Tracking the *Diprotodon* - microtremor passive seismic profiling as a tool for location of megafauna bone beds

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SUMMARY

Bone beds containing Pleistocene megafauna fossils dated to between 35ka and 60ka occur near Lancefield (Victoria). The bones lie within clays above gravels and extensive Quaternary basalt flows. Evidence that the bones have been subject to alluvial transportation suggests that profiling the basalt basement for paleo-channels will assist with locating further bone beds. Passive seismic (microtremor) methods, as developed variously for earthquake hazard studies and regolith studies, have been applied to this problem, using both HVSR spectral ratio methods and two-station SPAC (spatially averaged coherency) methods. Clay layers have shear-wave velocities (Vs) in the range 120-180m/s and thicknesses 1.5 to 2.5m. Microtremor data in the frequency band 5-60Hz provides excellent resolution of the Vs and thickness of the clay layers, allowing the bedrock profile to be established to an accuracy of 0.5m or better. The results indicate existence of soft clays some 40m west of an existing excavation site and thus identify a future site for excavation.
Key words: Pleistocene megafauna, *Procoptodon*, *Diprotodon*, Lancefield, passive seismic, microtremor, surface wave, Rayleigh wave.

INTRODUCTION

The locality of the Lancefield (Victoria) bone beds has been of scientific interest since the discovery in 1843 of megafaunal bones by a local well-digger. The region is capped by the Older Basalts of Pliocene age, and the megafaunal bones appear to lie on and within swamp clays, probably transported and deposited in local depressions in the upper basalt surface. Detailed archaeological and palaeontological investigations of the 1970s are given by Gillespie et al (1978) and of the 1990s by van Huet et al (1998, 1999), Dortch (2004) and Dortch et al (2016). The site lies 1.1 km south-east of the town of Lancefield, central Victoria. The site lies within the Lancefield Recreation Area, between a trotting track and a football oval and has largely been preserved from encroachment by residential or farm development.

Figure 1 shows the locality of the Mayne fossil Site and the Classic fossil Site where the majority of Pleistocene-aged megafaunal fossils have been discovered. Fossils are from both grazing animals (such as the extinct large *Macropus giganteus titan* –similar to a very large Eastern grey kangaroo *)* and browsing animals such as the 230 kg *Procoptodon goliah* (a huge short-faced kangaroo-like creature) and *Diprotodon optatum* (similar to a wombat, but at 2800 kg the size of a modern small rhinoceros). The most recent excavations at the Mayne Site in 2016 found an array of *Diprotodon* and *Macropod* dental and bone material, so in order to better understand the location, and help target future digs, this initial geophysical survey aimed at characterizing seismological response of this site. Figure 2 shows examples of the excavated fossilized *Diprotodon* teeth.

The geophysical survey was designed as a trial to evaluate whether passive seismic (surface wave) methods might assist in identifying a signature of swamp clays which form a basal layer to known bone beds. Passive surface-wave methods using microtremor wave energy are well-established in engineering and earthquake hazard applications, making use of cultural noise from vehicle and other anthropogenic sources in the frequency band 1 to ~30Hz, and naturally-generated seismic noise from meteorological phenomena in the frequency band 0.1 to 1 Hz. Asten and Hayashi (2017), Garofalo et al (2016), and Foti (2017) provide recent reviews of such methods, which generally use 2D arrays of geophones along with processing by the Spatial averaging of coherencies (SPAC) method in order to extract a layered-earth model of shear-wave velocity Vs versus depth. Such passive surveys give information over a depth range of meters to the order of a kilometer (where soft rock over basement exists to those depths); Asten et al (2014) provide examples over deep basins in Turkey, while Asten et al (2013) and Volti et al (2016) provide examples in urban and suburban fringe sites in Australia. Active surface-wave methods such as MASW (Park et al, 1999) are frequently deployed for shallow investigations using hammer or other impact sources and linear arrays, and these typically yield Vs data for the upper 30m of soils and sediments. However Hayashi et al (2016) and Asten and Hayashi (2017) demonstrate that passive methods with linear arrays, when combined with use of a direct-fitting SPAC processing algorithm (described and termed multimode SPAC, or MMSPAC, by Asten, 2006) are capable of a similar range of frequencies as active methods. With the high scientific interest in the Lancefield site, and the availability of suitable seismometers from the AGOS inventory (see Acknowledgements below) it was decided to deploy linear arrays in a passive seismic experiment at Lancefield, Vic.

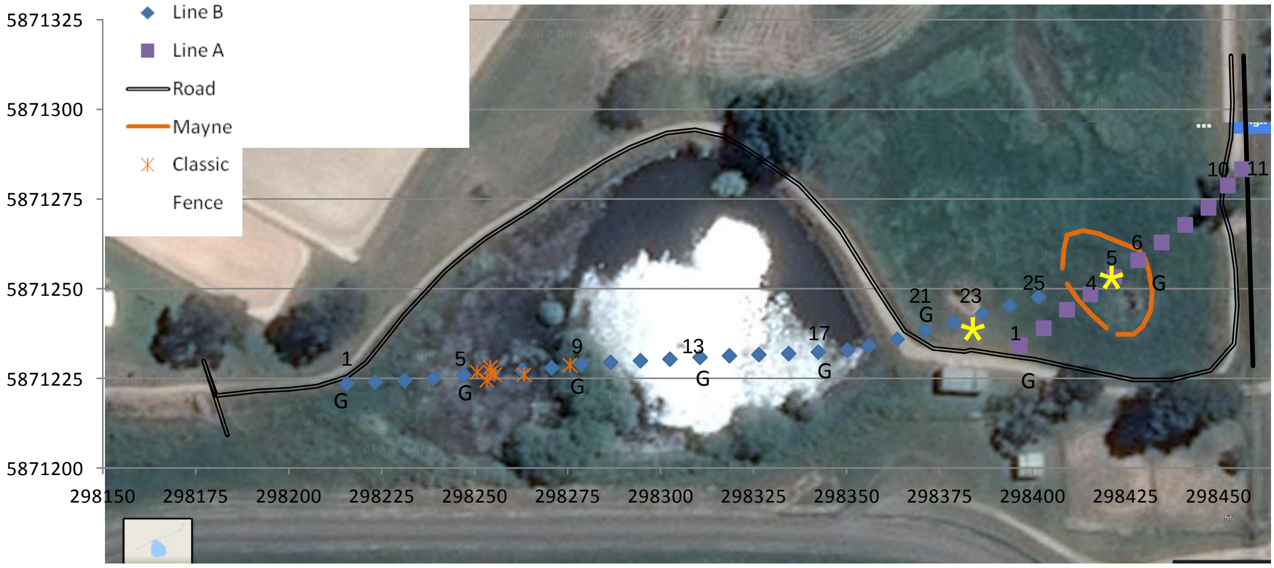

Figure 1: Site of the Pleistocene megafaunal bone beds, Lancefield Vic. The general drainage pattern is downstream to the north-east or ENE. Coordinates shown are Zone 55 AMG Eastings and Northings in meters. The orange ellipse at right is the Mayne Site. The orange symbols at left are remnants of the digging at the Classic Site (Gillespie et al, 1978 and Dortch, 2004). Purple squares and blue diamonds are Line A and Line B respectively, as geophysically surveyed in 2017. At the time of the survey the lake was dry. Symbols G denote the western end of successive deployment of sets of 6 or 5 seismometers. Numbers are station numbers along each line used to identify plots in Figures 5&6. Yellow asterisks mark sites with notably soft clay interpreted at depth 2+m. The Mayne Site is at latitude 37°17'0.70"S, longitude 144°43'34.28"E.

GEOLOGY

The locality of Lancefield is generally flat, with soils being basalt weathering products. Surficial layers are typically pisolitic weathered basalt products or brown-black clay of Holocene age to Late Pleistocene age with Pleistocene bones of age~60 ka at the base. Basal to the bone beds are swamp deposits of green smectite (montmorillinite) clay. This latter clay when saturated appears very soft and allows a working hypothesis that it may be detectable by its low shear strength (and hence low Vs velocity), thus providing a geophysical sensitivity to the location of swamp deposits likely to be associated with formation of bone beds. Figure 3 shows a schematic geological section, including the presence of unconsolidated sand/gravel below the Pliocene Older basalt; these unconsolidated sediments are detected unambiguously in this survey and we hypothesize they represent pre-Pliocene weathering products of Devonian granites of surrounding hills.

METHOD AND RESULTS

Two survey lines were surveyed, one (eastern) crossing the Mayne Site, and one (western) believed to cross the Classic Site (although actual location is poorly specified in records, and the best indicators are stakes and plastic sheeting in an area frequently covered by water depending on seasonal rainfalls). The lines were surveyed at 8m intervals. Seismometers used were Guralp CMG-CT, instruments, frequency range is 1s-100Hz, sensitivity listed as 2x1200 V/M/S. Recorders were Echo Pro 24bit recorders, each recorder operating with 6 channels and being wired between two seismometers. A set of six seismometers and three recorders was thus used to survey the lines in 40m spreads, where each seismometer was placed on a concrete tile in a hole between 10 and 30cm deep (depending on soil softness). The recorders were synchronised via GPS signals. Recording for each spread was typically 60 minutes with some time-segments having a quiet background, and some segments typically supplemented by driving a vehicle on nearby roads or tracks.

Processing of the data utilized the multimode SPAC method which achieves a fit of observed and model SPAC spectra by the MMSPAC method, which uses iterative least-squares fitting, to yield a layered-earth model (Asten, 2006). This method bypasses the need for conversion of observed SPAC spectra to phase velocity dispersion curves and provides improved stability and improved bandwidth of useable data relative to other SPAC processing methods. In this application consideration of multiple Rayleigh wave modes via the concept of the “Rayleigh effective mode” proved crucial; the effective mode R_e is a concept using a combination of fundamental and higher modes R_0, R_1, R_2,... where the frequency-dependent power partition between modes is set by theoretical considerations for vertical point sources acting on the surface of the earth (Ikeda et al, 2012; Asten and Hayashi, 2017).

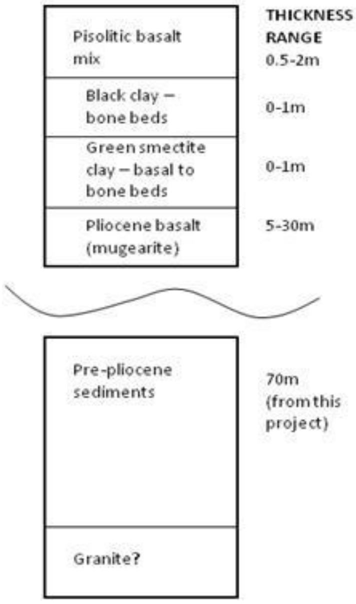

Figure 2: Artists reconstruction of (a) the *Diprotodon* (b) *Procoptodon*. Drawings by Anne Musser. (c) Co-authors Sanja van Huet and Nidhi Srivastava with a *Diprotodon* incisor, partial lower jaw and one molar, as excavated from the Mayne Site in 2016.

Figure 3: A generalized geological section for the locality. The green smectite clay is believed to be a transported product indicating swamp filling; if present it may be an indicator of likely bone beds.

Unlike conventional array processing of SPAC data, each pair of seismometers is treated as a separate "observation" and a separate layered model is yielded for each pair of the spread, being notionally 5 pairs with 8m separation, 2 or 3 pairs with 16 m separation, and one pair with a 40m separation. While the SPAC spectra are noisier for such 2-station pairs, relative to what is customary for multi-station arrays, the results here show sufficient signal to unambiguously resolve geological units of interest.

Figure 4 shows Rayleigh wave theoretical and measured properties for a layered-earth model approximating the earth for the spread of seismometers Line A, spread 1 stations 1-6. The model phase velocity dispersion curves for four modes plus the effective mode R_e are informative but they are not used for interpretation in the MMSPAC direct-fitting method employed here. It is however useful to note the very strong influence of higher modes at frequency 11 Hz; this gives rise with this model to spikes near 11 Hz in SPAC curves such as Figures 5b,5c which if erroneously ignored as noise result in loss of vital information in the interpretation process. Figure 4b shows the quarter-wavelength of the modelled fundamental Rayleigh mode versus frequency, a plot which is useful in giving a guide as to the sensitive depth of different frequencies of spectral or SPAC plots. The quarter-wavelength rule is strictly valid for showing the depth to a single high-contrast interface in a two-layer model; it is progressively less use as models proceed to multiple layers and low velocity contrasts between layers. It does however provide a useful guide within a factor of about two when assessing significance of features in observed spectra.

Figure 4 (c-e) show observed and model horizontal:vertical spectral ratios (HVSR) and MMSPAC spectra for the same stations 1-6. The station separation of 40m for SPAC data and the HVSR spectrum allows unambiguous resolution of a thickness of 70-90m of pre-Pliocene sediments below the basalt; they have a Vs in the range 380-400m/s which corresponds to that expected for sand or gravels.

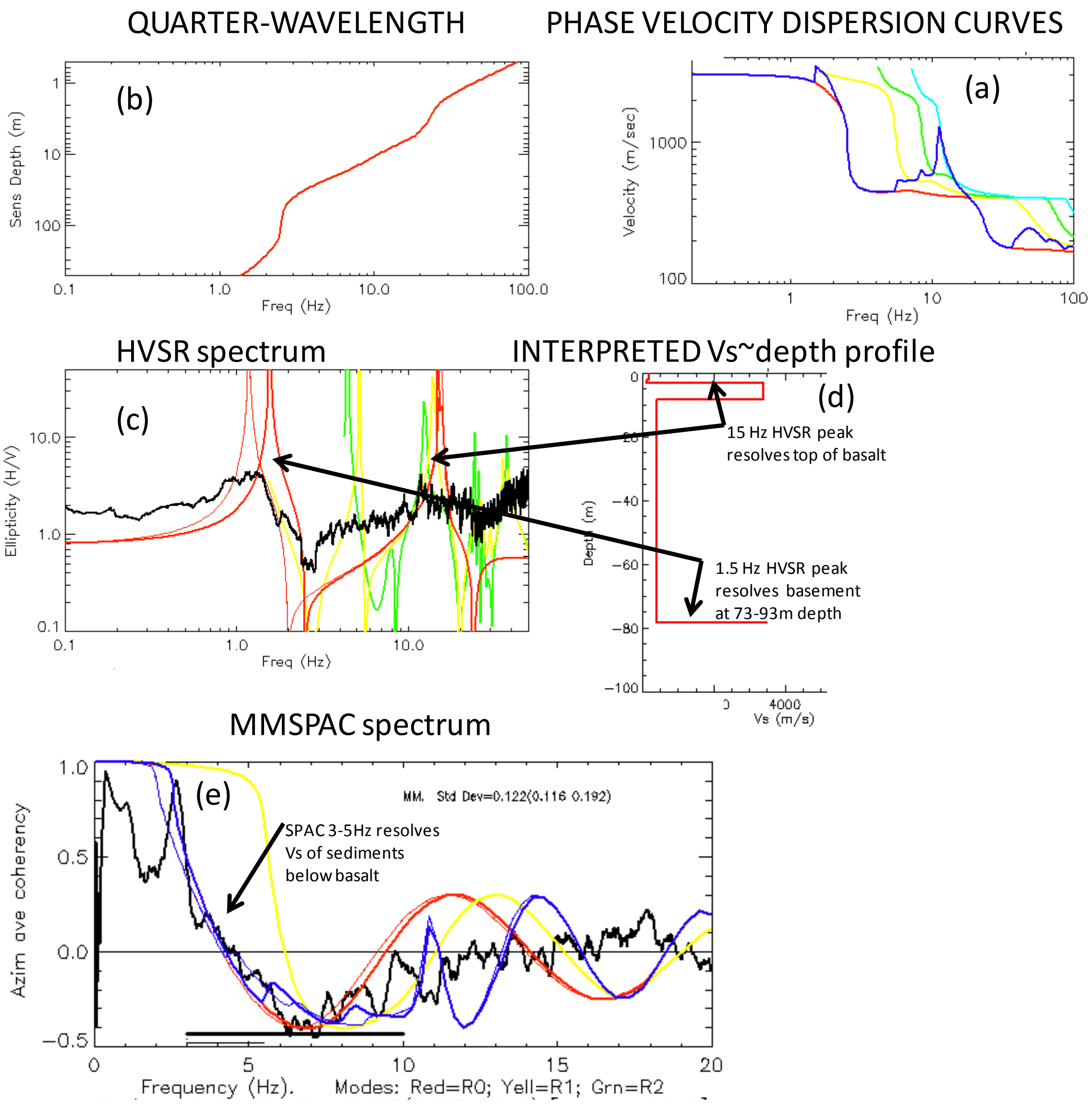

Figure 4: (a) Top right; phase velocity dispersion curves for the model shown in Figure 4d. Rayleigh modes R_0, R_1,R_2 R_3 appear in colors red, yellow, green, aqua respectively. The Rayleigh effective mode R_e is in blue and overwrites much of the R_0. (b) Plot of quarter-wavelengths versus frequency for the R_0 mode. This is conventionally considered to indicate the sensitive depth to an interface.
(c) HVSR spectrum Line A stn 1. Two peaks resolve depth to basalt and depth to basement as shown on Vs~depth profile). Thick red: model basement depth 73m. Thin red: model basement depth 93m.
(d) Interpreted model for Vs~depth profile.
(e) MMSPAC spectrum for 40m separation, Line A stn 1-6. Black line: observed data. Thick blue: Effective mode R_e with model basement depth 73m. Thin blue: depth 93m. Red, yellow lines are model R_0, R_1 modes.

We now address the most important point of the survey; can we resolve a clay layer in the upper 5m, likely to correspond with the green clay reported as basal to the known bone beds? At the time of writing, only results for the eastern half of the survey area are available, so results presented here are preliminary. Modelling of surface waves for the layered-earth model is challenging because it involves two low-velocity layers, the clay (whether black or green, below pisolitic basalt and above unweathered basalt) and pre-Pliocene sediments below the basalt. Low-velocity layers increase the occurrence of multiple modes and ambiguous model fits, but with sufficient bandwidth correct interpretation of such layers may be achieved. Roberts and Asten (2008), Asten and Hayashi

(2017), Garofalo et al (2016) and Foti et al (2011) give examples where LVLs are successfully identified using passive surface-wave methods.

Figure 5 shows a subset of SPAC spectra for four selected locations from east to west on Lines A and B of Figure 1. The differing SPAC spectra in the east (Figure 5a, 50 m north-east of the Mayne Site) compared with that of stations 4-5 (Figure 5b) over the Mayne Site is clear. The SPAC spectrum for the east end of Line B, stations 24-25 (Figure 5c) is similar to 5a. Of particular interest is the SPAC spectrum for stations 23-24, which has a clear similarity to Figure 5b (the Mayne Site).

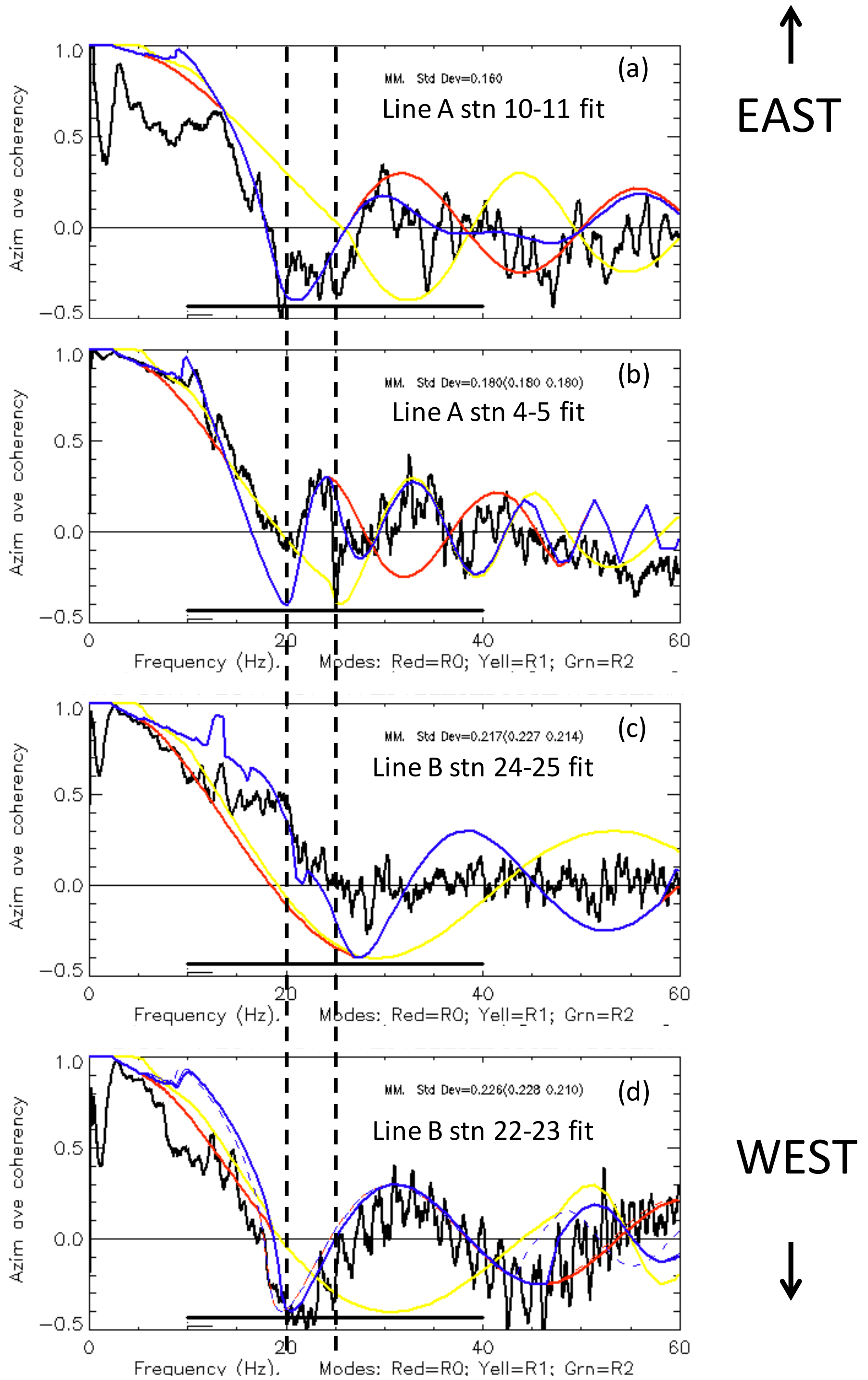

Figure 5: SPAC spectra for four stations selected from east to west from Lines A, B of Figure 1. The frequency band 15-25Hz is highly sensitive to existence of soft clay at depths of 2+m, above the basalt layer.
(a) Line A stations 10-11. (b) Line A stations 4-5, corresponding to the location of the Mayne pit. (c) line B stations 24-25. (d) Line B, stations 23-24.

Quantitative interpretation of Vs~depth profiles are plotted in Figure 6. It is clear that the Mayne Site is characterized by a low velocity clay layer (LVL) beneath surficial soils/pisolites/black clay, and equally clear that no LVL exists in interpretations east of the known Mayne Site, or north of Line A at the eastern end of Line B. However Line B station 23-24 shows a thick LVL similar to that of the Mayne pit. If we may borrow a famous quote, "This will be the place for a dig" (with apologies to John Batman, speaking when founding the village of Melbourne in 1835).

The interpreted base of basalt is poorly resolved (perhaps subject to a factor of two uncertainty) and should be subject of further sensitivity studies. The sites interpreted as having the weak basal green clay appear to be striking sub-parallel with the survey lines. Future surveys in this locality will need to be placed transverse to the existing Lines A and B.

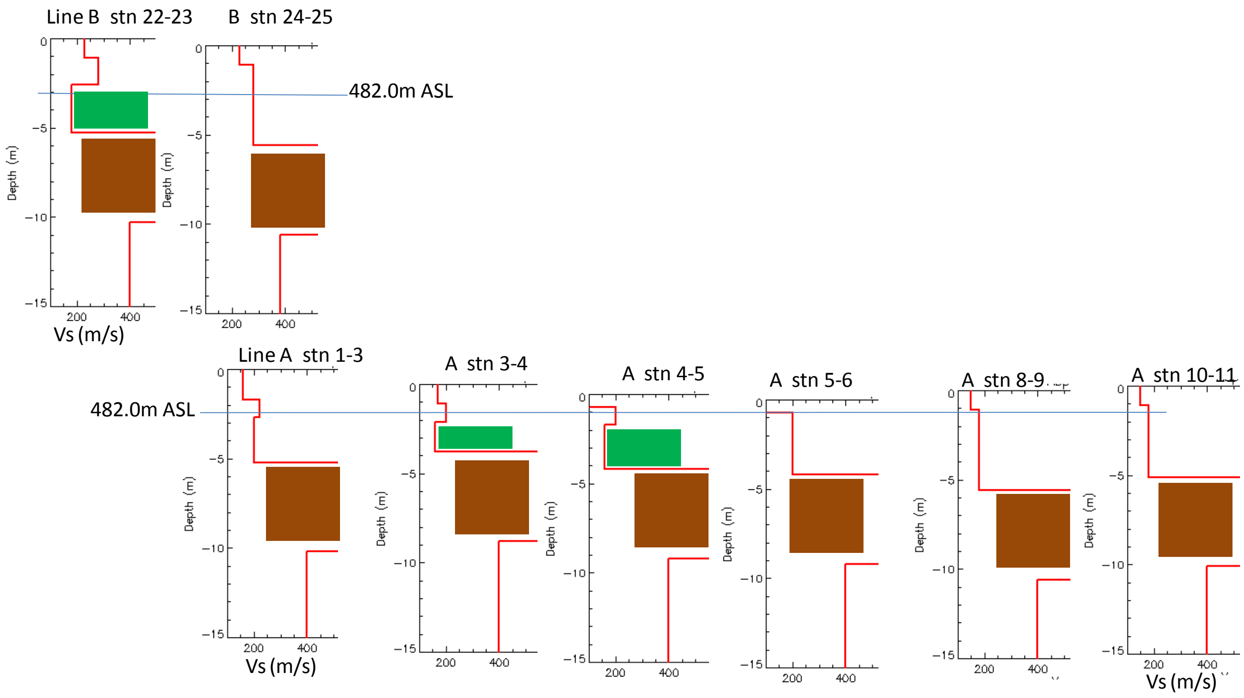

Figure 6: Interpreted Vs~depth profiles from SPAC data at selected sites from west to east on Line B (Top) and Line A (Bottom). Vertical offset corresponds to elevation variation along the lines, with blue line indicating elevation 482.0m above sea-level. Brown and green shading indicate respectively interpreted basalt (high Vs) and soft clay (low Vs).

CONCLUSIONS

Results thus far are based only on interpretation of the eastern half of the survey area. Passive seismic data with a linear array of seismometer spacing 8m allows imaging of the earth in layers from a surficial depth of <1m, to a maximum depth of order 100m. The useful frequency range of coherency spectra is 5 to 40Hz, and in some cases up to 60 Hz. Despite the existence of two low-velocity layers in the section, interpretation by direct-fitting of observed and model SPAC spectra for the Rayleigh wave effective mode allows detection of a soft clay layer below the Mayne Site, which we interpret as the green clay basal to the Pleistocene bone beds known at this location. An interpretation of geophysical data at a site 40m west of the Mayne Site suggests that similar weak clay exists; we predict this new site, as yet untested, is an extension of the green clay swamp deposits and is thus a target for future paleontological investigations.

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