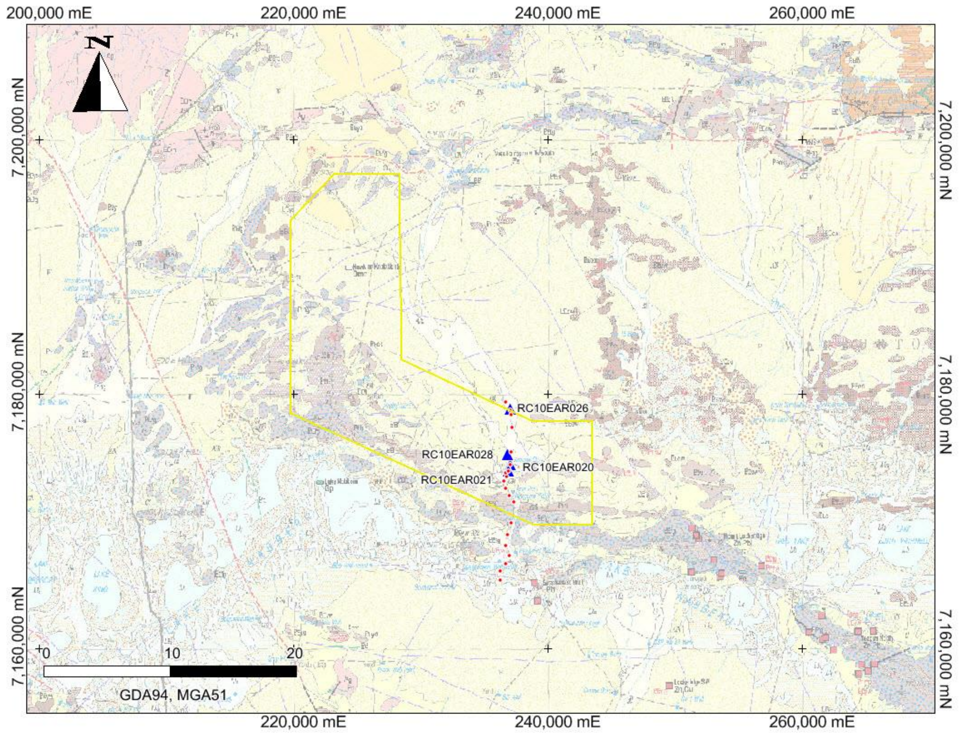
112 min

15 min optimal

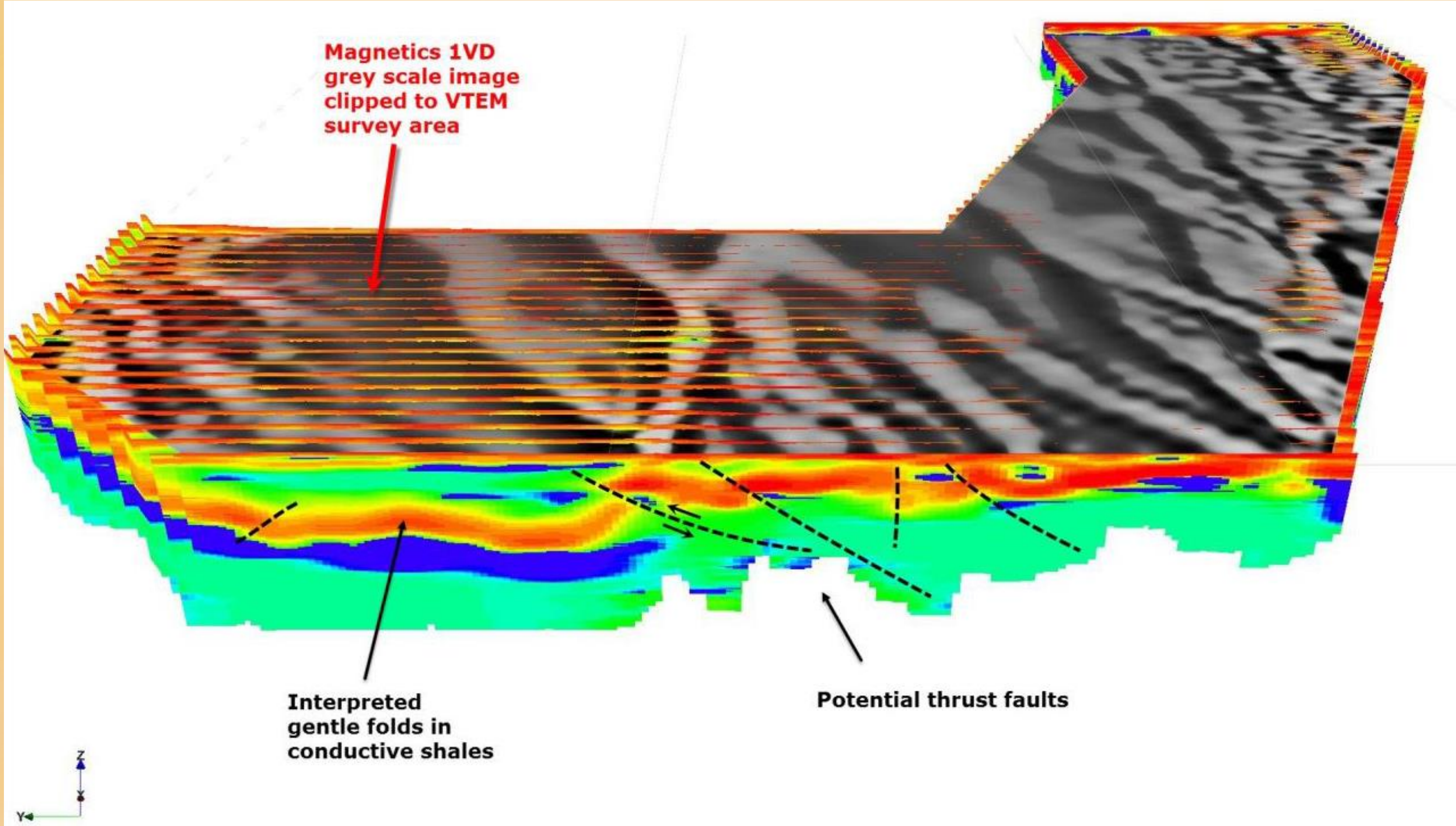


Earaheedy, WA: manganese and jaspelite

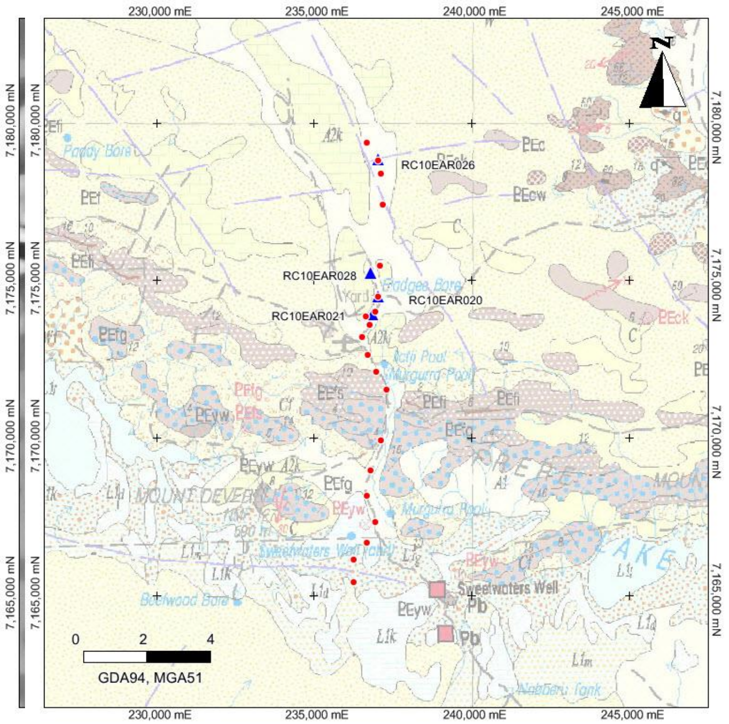


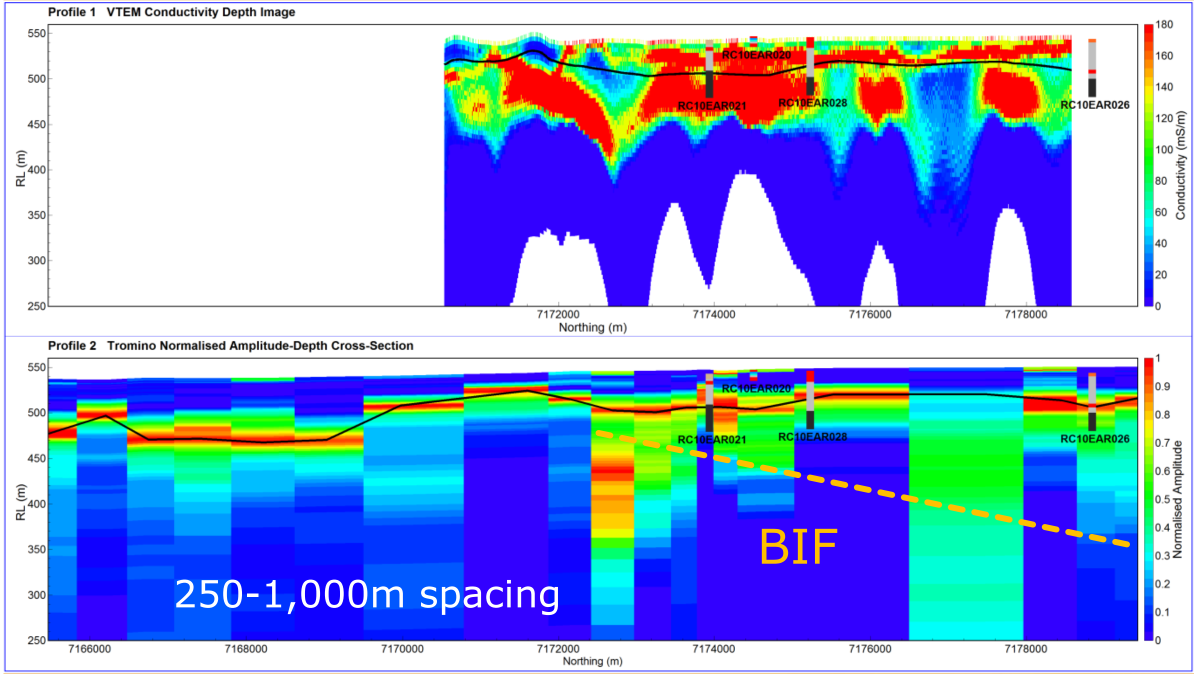


Earaheedy, WA: manganese and jaspelite

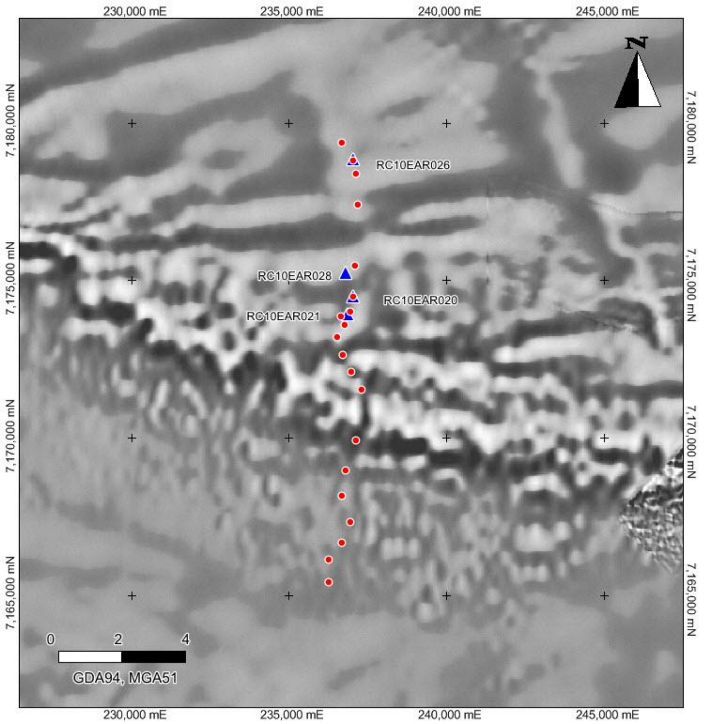


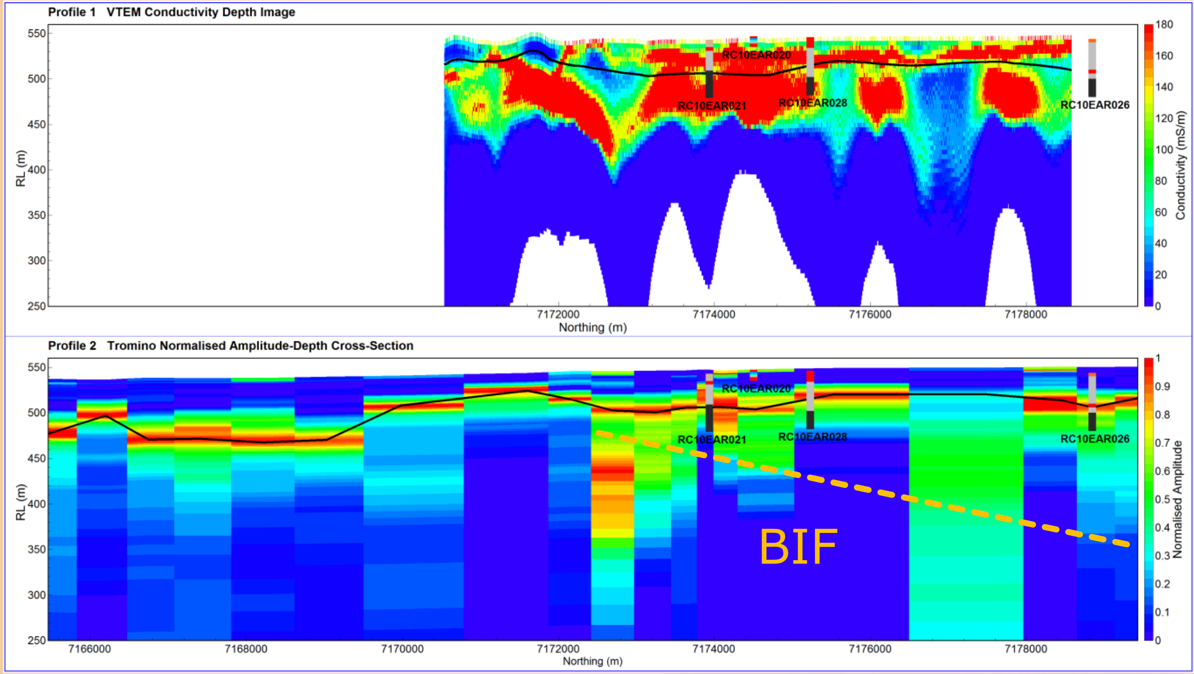
Earaheedy, WA: manganese and jaspelite



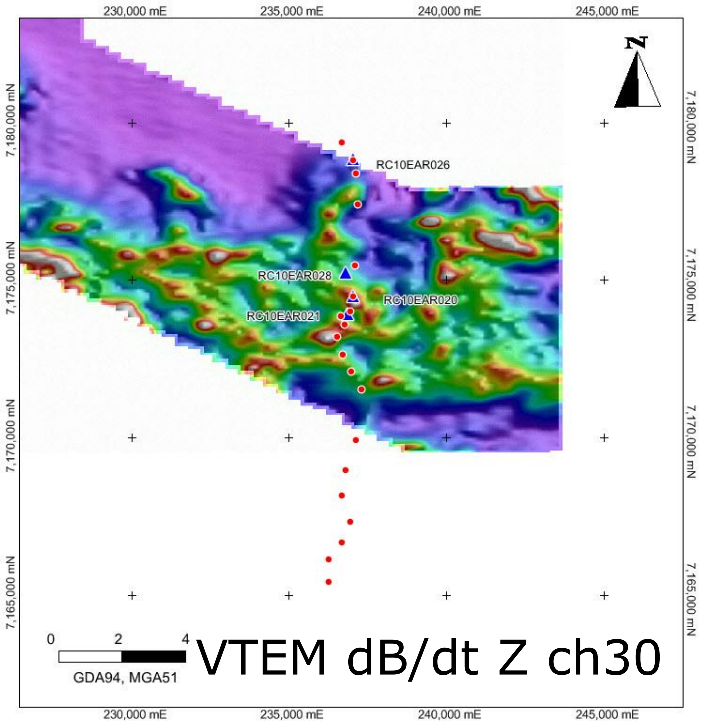


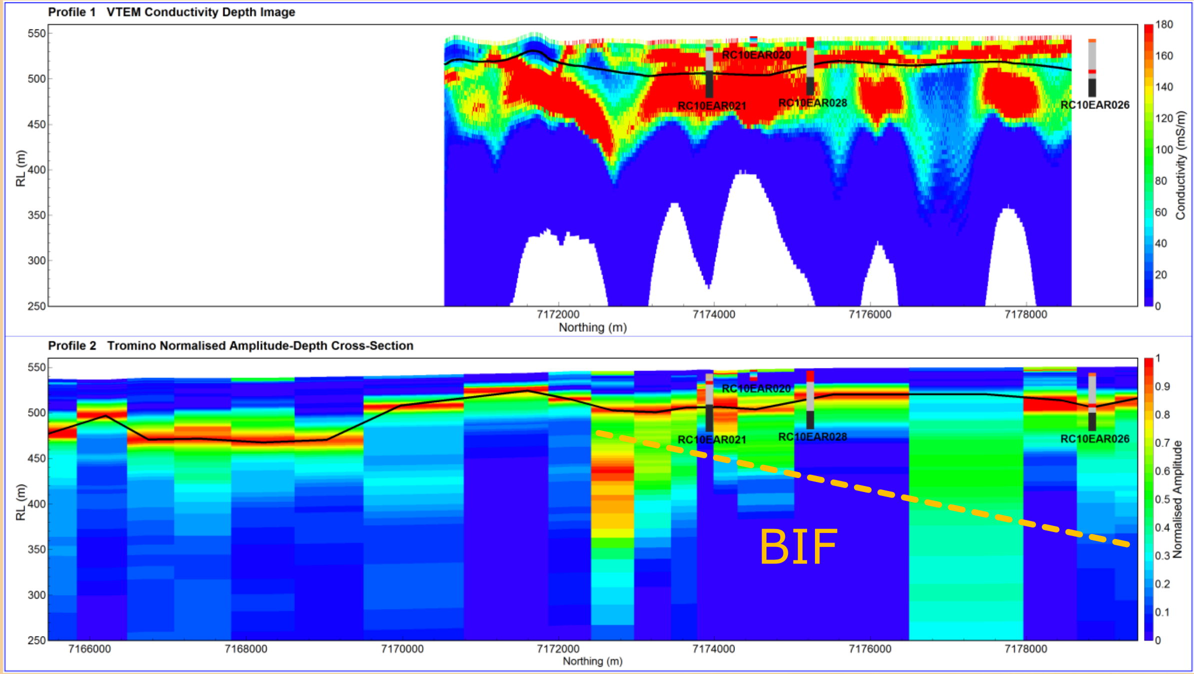
Earaheedy, WA: manganese and jaspelite



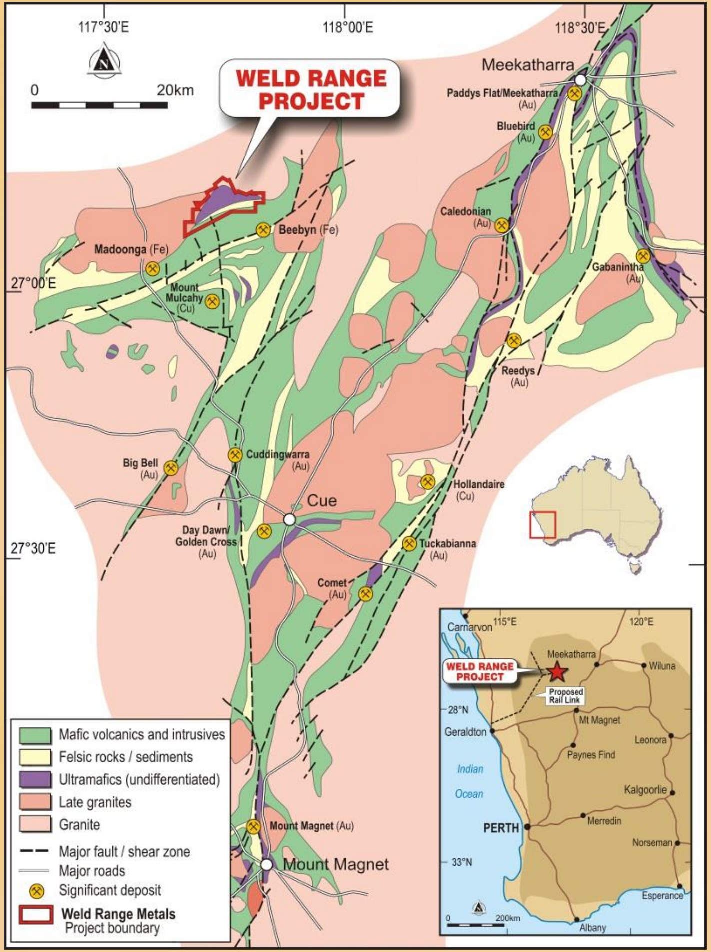


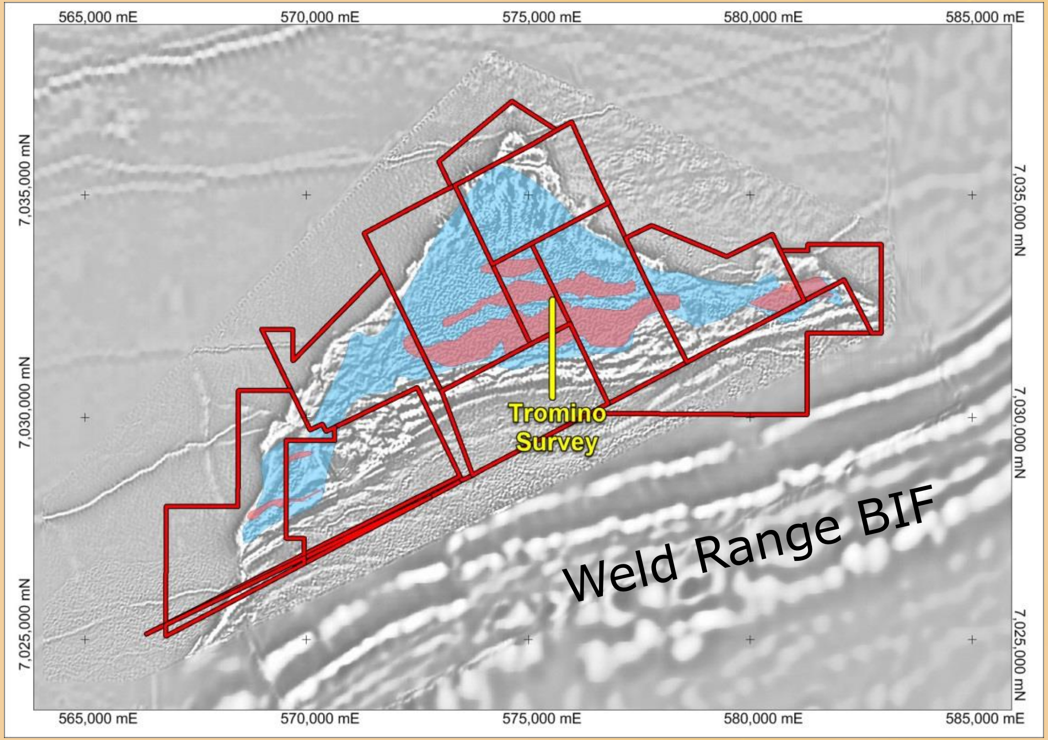
Earaheedy, WA: manganese and jaspelite



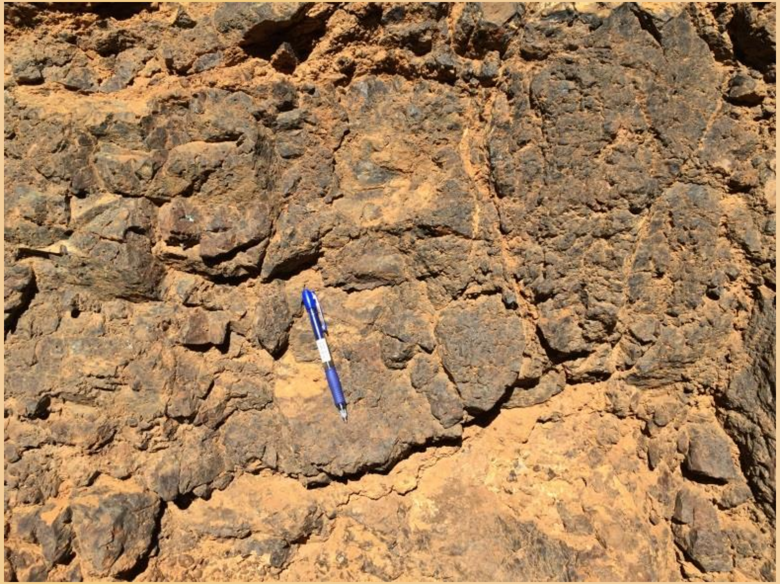


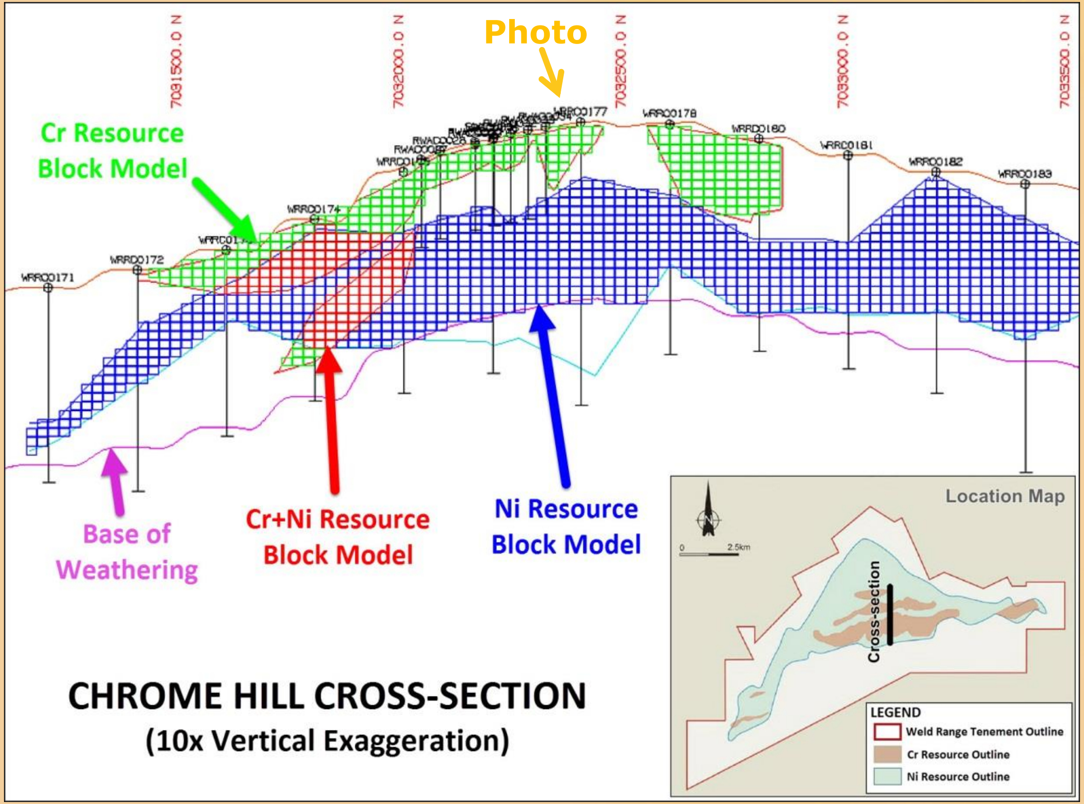
Chrome Hill, WA: Cr and Ni laterite





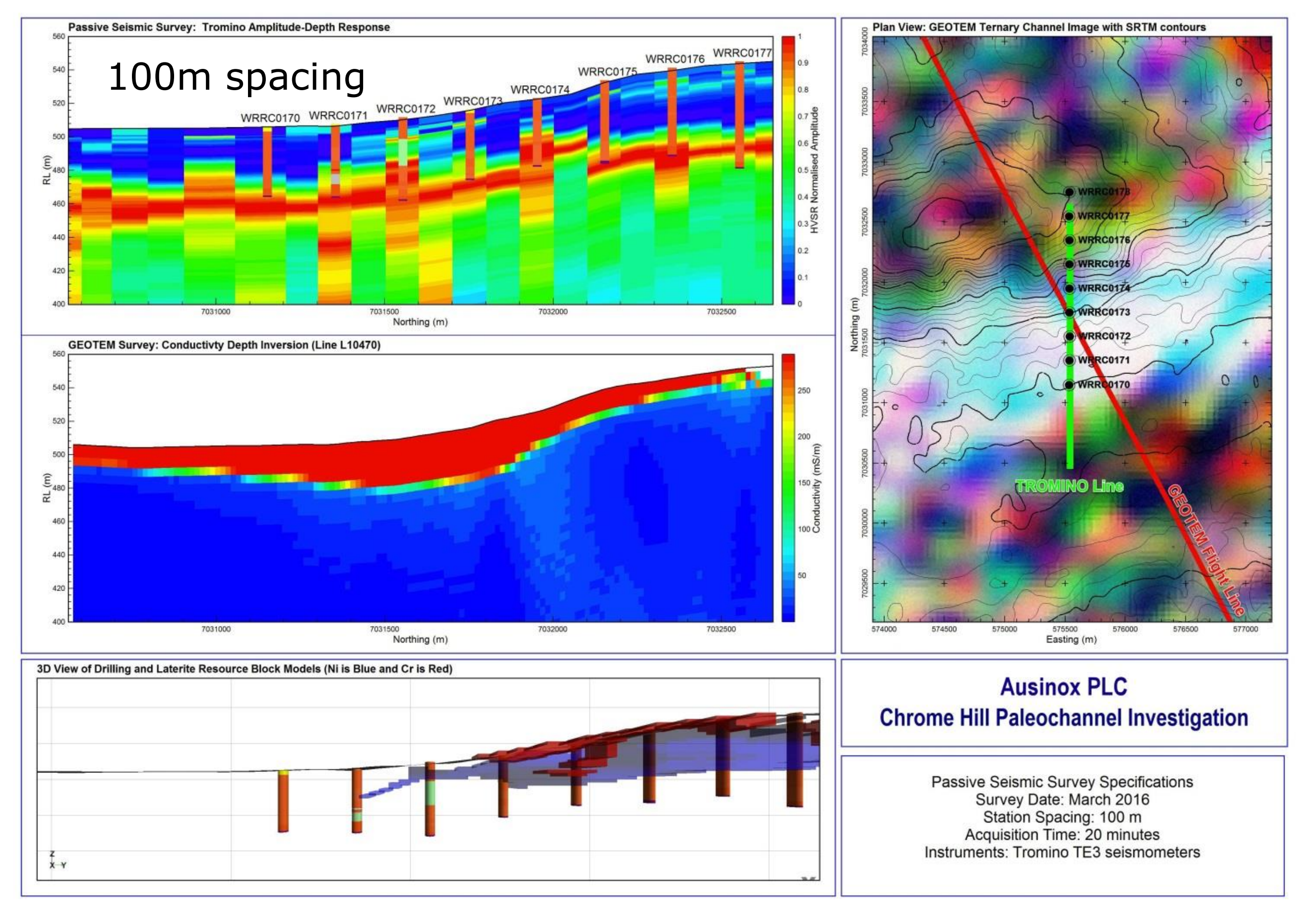
Chrome Hill, WA: Cr and Ni laterite



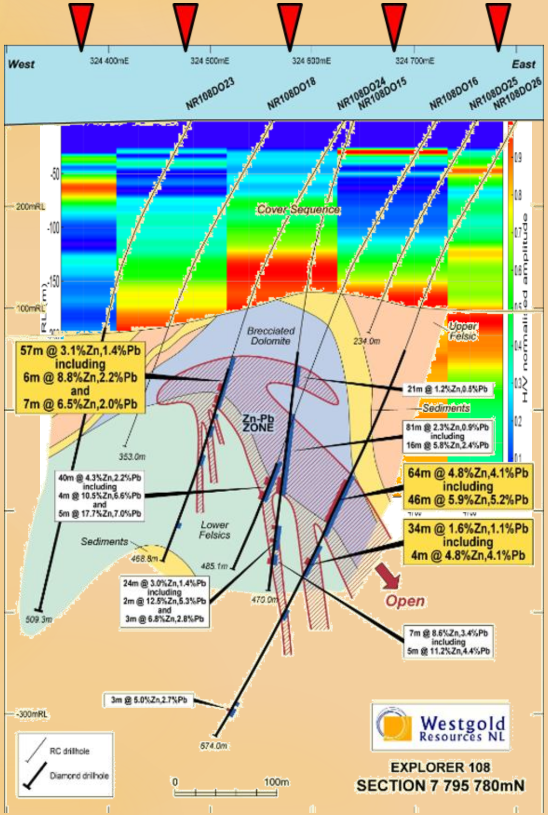


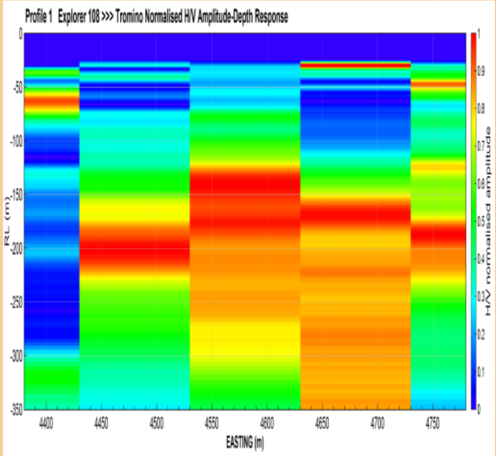
Chrome Hill, WA: Cr and Ni laterite

100m spacing
Under sampled?



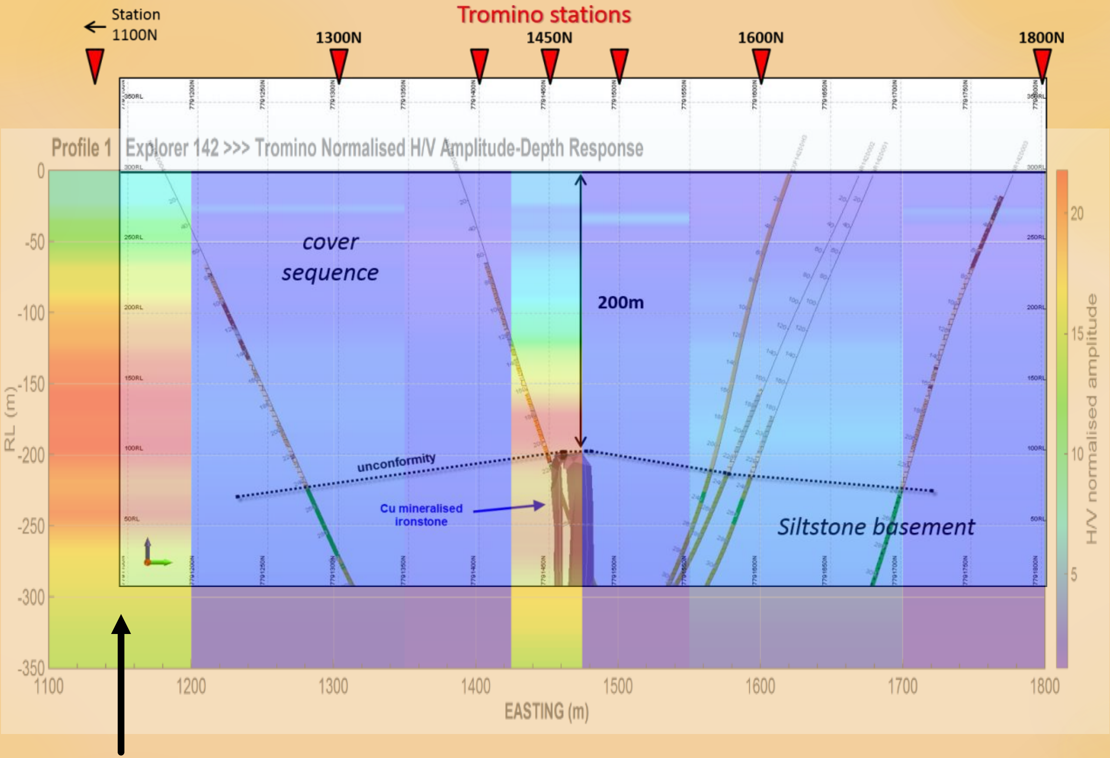
Explorer 108 Modelling Results





The max H/V response can be forced deeper by increasing the cover layer Vs to 3,000 m/s, to provide a nice fit with geology, but the cover layer velocity 3,000 m/s is too high and unrealistic.

Explorer 142 Modelling Results

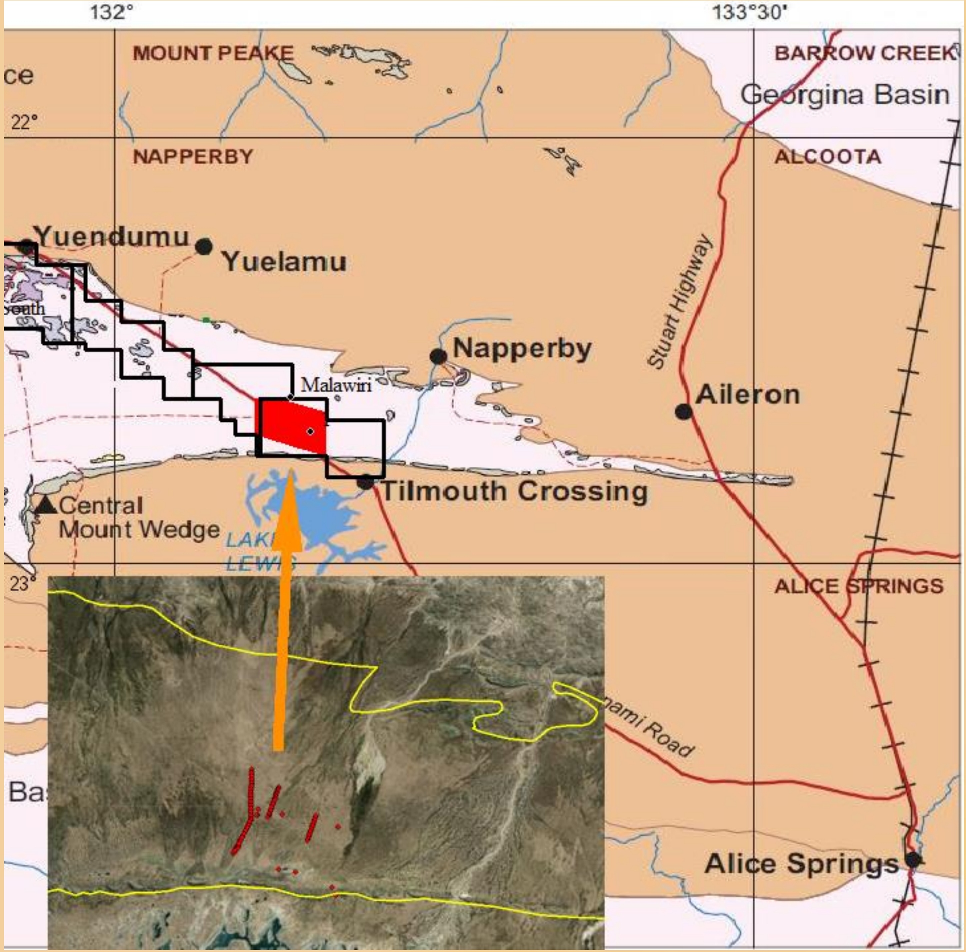


High amplitude response from greater density basement rock? Potential untested target?

Very likely a fantasy, but worth looking into other datasets to check.

Central Australia uranium target

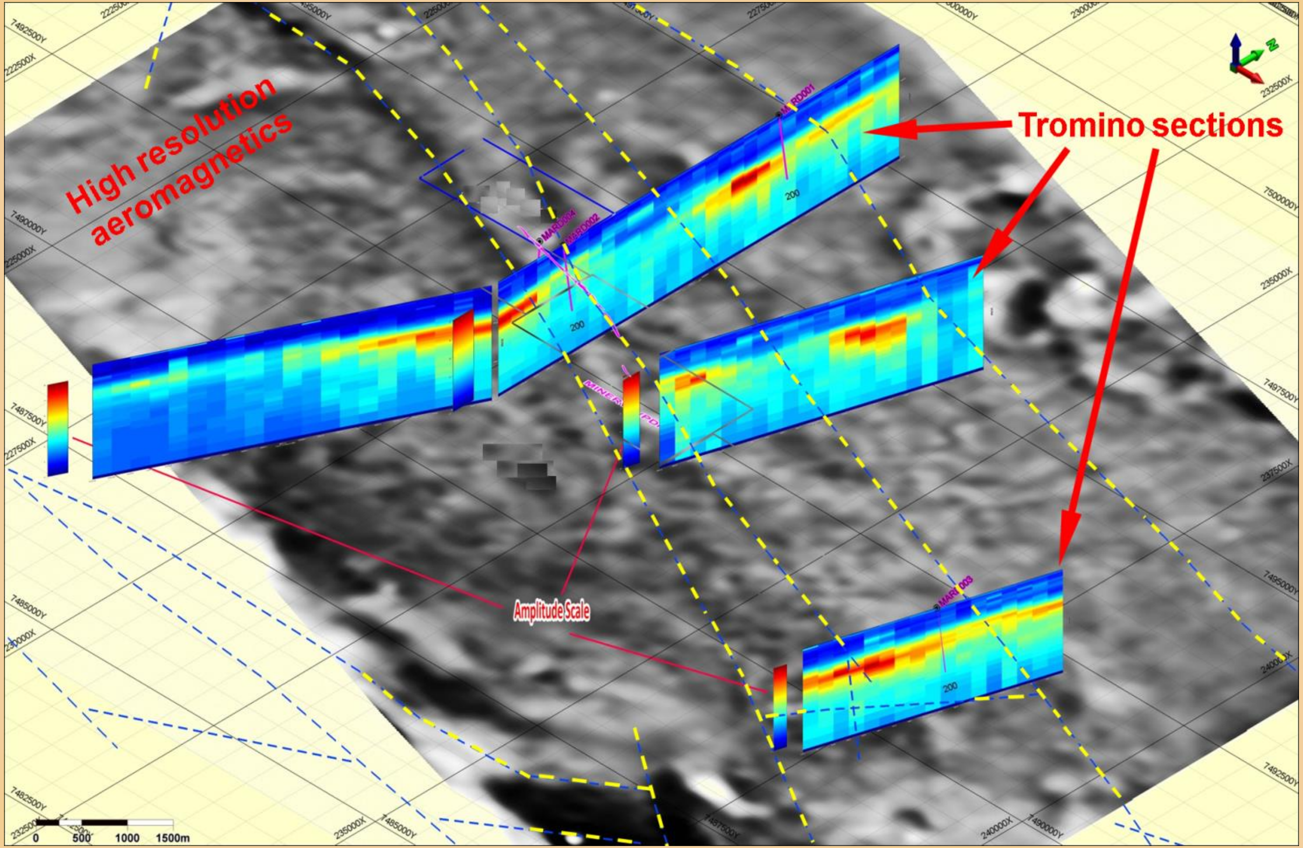
Mesozoic-recent sediments over Neoproterozoic Gnalia Basin sediments for unconformity U deposits



Central Australia uranium target

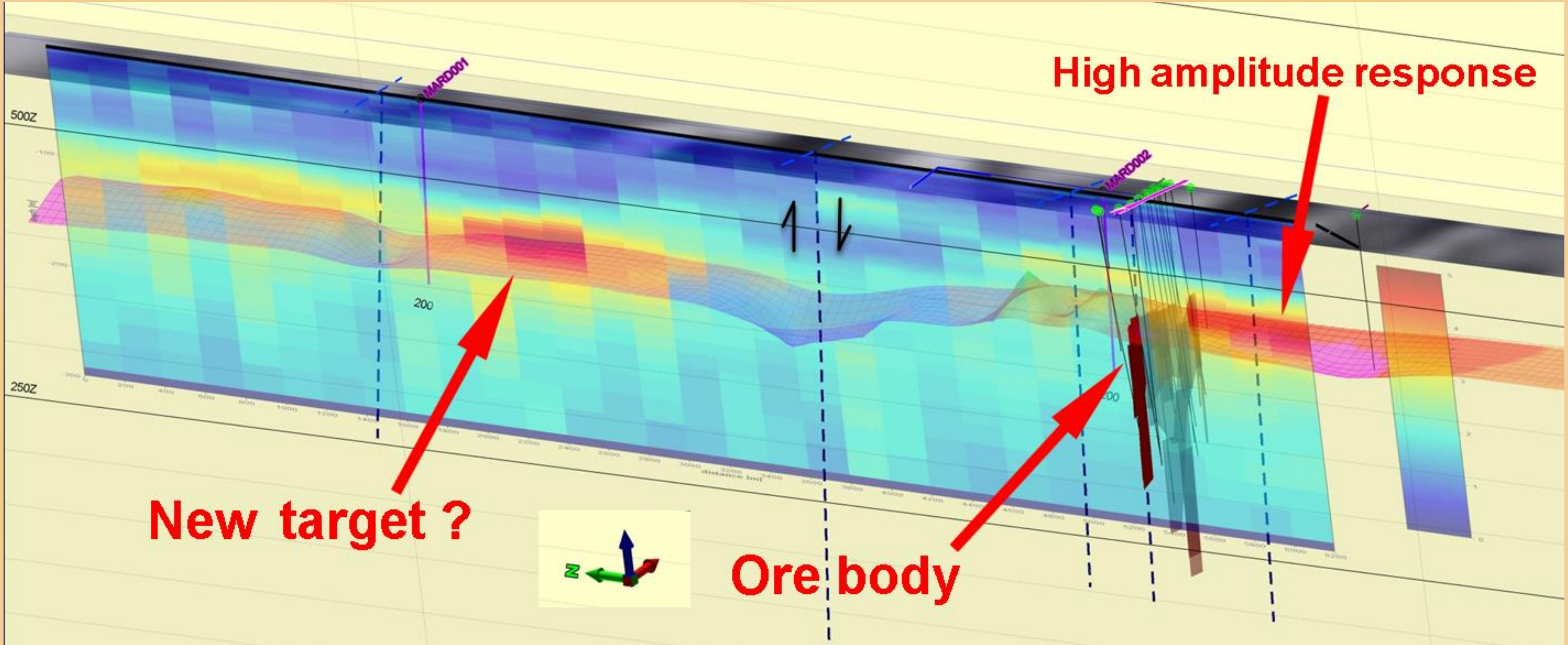
Resource Potentials
Mineral Exploration Technologies

- Tromino survey acquired in July 2016: 3 survey lines oriented N-NNE over known uranium deposit
- U deposit is a vertically-dipping sandstone-hosted stratiform body with some late remobilisation
- Faults interpreted from high resolution aeromagnetic survey (flown late 2014)



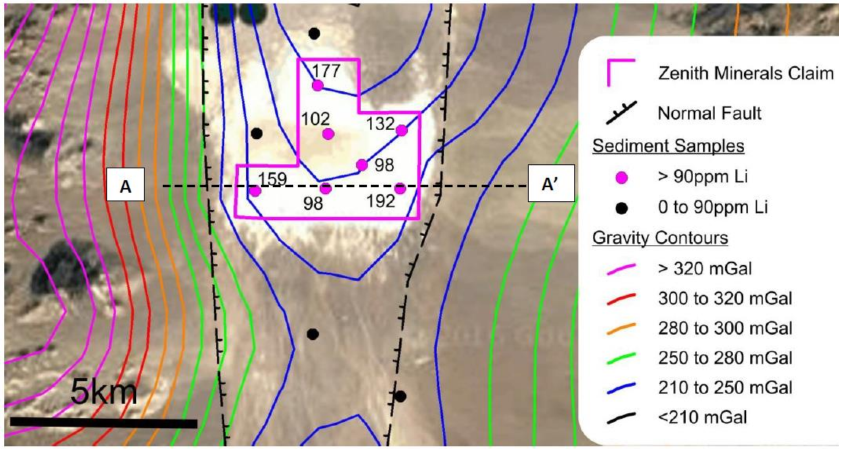
Central Australia uranium target

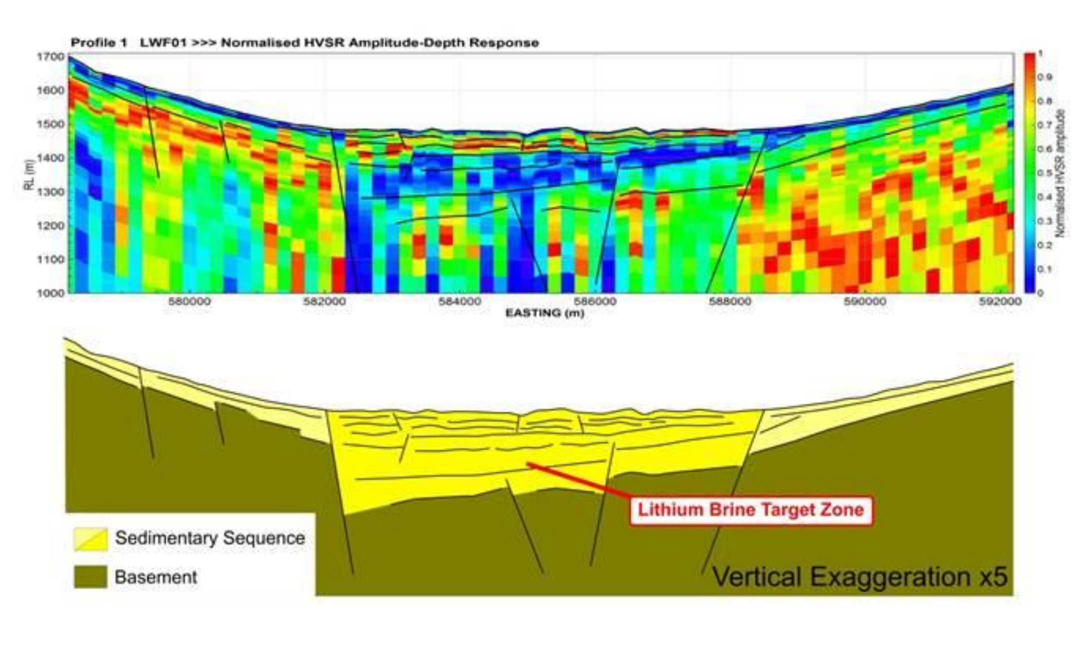
- Passive seismic peak H/V frequency highlighted the depth to fresh bedrock/base of cover, emphasising zones of cementation
- High amplitude response over main U target -> highlighted another potential target



Basin and Range, USA– graben for Li brine

Zenith Metals (ZNC), Wilson Flat Li Project, ASX 2/2/17





The Future

- The HVSR passive seismic method is an innovative use of existing technology that will impact the future of exploration in regolith covered areas, for direct detection of paleochannels, and for other sedimentary related mineral and coal deposits, water supplies, quarry sites, construction site characterisation, etc
- Tromino seismometers are miniaturised into a small box, lightweight, fully self-contained, easy to use, two units can leap-frog during surveying to collect 40 stations per day per field operator, data processing to be carried out by specially trained geoscientists using Grilla software which comes with the Tromino
- The Tromino instrument and software package is the only "industry ready" passive seismic system available
- Inversion techniques, and cooperative inversion with EM and gravity
- Horizontal anisotropy studies over dipping layers and faults

Thank you!

SPECIAL THANKS TO:

- CSA Global
- Zenith Metals
- Westgold
- Energy Metals
- Ausinox
- Brines and Mines