

Summary Report for
PASSIVE SEISMIC PILOT PROJECT

In the area of

NORTHERN TASMANIA

On behalf of

**UNIVERSITY OF TASMANIA /
MINERAL RESOURCES TASMANIA**

Submitted by

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Oct. 22, 2018

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1. EXECUTIVE SUMMARY

Passive seismic data were collected at three locations across northern Tasmania as part of a pilot project to assess the ability of passive seismic methods to map the thickness of high-velocity igneous cover overlying lower velocity sedimentary bedrock.

Forward modelling using generalised physical property models, and cover thickness and lithology information from previous drilling was completed, with results indicating a response due to the cover – bedrock interface, and seismic velocity structure of the cover would be generated.

Observed data were analysed using the HVSR method to estimate ground resonance, and the SPAC and FK methods to estimate the surface phase velocity dispersion. HVSR analysis returned a useful result, broadly consistent with forward modelling. SPAC and FK analyses returned poor results. It is interpreted that diffuse wavefield conditions and/or a lack of microtremor surface wave energy characterises the wavefield at the survey sites.

It is suggested that routine HVSR surveying would be useful for mapping the thickness variation of high-velocity cover in northern Tasmania, where HVSR interpretation and inversion modelling be constrained with cover average velocity information from physical property measurements made on rock samples, or a generalised velocity model for the local survey region constructed using other geophysical methods.

It may be possible to use SPAC and FK methods to construct the local velocity model by deploying more instruments for longer durations, and artificially increasing the surface wave microtremor energy.

2. INTRODUCTION

During January 2018 PassiveX Pty. Ltd. Undertook a collaborative passive seismic pilot project also involving the University of Tasmania (UTAS) and Mineral Resources Tasmania (MRT). The project aim was to assess the suitability of passive seismic methods for mapping depth of high-velocity igneous cover overlying prospective sedimentary and volcanic bedrock in northern Tasmania. Data collection was initially planned for approximately 7 sites in north-western Tasmania to the north and north-east of the Hellyer mine, but due to access difficulties a total of three sites were surveyed with alternate sites near Frankford and Fingal chosen with input from MRT. Data were collected using arrays of Guralp portable broadband seismometers at three locations across northern Tasmania (Figure 1) and data analysis were made using the Horizontal to Vertical Spectral Ratio (HVSr), Spatially Averaged coherency (SPAC) and beamforming (FK) methods.

This report provides a summary of data collection, forward modelling of waveforms for representative geological properties and summary of observed data analyses, along with recommendations for further work.

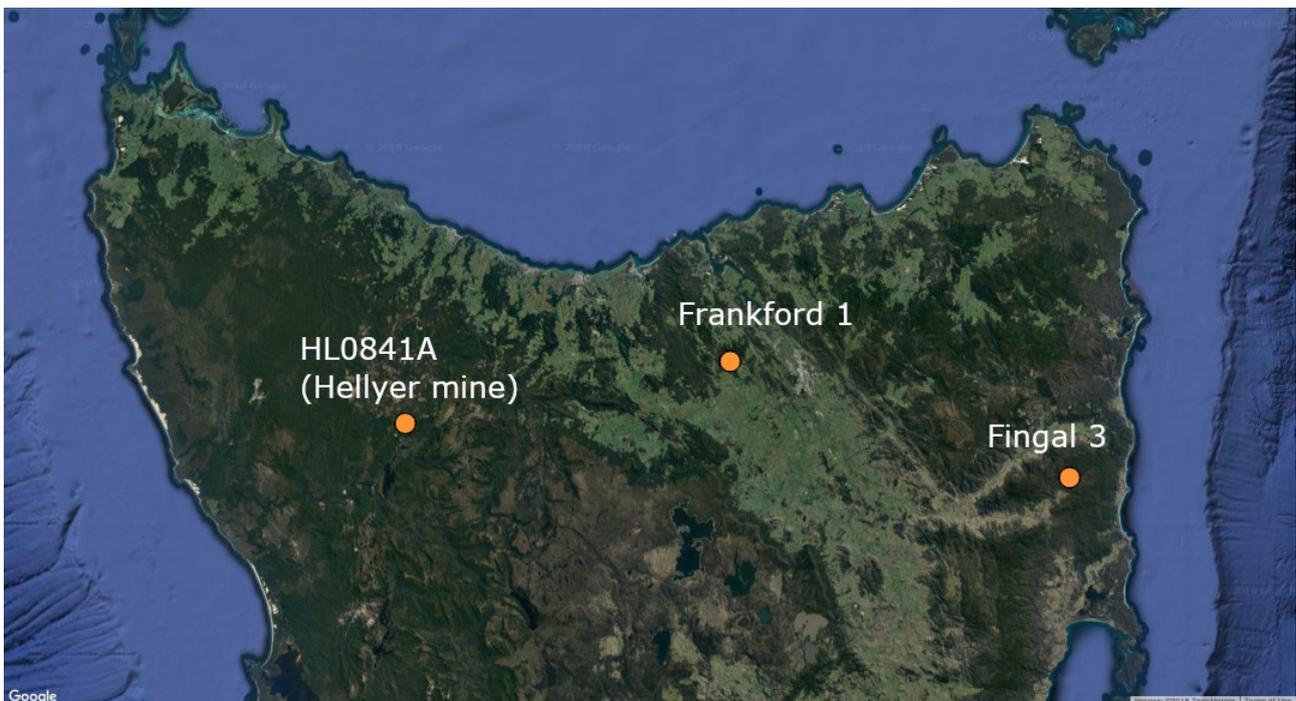


Figure 1: Map of northern Tasmania showing survey locations.

3. SUMMARY OF DATA COLLECTION

Data collection was carried out by a two person team comprising Nick Smith (PassiveX, field lead) and Martin Gal (UTAS). Passive seismic data were collected using an array of 10x Guralp CMG-6TD digital force-feedback broadband seismometers. The instruments were deployed following guidelines from Smith *et.al.*, (2013) in a three-arm expanding spiral configuration (Figures 2 – 4), with array aperture selected based off the expected cover thickness for each site. For a limited number of instruments, a three-arm spiral array configuration gives an optimal trade-off in terms of the range of inter-station distances and orientations and also gives an array response function with minimised side-lobe energy (e.g. Kennett, *et. al.*, 2015), which are important considerations for array analysis.

For each site instruments were deployed for ~20hrs, with deployment and uplift completed by around 12:00pm local time on consecutive days (Table 1).

Table 1: Summary of deployments.

Site	Start (GMT)	Stop (GMT)	Easting (MGA z55)	Northing (MGA z55)	Nominal Array Aperture
HL0841A	8/1/18, 01:00	9/1/18, 07:00	394183	5397419	100m
FRANKFORD_1	11/1/18, 00:00	11/1/18, 22:00	490170	5416601	320m
FINGAL_3	12/1/18, 06:00	13/1/18, 01:00	590519	5381579	145m

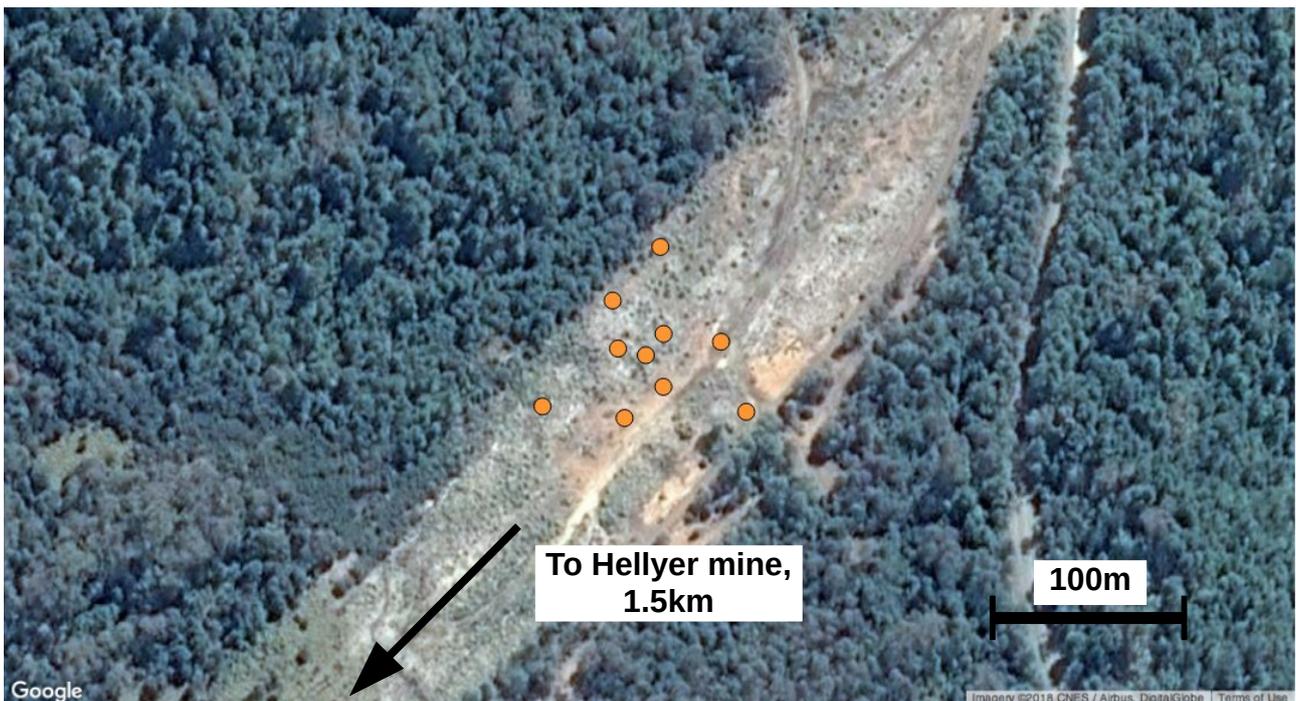


Figure 2: Overview of site HL0841A.

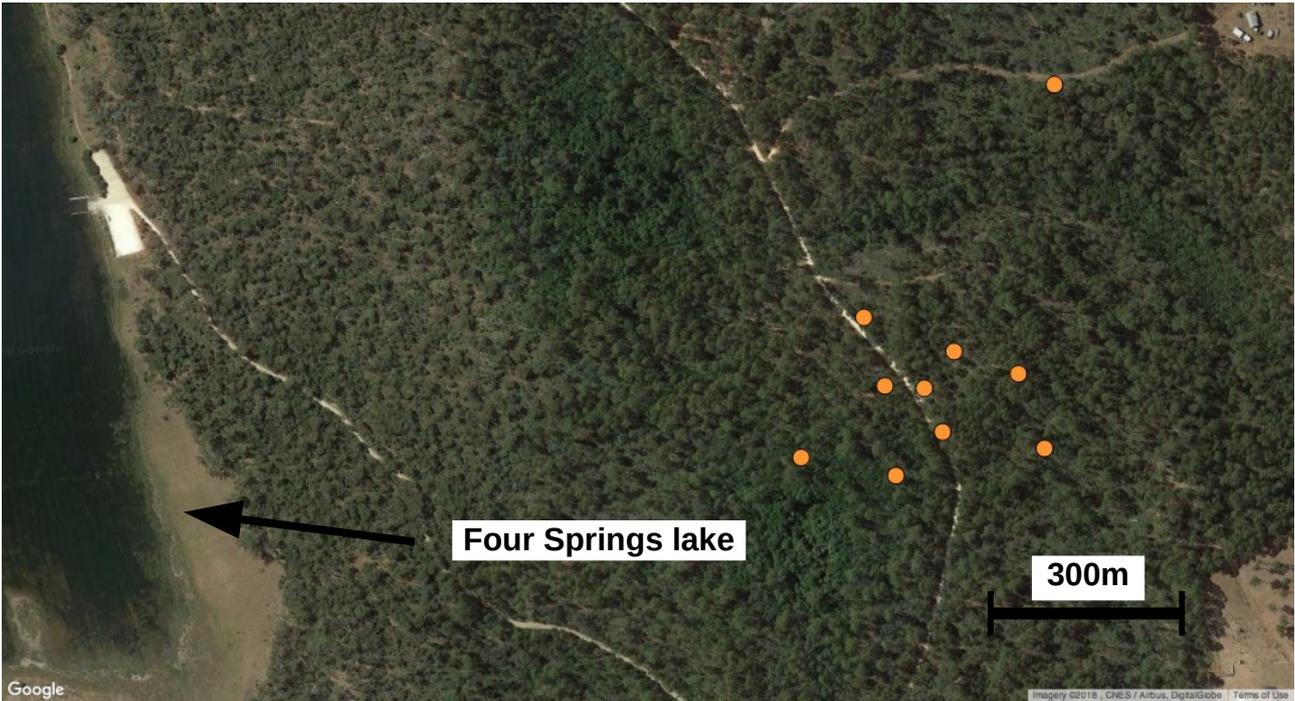


Figure 3: Overview of site Frankford 1



Figure 4: Overview of site Fingal 3.

4. FORWARD MODELLING

The geological conditions at the sites surveyed in this project present a challenge for passive seismic methods. Traditionally, passive seismic methods are used for near-surface surveying where unconsolidated and/or consolidated sediments overly a crystalline bedrock, and where the sedimentary sequence presents as flat lying, of relatively low seismic velocity and with a large contrast in acoustic impedance compared to the bedrock. Such geological conditions are well suited to passive seismic studies using relatively small-aperture arrays, to determine the depth to the cover-bedrock interface and the cover seismic velocity structure, estimated through the analysis of ground resonance and surface wave dispersion.

Table 2: Summary of known geology, and estimated physical properties used for forward modelling.

Site	Cover Lithology	Cover Velocity (S-wave, m/s)	Cover thickness (m)	Bedrock Group	Bedrock Velocity
HL0841A	Basalt, Sediments	~3000, ~2500	59	Mt. Read Volcanics	~4000
FRANKFORD_1	Dolerite	~3000	194	Up. Parmeener Sediments	~2500
FINGAL_3	Dolerite	~3000	81.5	Up. Parmeener Sediments	~2500

When three-component instruments are used for passive seismic surveying, the Horizontal to Vertical Spectral Ratio (HVSr) of the observed data commonly shows a resonance on the horizontal components and corresponding peak in the HVSr which is indicative of the thickness and average seismic velocity of cover material overlying bedrock. This resonance begins to occur when the acoustic impedance contrast between cover and bedrock is a factor of >1.5 and is amplified as the contrast increases.

The ground resonance frequency (f_0) and its relationship with cover thickness (h) can be modelled using a power law function and an assumed average shear-wave velocity (V_s) for the cover. In its simplest form, this power law takes the form:

$$f_0 = V_s/4h$$

The HVSr waveform can be modelled for a given 1D profile of seismic velocity structure using a diffuse wavefield approach (e.g. García-Jerez, *et. al.*, 2016).

Forward modelling for ground resonance frequency using constant velocity and HVSR curves for representative geological models was carried out to assess the likely HVSR response and assist with interpretation of observed data. The physical properties used to construct the geological models are summarised in Table 2. Resonance frequency modelling (Figure 5) was carried out for constant velocities of 2000 m/s and 3500 m/s which are values chosen to represent the likely lower and upper bounds of the cover average shear-wave velocity. Forward modelling of HVSR curves and phase velocity dispersion (Figures 6 – 8) was carried out using the HV-Inv software utilising the diffuse wavefield approach.

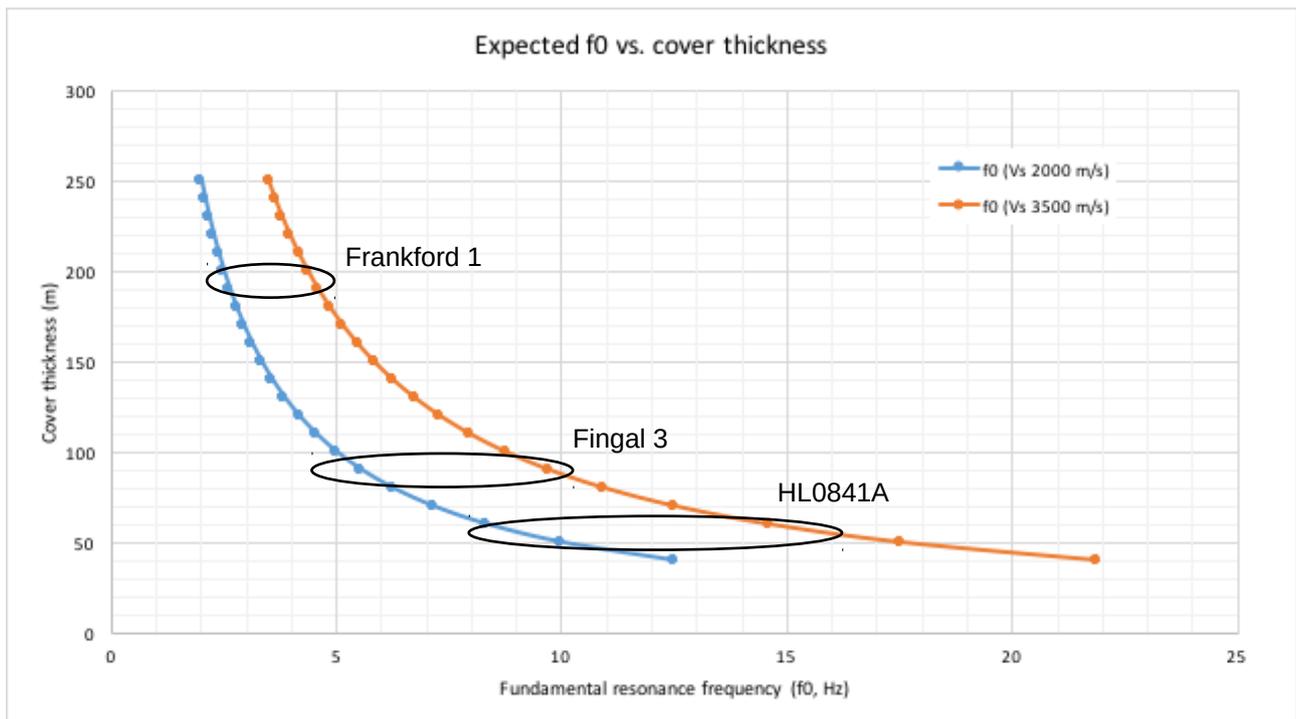


Figure 5: Power law curves relating resonance frequency to cover thickness, assuming constant cover shear-wave velocity. Ellipses indicate the estimated frequency range for ground resonance at the survey sites.

4.3 Forward modelling results

4.3.1 HL0841A

Drill hole information from site HL0841A shows a thin basalt layer overlying compacted sediments – together forming the ‘cover’ – overlying a volcanic basement. Forward modelling of physical properties representative of these lithologies indicates a relatively low-amplitude ground resonance but with well-defined HVSR curve shape, associated with the interface between cover sediments and the underlying volcanic bedrock. Deep and shallow bedrock models were generated by increasing and decreasing the thickness of the sediment cover layer by 20m. Thick and thin basalt models were generated by halving and doubling the thickness of the basalt layer. An increase in the resonance frequency for both the ‘shallow bedrock’ and ‘thick basalt’ models is mainly due to an increase in the overall thickness of the cover for the first case, and an increase in the average velocity of the cover for the second case. These characteristics are illustrative of the trade-off between cover average velocity and thickness which presents a challenge to interpretation of observed data.

Forward modelling of phase velocity dispersion shows negligible ‘reverse dispersion’ below 50Hz due to the high velocity basalt layer for the ground truth model, and a general increase towards the phase velocity of the half-space between 10 – 30Hz. A shift towards higher velocities at high frequencies is observed for the ‘shallow bedrock’ and ‘thin basalt’ models, and reverse dispersion is observed for the ‘thick basalt’ model between 30 – 50Hz.

Forward modelling results for site HL0841A suggest that:

- HVSR methods may be able to detect a weak response from the interface between cover and bedrock, but no response from high-velocity basalt overlying sediments;
- dispersion methods would be detect the increase in phase velocity with decreasing frequency due to the general cover-basement velocity structure, but would struggle to detect the reverse dispersion associated with the thin near-surface basalt layer below 50Hz.

Table 3: Physical properties for ‘ground truth’ model for site HL0841A. Layer 1 represents basalt, layer 2 represents compacted sediments and layer 3 represents a volcanic bedrock

Layer thickness (m)	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m ³)
10	5000	3000	2500
50	4000	2500	2300
half-space	6000	4000	2670

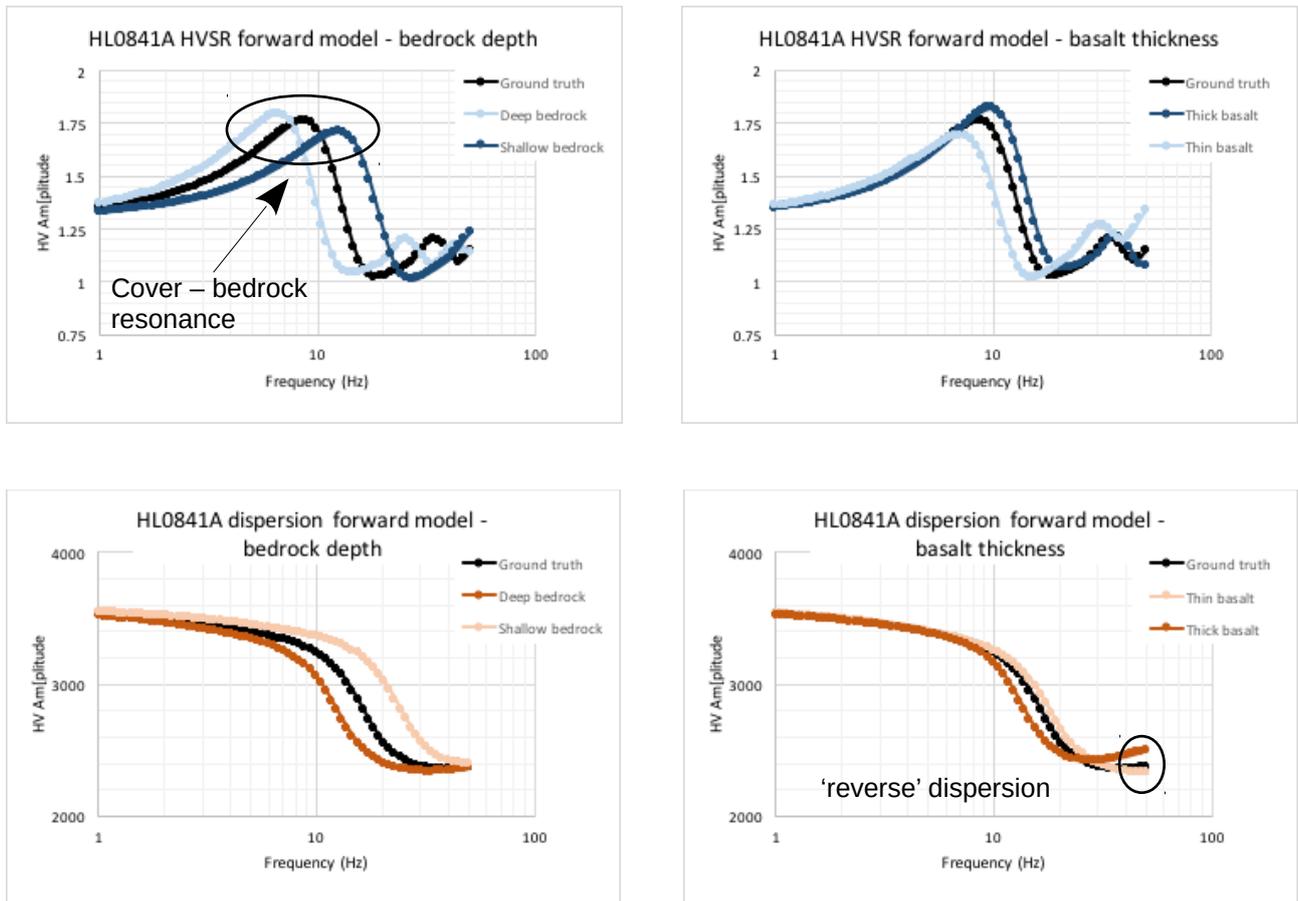


Figure 6: Forward modelling results for HVSR and Rayleigh wave phase velocity dispersion for site HL0841A.

4.3.2 Frankford 1

Drill hole information for the Frankford 1 site shows a relatively thick layer of dolerite overlying a sedimentary bedrock. A physical property model representative of this geology was made using layer depths from the drill hole information and values for seismic velocities and density generalised from a range of previous studies of similar lithologies in Tasmania. Properties of the ground truth model are shown in Table 4, and the ‘thick dolerite’ and ‘thin dolerite’ models were made, respectively, by increasing and decreasing the dolerite layer thickness by 100m.

Forward modelled HVSR curves show a broad, low-amplitude but poorly defined resonance peak between ~3 – 15Hz associated with the dolerite – bedrock interface. Dispersion results show clear reverse dispersion between ~1 – 10Hz, with a shift to lower and higher frequencies of the reverse dispersion for the ‘thick dolerite’ and ‘thin dolerite’ models (Figure 7).

Table 4: Physical properties for ‘ground truth’ model for site Frankford 1. Layer 1 represents dolerite, layer 2 represents sedimentary bedrock and layer 3 represents a deep bedrock with increasing seismic velocity as required by the modelling software.

Layer thickness (m)	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m ³)
200	5000	3000	2500
1000	4000	2500	2670
half-space	5000	3000	2670

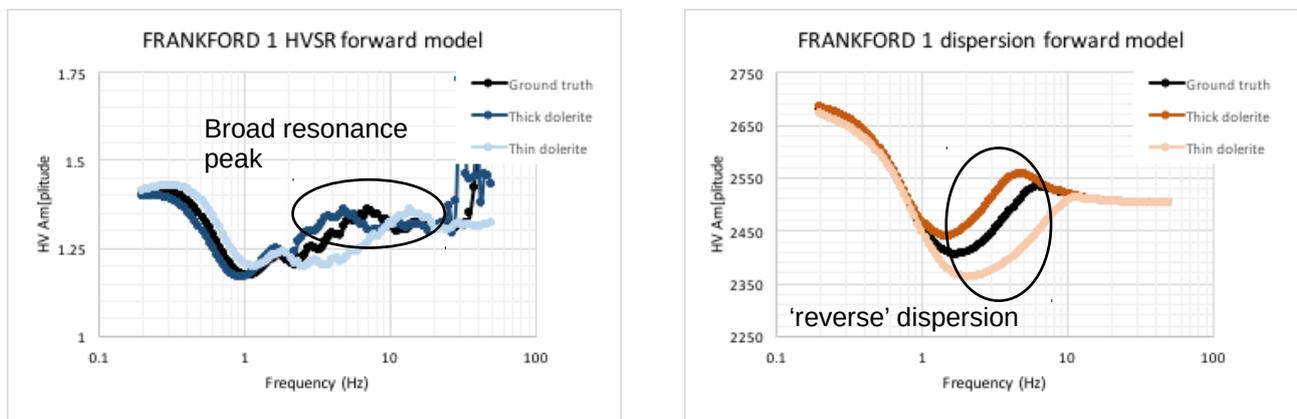


Figure 7: Forward modelling results for HVSR and Rayleigh wave phase velocity dispersion for site Frankford 1.

4.3.3 Fingal 3

Drill hole information for site Fingal 3 indicate a moderately thick layer of dolerite overlying sedimentary bedrock. A physical property model for this site (Table 5) was constructed with layer thicknesses taken from drilling information and values for seismic velocity and density the same as those for the Frankford 1 site. Models for ‘thin dolerite’ and ‘thick dolerite’ scenarios were made by decreasing and increasing the dolerite layer thickness by 40m. Due to the similarities between site forward modelling results for Fingal 3 are similar to those for Frankford 1, although with a shift to higher frequencies for the HVSr peak associated with the dolerite – bedrock interface and the reverse dispersion, due to the relatively thinner dolerite cover layer (Figure 8).

Table 5: Physical properties for ‘ground truth’ model for site Fingal 3. Layer 1 represents dolerite, layer 2 represents sedimentary bedrock and layer 3 represents a deep bedrock with increasing seismic velocity as required by the modelling software.

Layer thickness (m)	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m ³)
80	5000	3000	2500
100	4000	2500	2670
half-space	5000	3000	2670

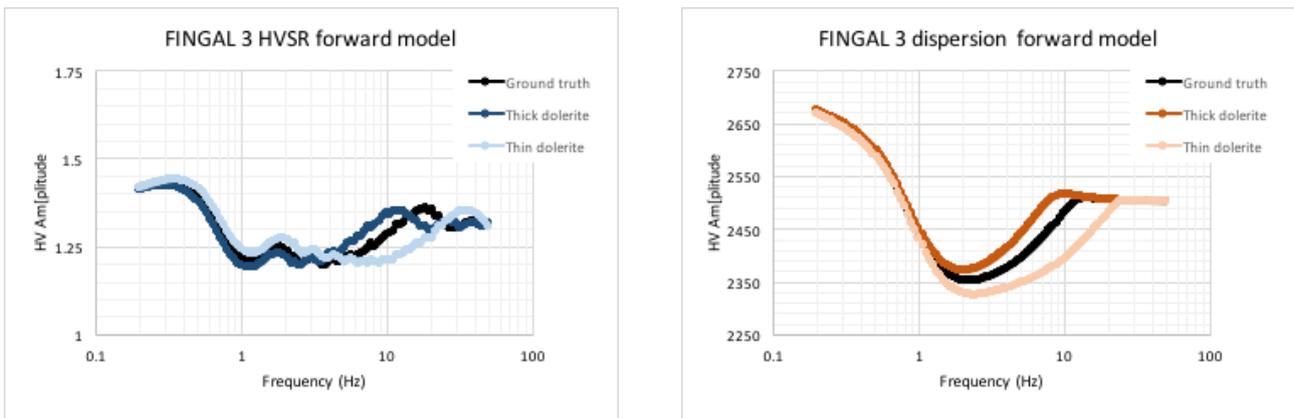


Figure 8: Forward modelling results for HVSr and Rayleigh wave phase velocity dispersion for site Fingal 3.

Forward modelling results for Frankford 1 and Fingal 3 suggest that:

- HVSR methods would not produce a clear, well-defined and high-amplitude resonance peaks for this geological scenario. A broad low-amplitude peak may be produced, but may be obscured by random noise in observe data, and thus observed HVSR waveforms may be challenging to interpret;
- Dispersion methods would show clear reverse dispersion characteristics within the frequency range of interest, diagnostic of high velocity cover overlying lower velocity bedrock.

5. SUMMARY OF DATA ANALYSIS

Observed data were pre-processed using the seismological Python package ObsPy (Beyreuther *et. al.*, 2010), and further HVSr, SPAC and FK analyses were carried out using the software package Geopsy (<http://www.geopsy.org/>).

Data pre-processing involved merging the raw data files, high-pass filtering (>0.05Hz), mean removal, and output of data files in miniSEED format.

HVSr, SPAC and FK analyses were carried out by first splitting the pre-processed time-series into a series of overlapping frequency-dependant time windows with parameters defined in Table 6. An anti-trigger algorithm based on the time series short-term average / long-term average value was then applied to reject time windows dominated by spurious energy from the ensemble prior to further analysis. For SPAC and FK processing spectral whitening was also applied to the pre-processed time-series prior to windowing.

Table 6: Summary of parameters used for Geopsy processing prior to HVSr, SPAC and FK analysis

Analysis bandwidth	Window length	Window overlap	Window taper	STA/LTA	STA/LTA acceptance ratio
0.05 – 50Hz	300 * T	50%	1% cosine	5s/60s	0.1 – 2.5

Following time-series windowing, HVSr, SPAC and FK analyses were carried out.

HVSr analysis is straight forward and consisted of calculating the spectral ratio between the horizontal and vertical components for each window, and calculation of the ensemble mean HVSr for all time-windows. The vector magnitude of north-south and east-west components used to define the horizontal component spectra.

SPAC analysis consisted of defining a set of array rings by their inner and outer radius to encapsulated instrument pairs with similar separation but different azimuthal orientation. SPAC coefficients were then calculated for 200 frequencies spaced logarithmically across the analysis bandwidth for each ring and averaged across all time windows. A histogram of SPAC coefficients vs. frequency was then used to define the SPAC curve for the site.

FK analysis consisted of array beamforming using Capon's method (Capon, 1969) for each time window, to estimate the slowness vector of dominant wavefield arrivals. The phase velocity dispersion curve was then for vertical, radial and transverse components were then

defines by picking the maxima of the histogram of normalised slowness vectors for all time windows, versus frequency.

5.1 HL0841A

5.1.1 HVSR

Observed HVSR curves show a well-defined moderate amplitude resonance peak at approximately 7Hz (Figure 9). For some instruments, higher frequency secondary resonance peaks occur at >20Hz. The fundamental resonance peak is broadly consistent with forward modelling and is interpreted to represent the cover – bedrock interface.

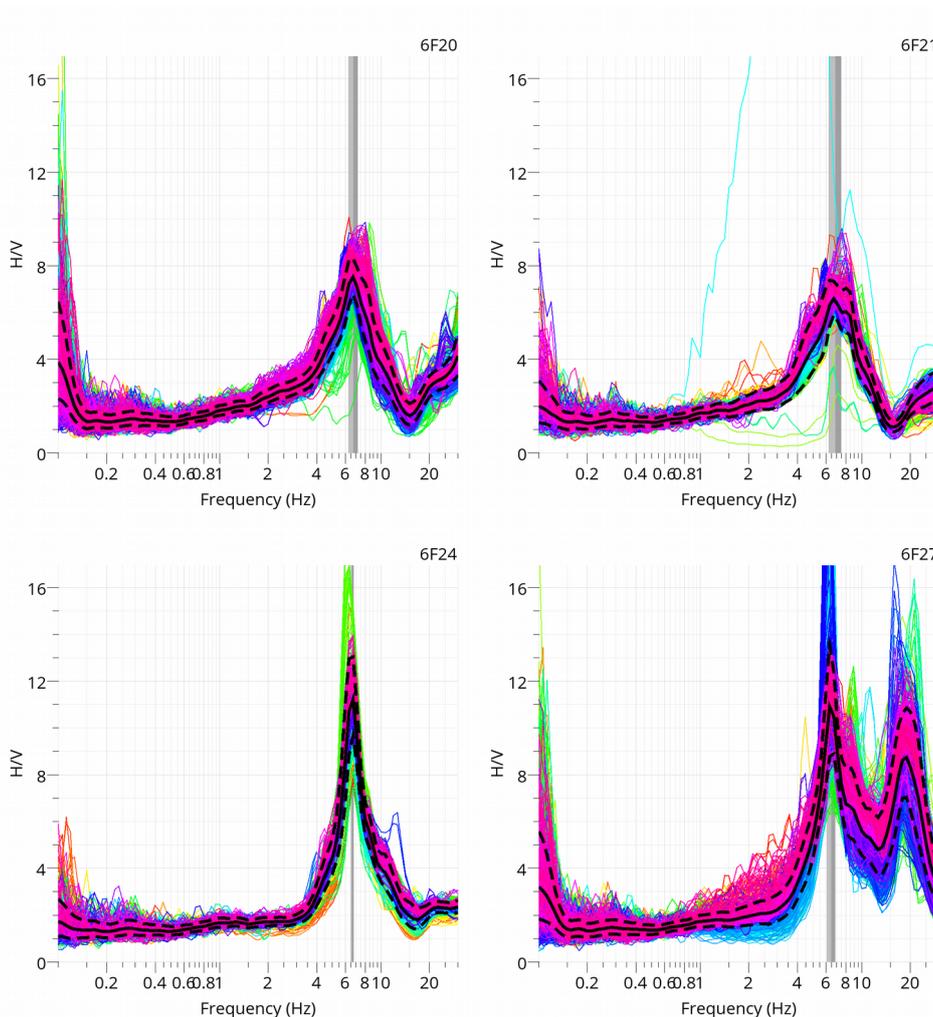


Figure 9: Observed HVSR curves for representative stations at site HL0841A. The coloured lines shows HVSR curves for each time window analysed, with the black solid and dashed lines showing the average HVSR curve and +/- 1 standard deviation. The grey vertical line shows the picked fundamental resonance frequency.

5.1.2 SPAC

Observed SPAC coefficient histograms converge well for different time windows, but the SPAC curve they define shows poor coherency and does not converge to a Bessel function (Figure 10). It is interpreted that the required geological assumptions for the SPAC method are invalid, and thus they are of limited use for inversion modelling.

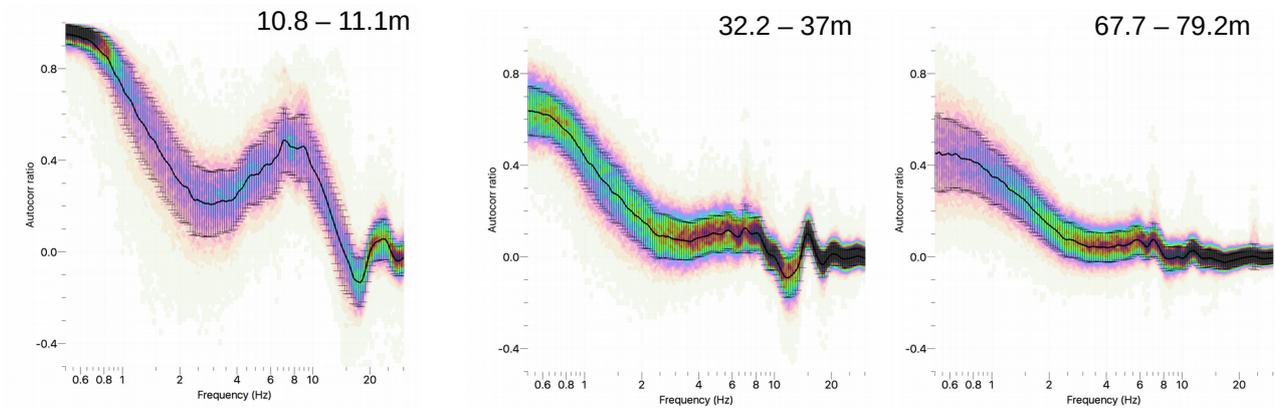


Figure 10: Observed SPAC coefficient histograms for three representative station separations for site HL0841A. The black line shows the picked SPAC curve with ± 1 standard deviation error bars.

5.1.3 FK

Observed FK histograms show a poorly defined phase velocity dispersion between ~7.5 – 10Hz (Figure 11), but it is unclear if this result is an artefact or representative of the site seismic velocity structure. Generally speaking, the Rayleigh wave dispersion can be estimated from vertical and radial component beamforming, and the Love wave dispersion from the transverse component beamforming. Due to this, the FK histograms are expected to define the same phase velocity dispersion for vertical and radial components, and because Love waves travel faster than Rayleigh waves, the transverse component should show a higher velocity dispersion. For site HL0841A this is not the case, therefore it is interpreted that the dispersion estimated from FK histograms is of limited use for inversion modelling.

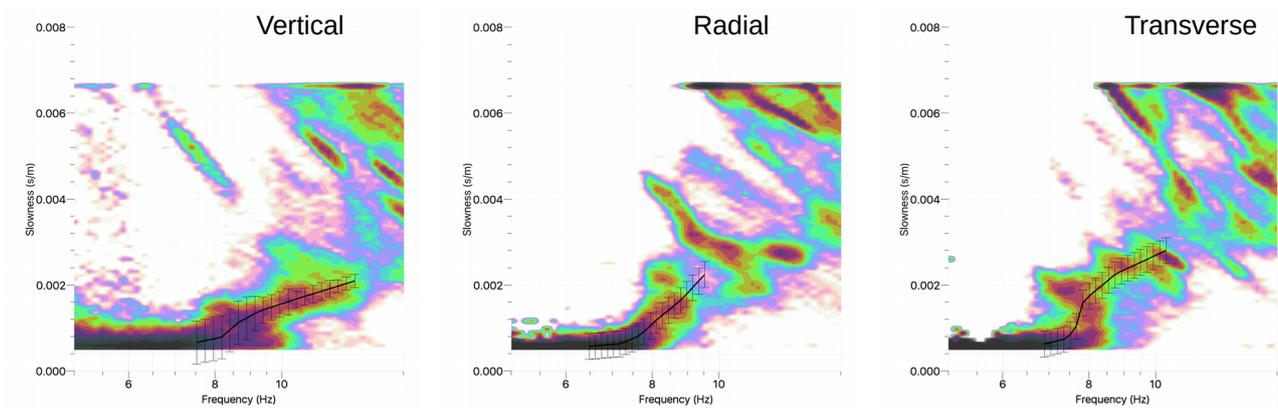


Figure 11: Observed FK slowness vector histograms for site HL0841A. The black line shows the picked dispersion curve and +/- 1 standard deviation error bars.

5.2 Frankford 1

5.2.1 HVSR

Observed HVSR curves show a well defined resonance occurring between ~6 – 10Hz (Figure 12). The change in frequency for the resonance is interpreted to indicate an angled acoustic impedance contrast, possible due generated by the cover – bedrock interface. The well defined characteristic of the HVSR curve and resonance peak is somewhat inconsistent with forward modelling results, which suggest a poorly defined and broad resonance peak. Further geological information, such as measured physical properties of the ground truth drill hole core are needed for further investigation and improved forward modelling.

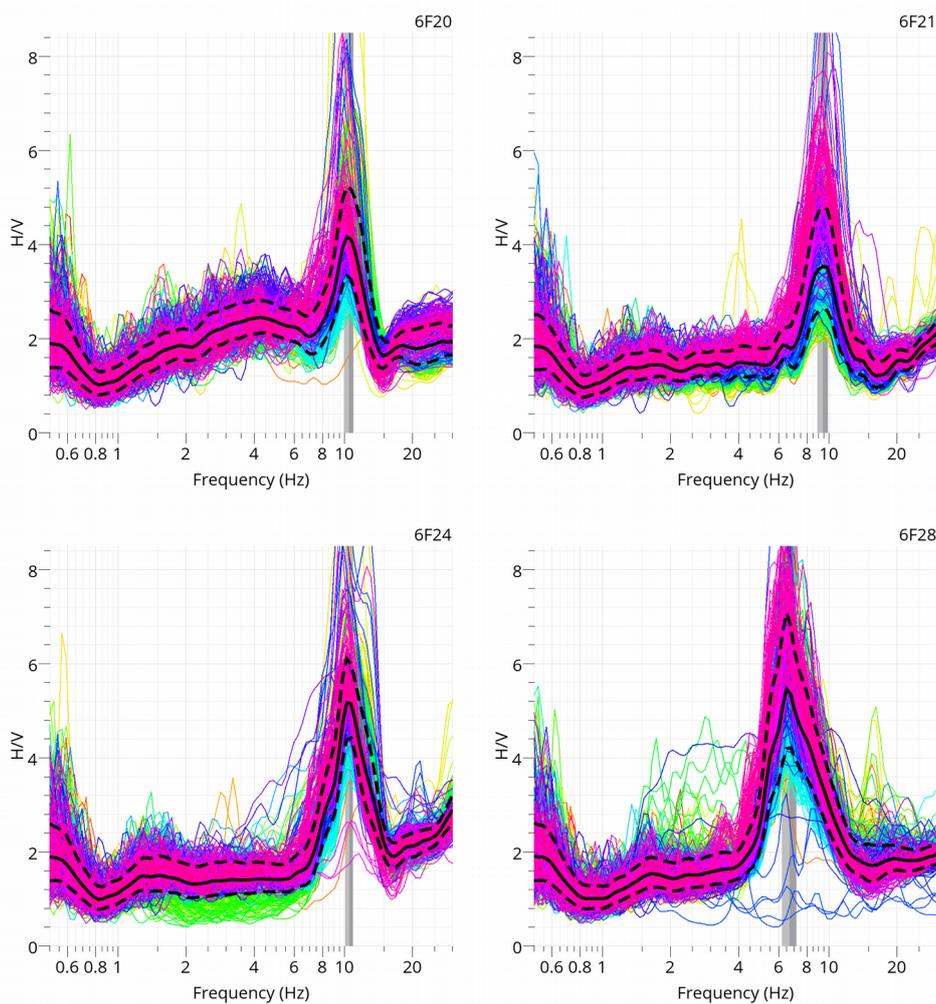


Figure 12: Observed HVSR curves for representative stations at site Frankford 1. The coloured lines shows HVSR curves for each time window analysed, with the black solid and dashed lines showing the average HVSR curve and ± 1 standard deviation. The grey vertical line shows the picked fundamental resonance frequency.

5.2.2 SPAC

Observed SPAC curves show poor coherency and do not converge to a Bessel function as for site HL0841A (Figure 13).

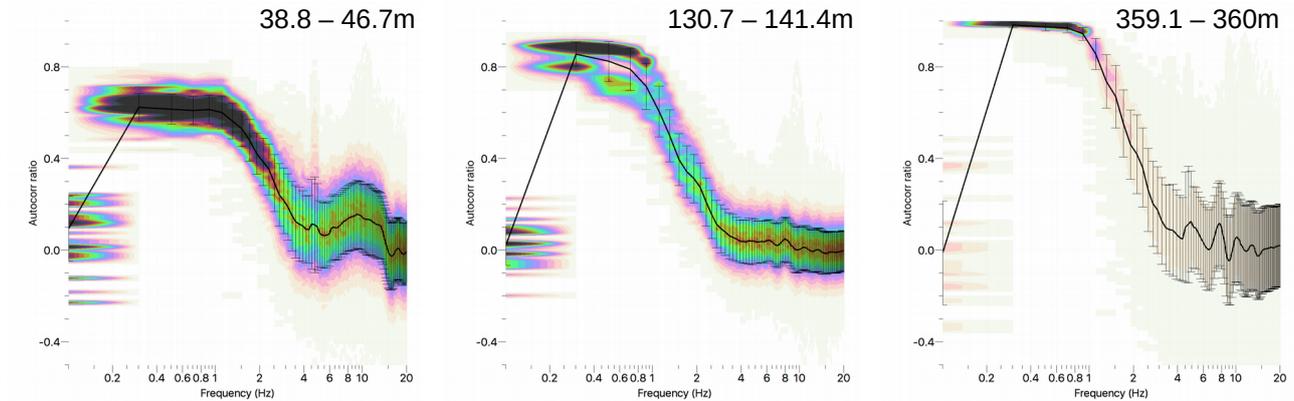


Figure 13: Observed SPAC coefficient histograms for three representative station separations for site Frankford 1. The black line shows the picked SPAC curve with +/- 1 standard deviation error bars.

5.2.3 FK

Observed FK histograms appear to define a clear reverse dispersion curve between 1 – 7Hz (Figure 14), but this curve is the same between vertical, radial and transverse components. As for site HL0841A, it is expected that the transverse dispersion velocities would be faster than the vertical/radial component velocities. It is therefore interpreted that the FK histogram response is not representative of the seismic velocity structure.

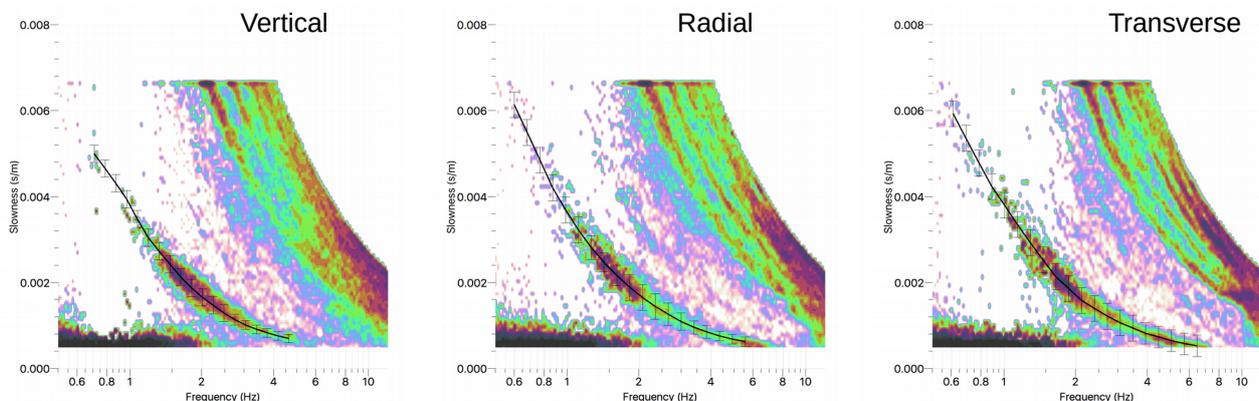


Figure 14: Observed FK slowness vector histograms for site Frankford 1. The black line shows the picked dispersion curve and +/- 1 standard deviation error bars.

5.3 Fingal 3

5.3.1 HVSR

Observed HVSR curves show a poorly- to moderately-defined HVSR curve, with resonance peak between $\sim 4 - 8$ Hz (Figure 15). The observed resonance frequency is inconsistent with forward modelling results, suggesting the resonance is generated by an interface other than the cover – bedrock. It is also possible that the resonance does indeed represent the cover – bedrock interface, but that the cover velocity value used for forward modelling was too low, suggesting that the dolerite cover at the Fingal 3 site is relatively unweathered and massive in nature. Further testing of the drill hole physical properties is needed for robust interpretation of the observed HVSR.

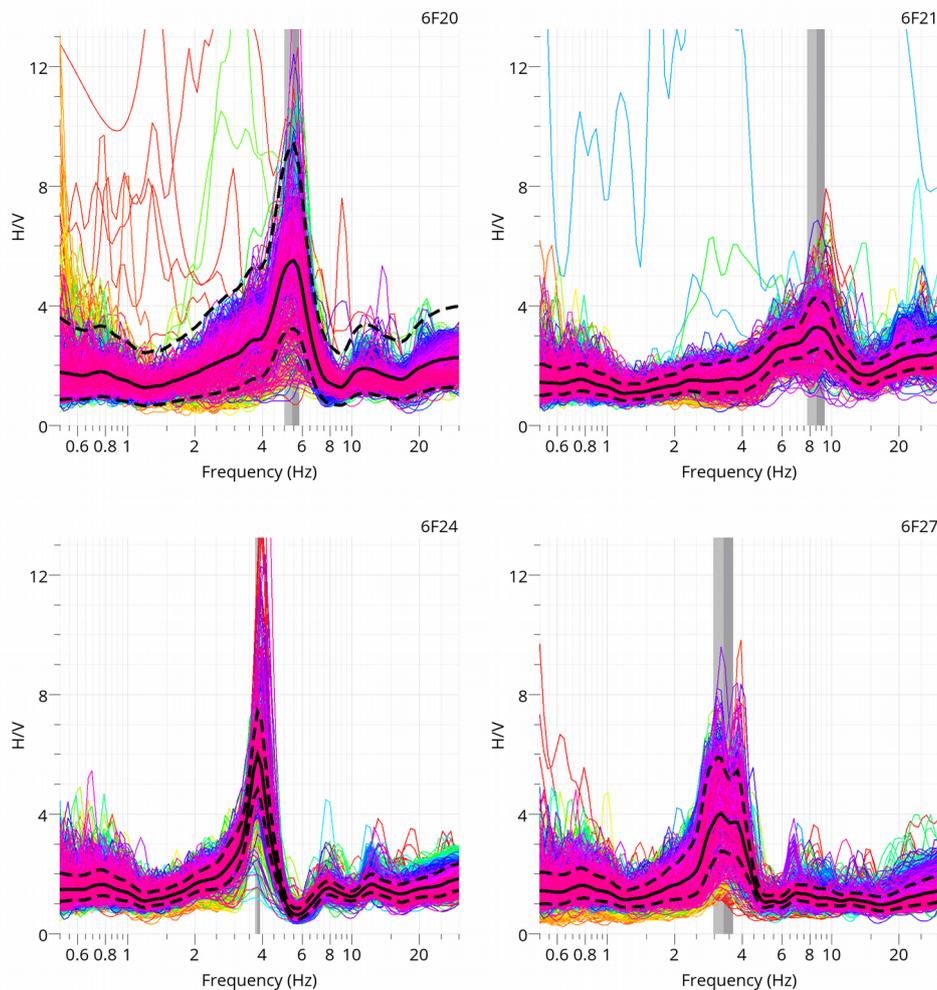


Figure 15: Observed HVSR curves for representative stations at site Fingal 3. The coloured lines shows HVSR curves for each time window analysed, with the black solid and dashed lines showing the average HVSR curve and ± 1 standard deviation. The grey vertical line shows the picked fundamental resonance frequency.

5.3.2 FK

Observed FK histograms do not show any velocity dispersion (Figure 16), and are not useful for further interpretation.

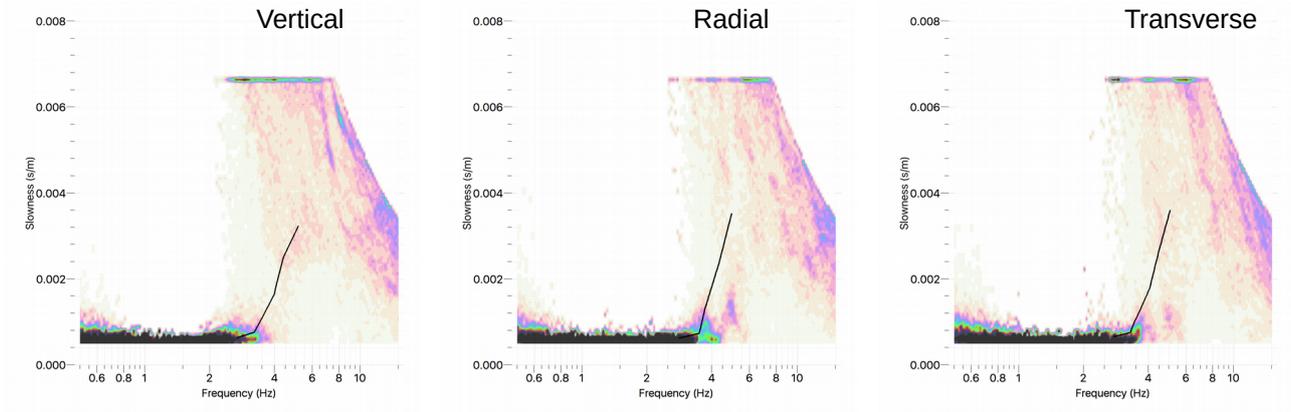


Figure 16: Observed FK slowness vector histograms for site Fingal 3. The black line shows the picked dispersion curve, which is poorly defined.

6. DISCUSSION & RECOMMENDATIONS

Passive seismic surveying of high-velocity cover in northern Tasmania has returned mixed results. HVSR analyses of observed data returned useful results which were broadly consistent with forward modelling results generated using a generalised physical property models. SPAC and FK analyses returned poor results, inconsistent with forward modelling and which were not useful for further inversion modelling.

Based on the experience from previous projects completed by PassiveX Pty. Ltd. in a range of locations globally, it is interpreted that the poor SPAC and FK results for this project are due to a lack of surface wave energy in the microtremor band (approx. >1 – 50Hz). This interpretation is consistent with a good HVSR result, as it is well-known that the HVSR response of the ground is persistent under different wavefield conditions and particularly well defined for diffuse wavefield conditions.

Further robust analysis and modelling of observed HVSR data requires accurate information on the cover average seismic velocity, which can be determined through analysis of seismic velocity on drill core, or the development of a velocity model for the local region using other geophysical methods.

It would be useful to collect more data for array analysis (SPAC and FK) with a deployment using more instruments in the array, and deployment time of around 1 week. Doing this would increase the probability of the acquisition of surface wave energy, and also increase the array's wavelength resolution and ability to resolve seismic velocity structure. It would also be useful to artificially create surface wave microtremor energy using a field vehicle, such as for Smith *et.al.*, (2013), with the aim to provide high-quality surface wave energy for analysis and development of a seismic velocity model representative of the local region, to be used for constraining the interpretation of HVSR data collected over the broader region.

7. REFERENCES

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