P- AND S-WAVE SEISMIC SOURCES FOR ULTRA-SHALLOW SEISMIC SURVEYING

Bowen Basin Symposium, 2015

Alan Meulenbroek[1], Simon McMonagle[1], Shaun Strong[1], Stewart Fletcher[1]

1. **Velseis Pty Ltd**

ABSTRACT

Velseis has implemented several P- and S-wave seismic sources specifically for use where greater resolution of the near-surface is required. The sources range from impulsive sources, both surface and sub-surface, coded-impact sources and a prototype controlled-frequency source. Each of these is compared to Mini-SOSIE shot records acquired both in pre-production testing and on a production seismic line in the Surat Basin. Coupled with appropriate survey design, the sources would be equally applicable to prospects in the Bowen Basin where greater near-surface imaging may be required.

Logistically, the simplicity and portability of the piledriver source makes it an attractive option for seismic surveys targeting the very near-surface. In a technical sense, the piledriver possesses adequate bandwidth and energy penetration characteristics. However the larger mass of Mini-SOSIE, and its effective stacking capability, means that it has greater energy penetration without compromising bandwidth.

These experiments support the view that optimum source selection is area dependent. For seismic surveys specifically targeting the near-surface, it is recommended that pre-production sources tests be carried out at multiple test locations. Each source has been formally risk assessed and Task Procedures have been developed for all sources.

KEYWORDS: Ultra-shallow, near-surface, seismic sources, P-wave, S-wave.

INTRODUCTION

The definition of the near-surface depends on the scale of a seismic survey. The near-surface to a solid-earth geophysicist will be very different to the near-surface of an engineering geophysicist. In the context of Australian coal basins, specifically the Bowen Basin, the near surface generally encompasses the weathering layer and the boundary between it and the subweathering. In many cases, the weathering layer can be made up of multiple layers of interbedded material and the structure of the boundary with the subweathering can be complex. Improved knowledge of this zone may be of direct relevance in the context of open-cut mining or geotechnical mapping. In addition, it will enhance the processing of seismic data at the conventional coal scale.

When designing a survey to target the near-surface, parameters such as the group interval and choice of far-offset are both important considerations. However, the source type is also an important factor. Different sources have different strength and frequency characteristics. It is generally accepted that, at least for impulsive sources, larger sources tend to have a lower dominant frequency but higher amplitude than smaller sources (e.g. Peet, 1960). However, when this energy propagates through the earth, variations in measured frequency are generally minimal because of the absorptive properties of the Earth (O'Brien, 1960). In light of this, it is necessary to consider sources which have a wide range of characteristics, both technical and logistical. In particular, higher frequency/larger bandwidth sources are required to resolve small-scale features often targeted by near-surface seismic surveys.

Velseis has recently implemented and tested several sources, specifically for use in the near-surface environment. Examples of these sources used in a production survey and subsequent processing are given in Meulenbroek (2015) and Strong (2015). Full Task Procedures and Task Risk Assessments have been developed for all sources. Both P- and S-wave sources have been implemented. To assist in the description to follow, a brief introduction into P- and S-waves is now given.

P-WAVES AND S-WAVES

A P-wave (compressional wave) is a seismic wave in which the direction of particle motion is parallel to the direction of wave propagation. An S-wave (shear wave) is a seismic wave in which the direction of particle motion is perpendicular to the direction of wave propagation. Figure 1 shows a representation of (a) P-waves and (b) S-waves in the form of springs and blocks. In both cases, the direction of propagation is from left to right.

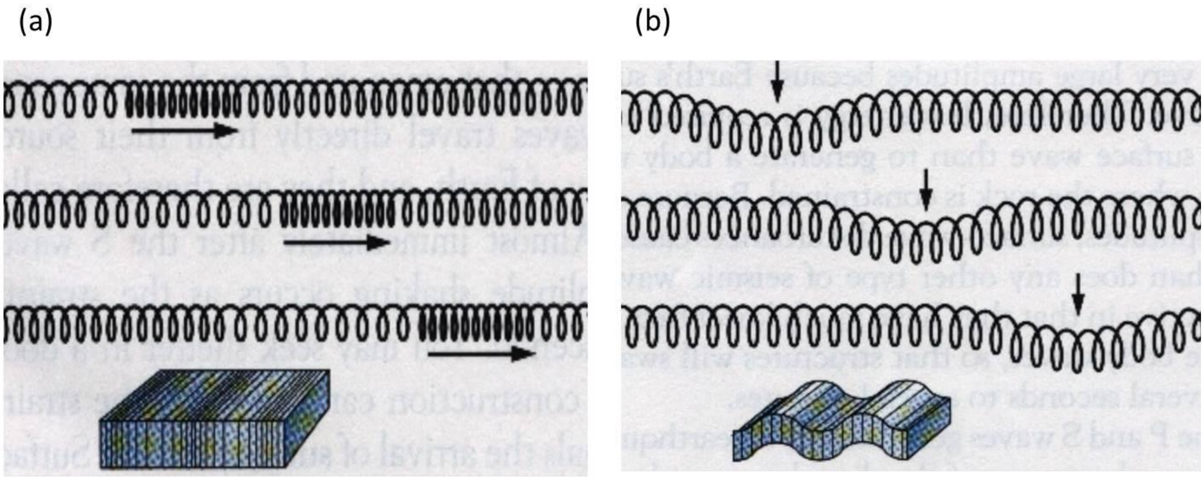

Figure 1. (a) P-wave and (b) S-wave. The direction of wave propagation is from left to right.

S-waves are also polarised in two directions, commonly referred to as SV and SH. The nomenclature of SV and SH is used with reference to the plane of incidence (see Figure 2). The SH-wave is polarised perpendicular to the incidence plane (Garotta, 2000). The SV-wave is polarised horizontally to the incidence plane. In the context of a 2D seismic line, the SV-wave is the S-wave polarised in the inline direction and the SH-wave is the S-wave polarised in the cross-line direction.

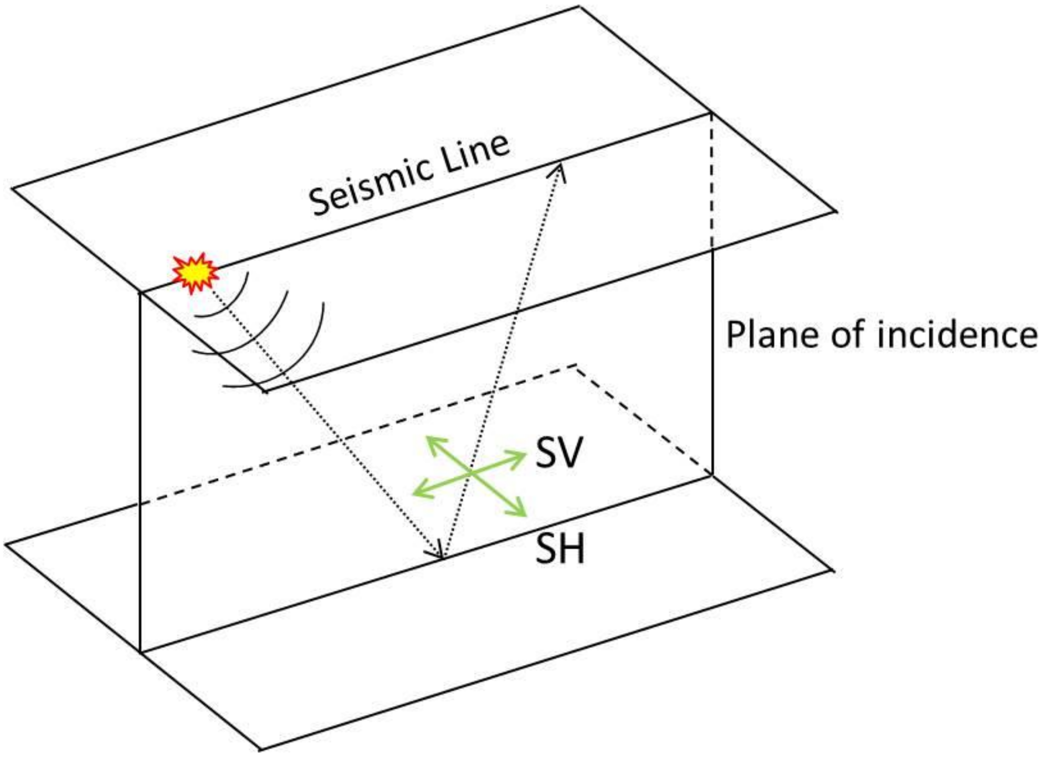

Figure 2. Polarisations of S-waves with respect to seismic line (after Garotta, 2000). The SV-wave is polarised in the direction of the seismic line (inline) and the SH-wave is polarised perpendicular to the seismic line (cross-line).

Recording the full wavefield (i.e. P, SV, SH) is only possible using three-component (3C) geophones. A 3C geophone comprises 3 elements oriented at right angles to each other placed into a single case (Figure 3). To maintain consistency, all geophones must be oriented in the same direction in a particular survey.

Figure 3. Three component (3C) geophone. The arrows on top of the geophone refer to the polarity of the horizontal components.

Exploiting the different wave-type characteristics can be beneficial for better imaging in the near surface (e.g. Strong, 2015). In a given medium, the velocity of S-waves is slower than the velocity of P-waves ($V_P > V_S$). The magnitude of this V_P/V_S ratio can be indicative of the physical properties of the material through which these waves propagate, (e.g. Garotta, 2000). In addition to the difference in velocity, S-waves do not propagate through fluids (liquid or gas) whereas P-waves do. This means that S-waves generally map geology, whereas P-waves also respond to pore fluids. This can be useful for determining structure in areas of fluid saturation.

Given a geological boundary at a certain depth, the time of a reflection event associated with this boundary will differ depending on which wave type is used to image it. An S-wave event from a particular boundary will project later in time than a P-wave event from the same boundary. In the near-surface, this can be beneficial because there is a lot of interference with other wave types. While the P-wave event may be swamped by this noise, the S-wave event may be more visible due to less interference with noise.

In conventional seismic exploration, structures are generally imaged by using a P-wave source recorded into vertical component geophones. These P-wave sources do generate other wave-types, e.g. Rayleigh waves/ground-roll; however these are generally treated as noise in the data and removed during processing. When a P-wave is incident on a geological boundary at a non-perpendicular angle, the shearing motion imparted on that boundary produces S-waves. This wave-type is called a converted-wave, also known as a PS-wave or a C-wave.

Thus, with the different source and receiver types, the three most common surveys used are:

- P-wave survey (P-wave source recorded into vertical component geophones)
- S-wave survey (SH-wave source recorded into 3C geophones. Useful information is predominantly on the cross-line component.)
- Converted-wave survey (P-wave source recorded into 3C geophones. Useful information is predominantly on vertical and inline components.)

SOURCES

The sources implemented by Velseis can be separated into three broad categories. These are:

- Impulsive sources
- Coded-impact sources
- Controlled-frequency source

The different sources have different amplitude and frequency characteristics. They also have different logistical and safety requirements. In each of the following shot record examples, the group interval is 1m. For the production shot records, the far offset is 200m.

P-wave sources

Impulsive sources

The impulsive sources are so called because they impart a single impulse into the ground via a single hit. Stacking of multiple hits can improve the signal to noise ratio (S/N). The most basic form of an impulsive source is a sledge hammer and a base-plate. This can be triggered by either a reed-switch or a piezo-electric device mounted on the hammer. However, repeatability can be compromised with operator fatigue. From a health and safety perspective, there is a risk of injury due to the repeated swinging of a large mass. It is therefore prudent to develop other sources where these potential causes of injury can be eliminated.

Piledriver

The piledriver source (also known as Bigfoot) was constructed by welding a base-plate to a crow-bar and hitting the top with a star-picket driver (Figure 4). This is triggered with a piezo-electric device mounted on the base-plate. In terms of health and safety, the linear movement required presents much less risk of injury than the swinging movement of a sledge-hammer. From a technical point of view, the use of a star-picket driver improves repeatability compared to the sledge hammer. In addition, plate-bounce, often a problem with the sledge-hammer source, is eliminated. The small size of the base-plate ensures that the energy which is imparted into the ground is not smeared. This is important in the context of near-surface seismic acquisition where high resolution is required. Bigfoot is very manoeuvrable between shots and only requires a single operator.

Figure 4. Piledeiver source, Bigfoot.

Figure 5 shows vertical component Bigfoot shot records acquired during pre-field trials. The group interval is 1m. Figure 5 (a) is acquired with 1 hit and Figure 5 (b) with 10 hits. The improved S/N with the extra hits can be seen on the far offsets.

Figure 6 shows a Bigfoot shot acquired during the production survey. A 150-200Hz highcut filter has been applied to remove random noise in the data. The coherent noise at the far offsets is significant enough to make first-break picking difficult at this stage in processing. Figure 7 shows a Mini-SOSIE shot record acquired at the same shot point at Figure 6. The larger mass of the wacker, and the high stack count, has the effect of penetrating through this far-offset noise. However, the energy on the near-offset appears to be contaminated somewhat by correlation noise.

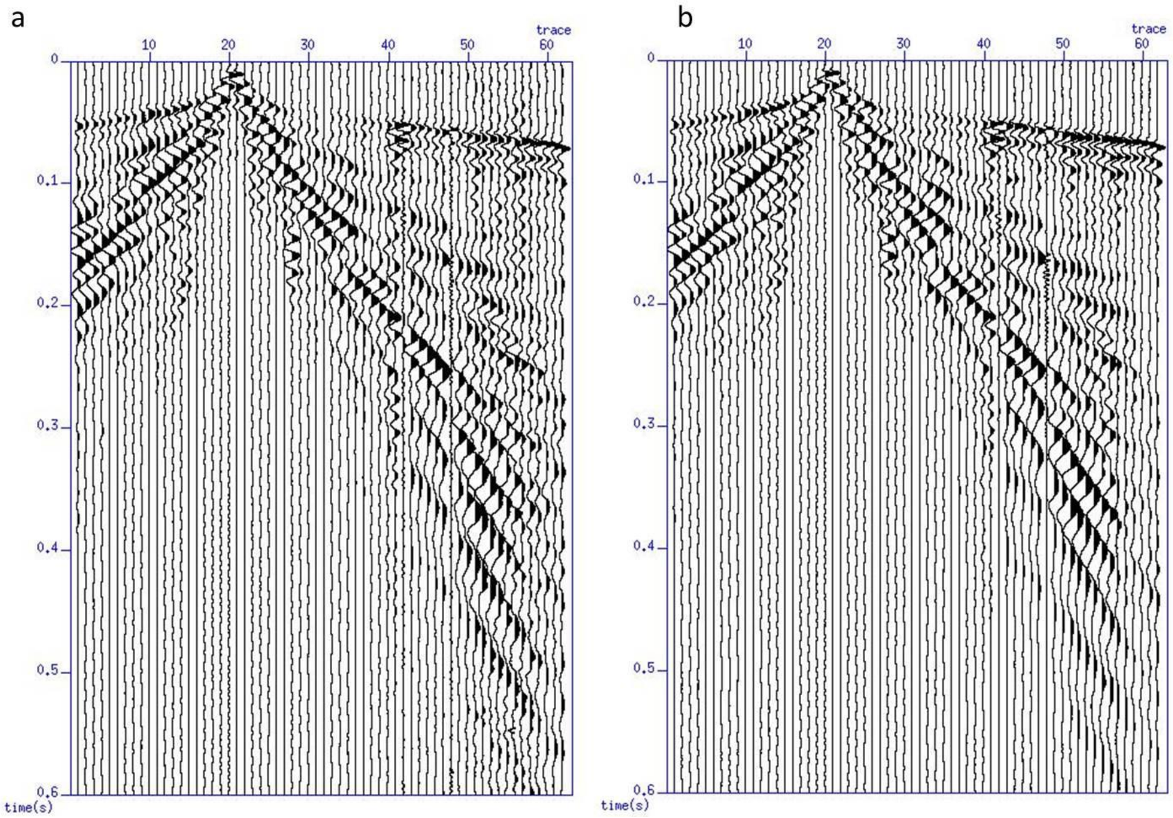

Figure 5. Bigfoot shot records (a) 1 hit and (b) 10 hits.

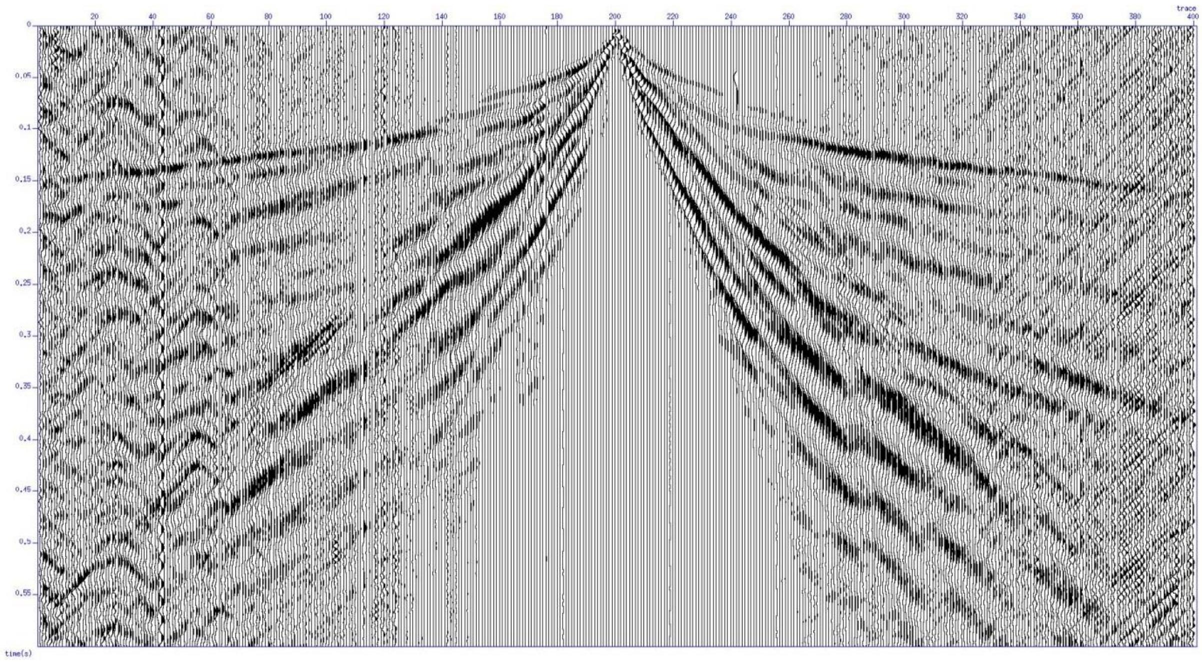

Figure 6. Production Bigfoot shot record, 10 hits.

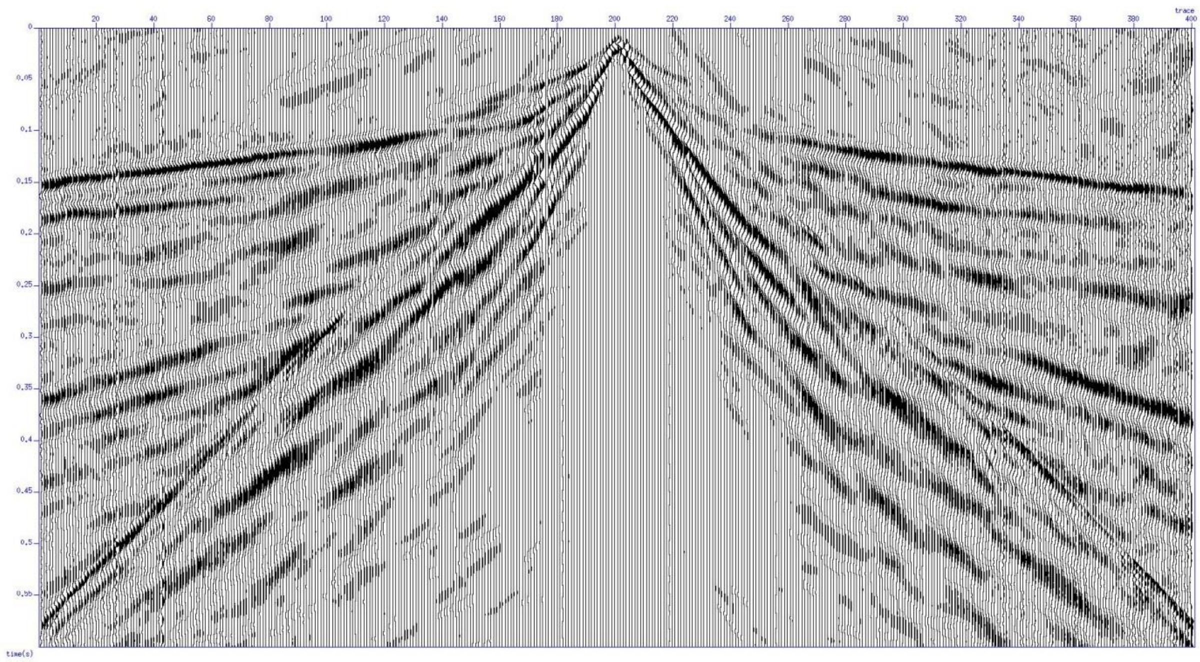

Figure 7. 300 hits Mini-SOSIE.

Pneumatic Vertical Piston

The pneumatic vertical piston (Figure 8 and Figure 9) is a source which uses the accelerated weight-drop concept. The piston is powered using an air-compressor with a holding tank on the back of a service truck. Using this compressed air, a 20kg piston is pushed to the top of the bore. The large hose running to the top of the device is also charged with compressed air to a specified pressure. Using a regulator, this air is released, firing the piston into the ground. A light vehicle is parked on top of the base-plate to increase ground-coupling.

Figure 8. Prototype pneumatic vertical piston (foreground) and shotgun source (background)

Figure 9. Pneumatic vertical piston with light vehicle parked on top. The air-line is shown going back the service truck.

The energy imparted into the ground is quantifiable when the parameters of the system are known. Equation 1 shows the energy which can be calculated from the pressure in the system (Hearn et al., 1991). From this, the force can also be calculated.

$$E = \frac{1}{2} m v^2 = \frac{\pi}{4} P t D^2 \qquad (1)$$

where: m = piston mass (kg)

v = impact velocity (m/s)

P = air pressure (KPa)

t = piston throw (m)

D = piston diameter (m)

Including the effect of gravity, the pneumatic P-wave generator will produce approximately 6.7KN of force at 80psi (~551KPa). Figure 10 shows vertical component shot records acquired during pre-field testing. Figure 10 (a) shows 1 hit and Figure 10 (b) shows 5 hits. As with Bigfoot, the S/N is improved at the far offsets with more hits. In general, the pneumatic piston exhibits lower dominant frequency than Bigfoot (compare Figure 5 and Figure 10).

Although the pneumatic piston has the advantage that the energy in the system can be calculated, moving the prototype pneumatic piston from one shot point to another is not trivial. It requires a truck mounted crane to move it and a second vehicle is required to park on top to improve ground coupling. The compressed air in the holding tank must be replenished every 4-5 shots. These logistical problems could be overcome with engineering effort. However, on this field-trial, the device was not considered technically competitive.

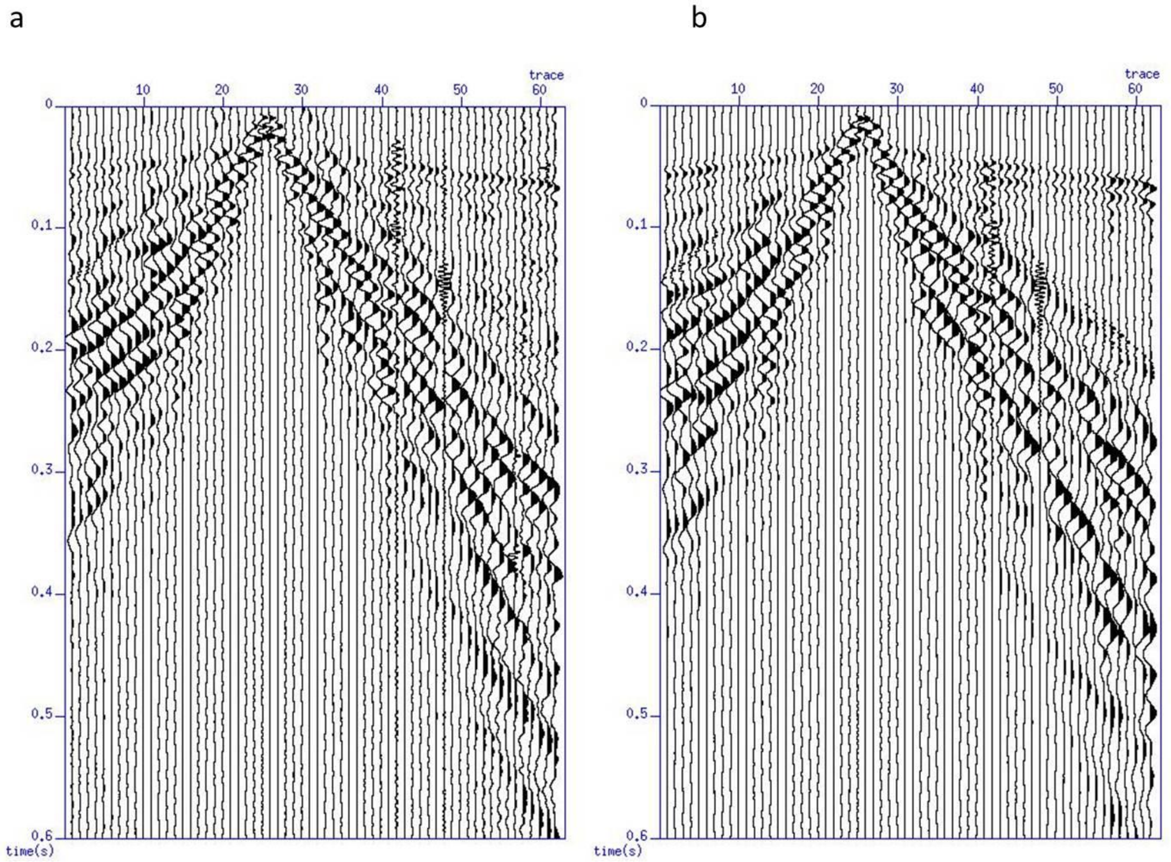

Figure 10. Pneumatic piston shot records (a) 1 hit, (b) 5 hits

Shotgun source

The shotgun source is shown as the long yellow pipe the background of Figure 8. The idea of this source is to inject the energy approximately 30-40cm below the surface of the earth. Form a technical point of view, placing the source below the surface of the earth means that the transmission of energy will be impeded less due to variations in very near-surface soil conditions. This is the same concept as dynamite where the source is placed below the base of weathering so the energy only has to propagate through the absorptive weathering layer once.

The source itself is a blank shotgun cartridge. The size of the source is dictated by the amount of powder in the shell. Testing ranged from 6cc (cubic cm) to 10cc charges. A 2cm wide hole is drilled using a large hammer drill and a long drill bit. The shell is placed in a specially manufactured barrel which is then placed in the ground. A collar consisting of a circular plate is placed over the barrel at ground level to contain the gasses in the ground. The reasoning for this is two-fold. Firstly, to maximise energy penetration, it is desirable to direct the energy into the ground, rather than out of the hole. Secondly, it prevents any material escaping the hole during a shot. The firer then places both feet on the collar to effectively couple the source with the ground. To set off the source, the firing-pin at the top of the barrel is hit with a hammer. This detonates the charge underground and the timing is recorded with an accelerometer mounted on the collar.

From a safety point of view, there are some risks associated with this source. However, these risks have been mitigated via the development of comprehensive risk assessments and task procedures. It is only operated by someone who holds both a current shot firer’s licence and a current firearms licence. A safety pin is built into the top of the barrel which is only removed when a shot is about to be taken and replaced immediately after. When this pin is in place, the firing pin cannot be pushed down.

The records produced are reasonably well defined for a small explosive source, but the S/N is generally relatively low (compare Figure 11 with Figure 6 and Figure 7). In addition, the shotgun source is not repeatable within the same shot location due to the anelastic deformation caused to the surrounding ground when the charge is fired. This is exhibited by the differences in the shot records shown in Figure 11 and Figure 12. Figure 11 shows the first record of a 4cc shot at a given ground location. Figure 12 shows the second record from a 4cc shot at the same ground location. The anelastic deformation caused by the first shot has impacted the ability of the energy contained within the second shot to propagate properly.

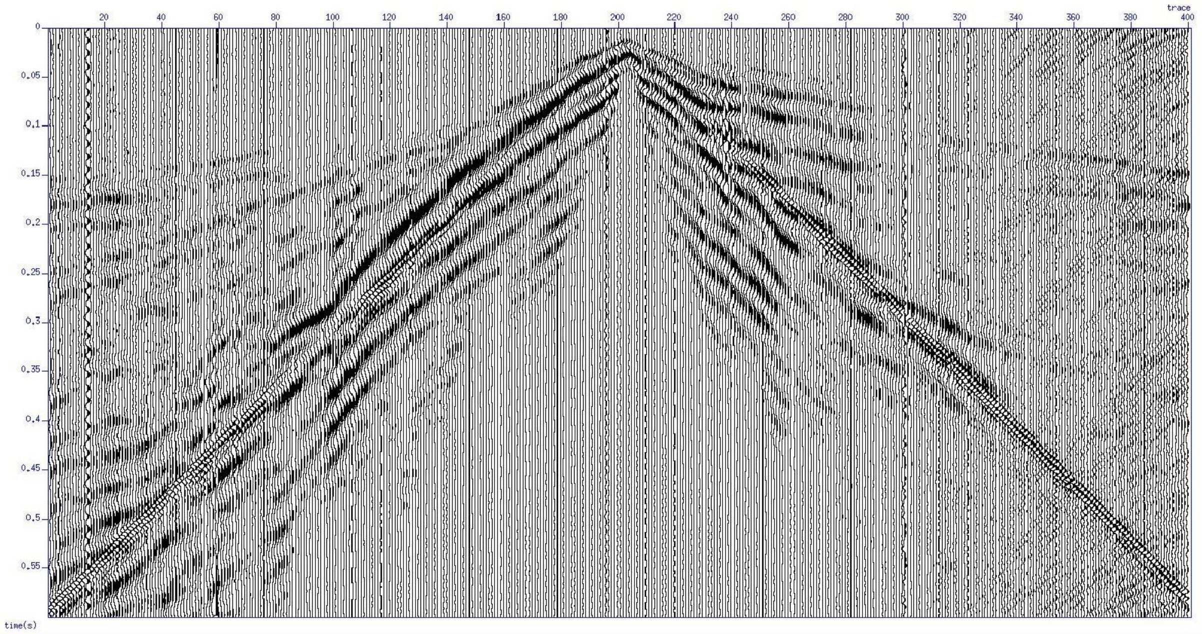

Figure 11. Shotgun source, 4cc, first shot.

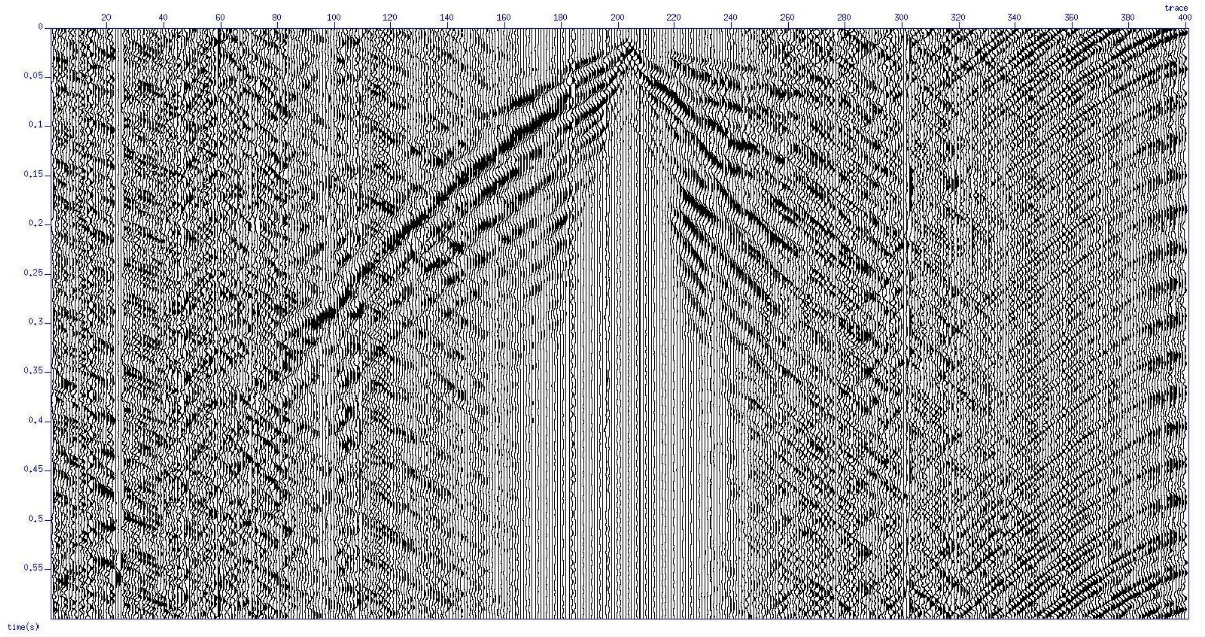

Figure 12. Shotgun source, 4cc, second shot.

Coded-impact sources

The Mini-SOSIE source, widely used for coal-scale seismic work, is an example of a coded-impact source. The basic concept is that a random series of impacts is generated using a portable compactor by varying the engine speed with a throttle. These impacts are stacked to give a record with improved S/N. Mini-SOSIE has a proven record at the coal-scale (50m-500m depth). A trial of a smaller-scale version using a jackhammer was undertaken with the aim of possible improvements for ultra-shallow work.

Jackhammer

The small-scale coded impact source implemented by Velseis involves a 16kg electric jackhammer with a tamping bit attached (Figure 13). Like with Mini-SOSIE, the input signal is randomised using the trigger on the jackhammer. A piezo-electric device is attached to the shaft of the tamping bit to record the input series. This particular source requires 240V for power. In the field, this was powered from the service vehicle via a 2KW DC-AC inverter.

Figure 14 shows a representative shot record acquired using the jackhammer source. Compared to the Mini-SOSIE shot at the same location (Figure 7), the energy penetration is reduced. In pre-production trials, the jackhammer exhibited a broader-band signal than Mini-SOSIE. However in the field, the frequency content was similar.

Figure 13. Jackhammer source. A 15kg electric jackhammer is used with a tamping bit attached.

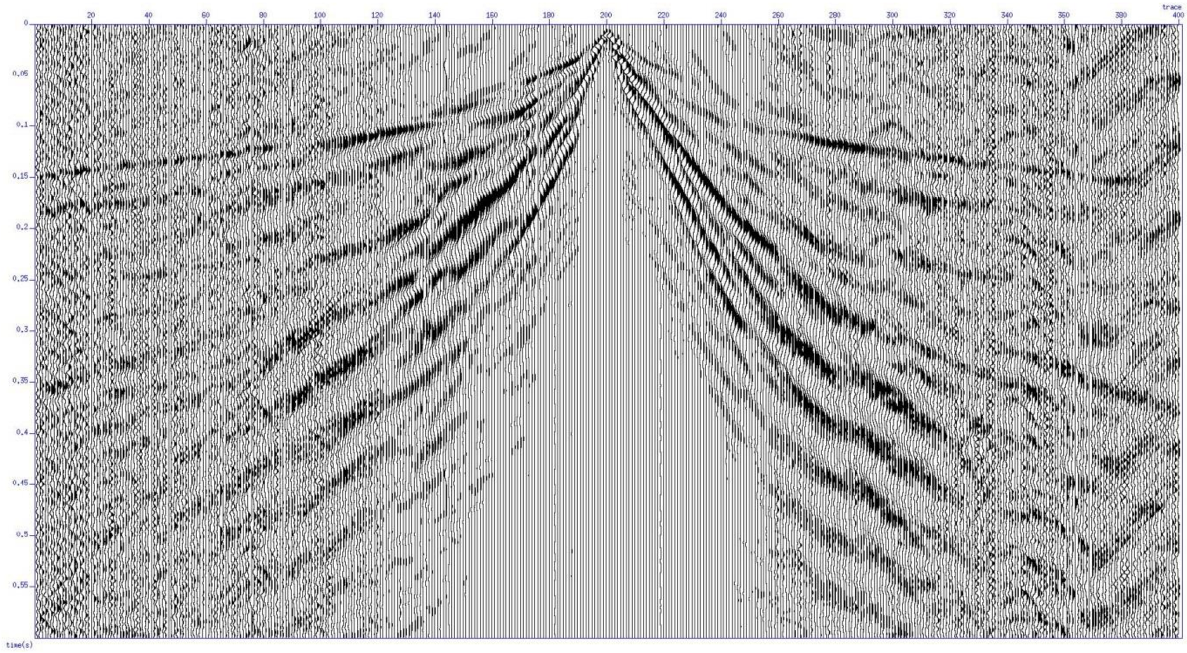

Figure 14. Jackhammer shot record - 200 hits.

Controlled-frequency source

A ubiquitous example of a controlled-frequency seismic source is Vibroseis. The Vibroseis method involves injecting a signal with specific sweep parameters (e.g. frequency range, amplitude, duration, tapering, etc.) into the ground and recording for a specified period of time. Correlating the raw recorded data with the input sweep creates an interpretable shot record. The obvious advantage with the Vibroseis method is that the sweep parameters can be tailored to the ground conditions. This has been used very successfully all over the world for surveys ranging in size from coal-scale to crustal scale.

In the context of the near-surface, however, a Vibroseis vehicles' engine can produce unwanted ambient noise. In addition, the large size of the vibrating plate may smear energy when a small group interval is required. There is an obvious advantage with a controlled-frequency source in the near-surface, namely the ability to control the input signal. Velsies has implemented a prototype small-scale controlled-frequency source called the microvibe. It is based on the design of Pugin et al. (2013) where multiple I-BEAM VT-300 tactile transducers (Figure 15) are mounted to a steel plate. However, rather than mounting the I-BEAMs on top of each other, our I-BEAMs are mounted on the four corners of the plate.

Space is left between the I-BEAMs to park a vehicle on top to increase coupling with the ground. The microvibe source is driven by an aftermarket car amplifier which requires 12V power from a vehicle. Figure 16 shows a prototype of the microvibe source during field testing. This source can be dragged from one shot point to another using a chain welded to the plate.

Figure 15. I-BEAM VT-300 tactile transducer (audiholics.com).

Figure 16. Microvibe setup including vibe plate with two I-BEAMS visible. The sweep control laptop is on the passenger seat.

Conventional Vibroseis systems mostly use frequency-sweeps as the source signal. These sweep from an initial frequency to a final frequency, generally via a monotonically increasing function (Figure 17 blue).

Figure 18 shows a correlated record from a linear sweep (10s, 40-250Hz). This record is quite ringy. An analysis of the uncorrelated records showed that the phase of the microvibe was dependent on frequency and therefore varied with time. This leads to errors during the correlation and consequently ringing in the correlated records.

In conventional Vibroseis the phase issue is overcome by hardware that monitors the phase in real-time and adjusts it accordingly. This has not yet been implemented for the microvibe but is a future recommendation.

An alternative type of Vibroseis signal is the pseudo-random sweep (e.g. Cunningham, 1979). This employs a reference sweep built from a sinusoidal carrier signal of constant frequency, and polarity flips are applied according to a pseudo-random binary sequence (Strong and Hearn, 2004) (Figure 17 red). The spectrum of the correlated pseudo-random sweep has frequency content from zero to twice the carrier frequency. However, the energy is not evenly distributed, with the maximum being near the carrier frequency and decaying away from this point.

Figure 19 shows a correlated record generated by using three separate carrier frequencies and binary sequences (60, 90, and 150Hz). These were chosen to give a flatter spectrum which would be comparable to the linear sweep. The pseudo-random record (Figure 19) is much less ringy than the linear sweep (Figure 18). This is due to the choice of carrier frequencies which produce no time dependent phase variation. The promising results obtained here suggest that this source warrants further investigations.

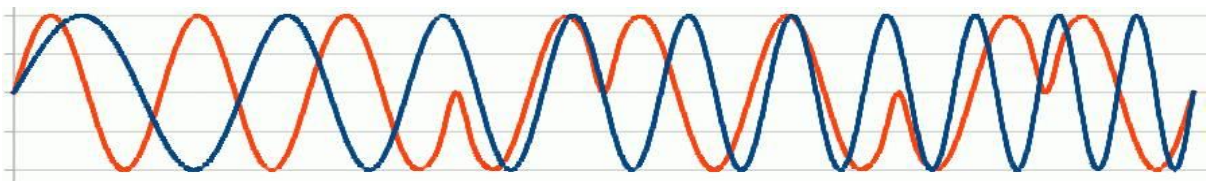

Figure 17. Comparison of conventional linear increasing sweep (blue) with speudo-random sweep (red). Only a short segment (~0.1s) of a full sweep is shown.

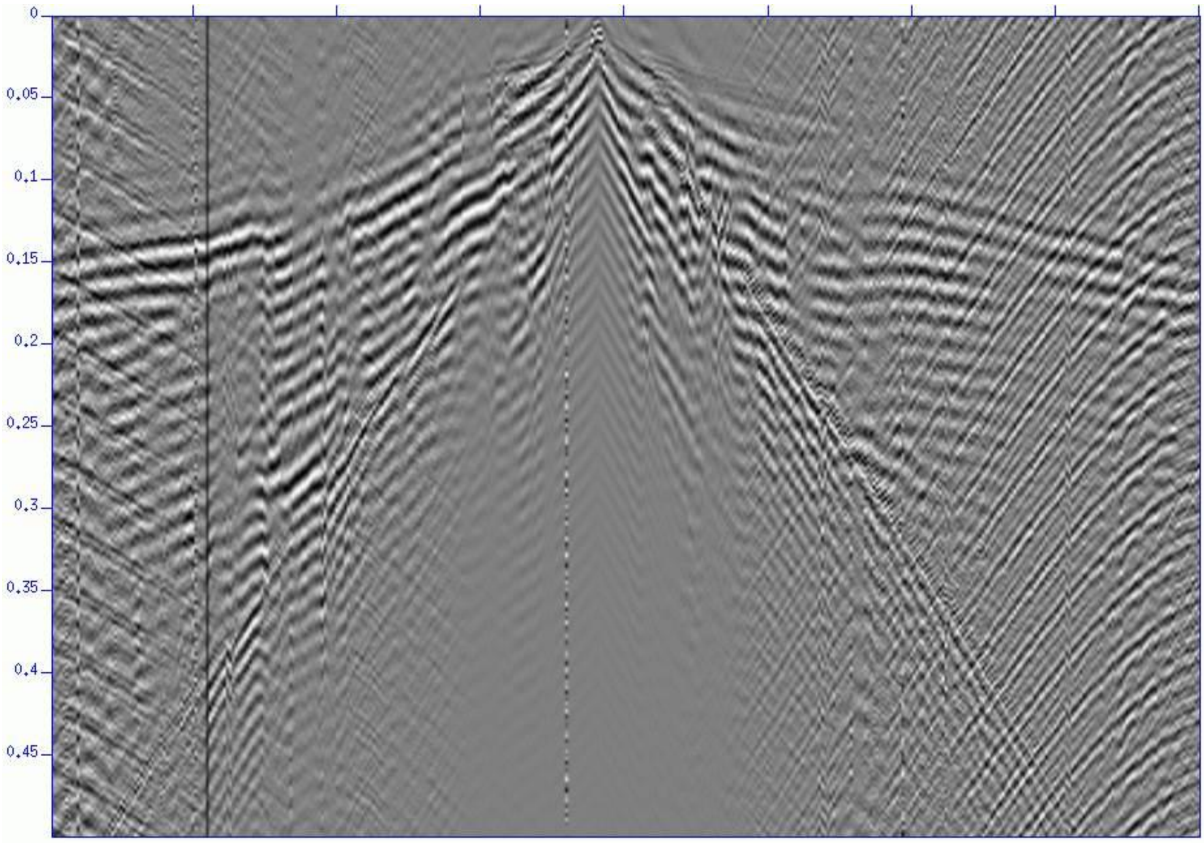

Figure 18. Microvibe sweep. Linear correalted sweep, 40-250Hz, 10s.

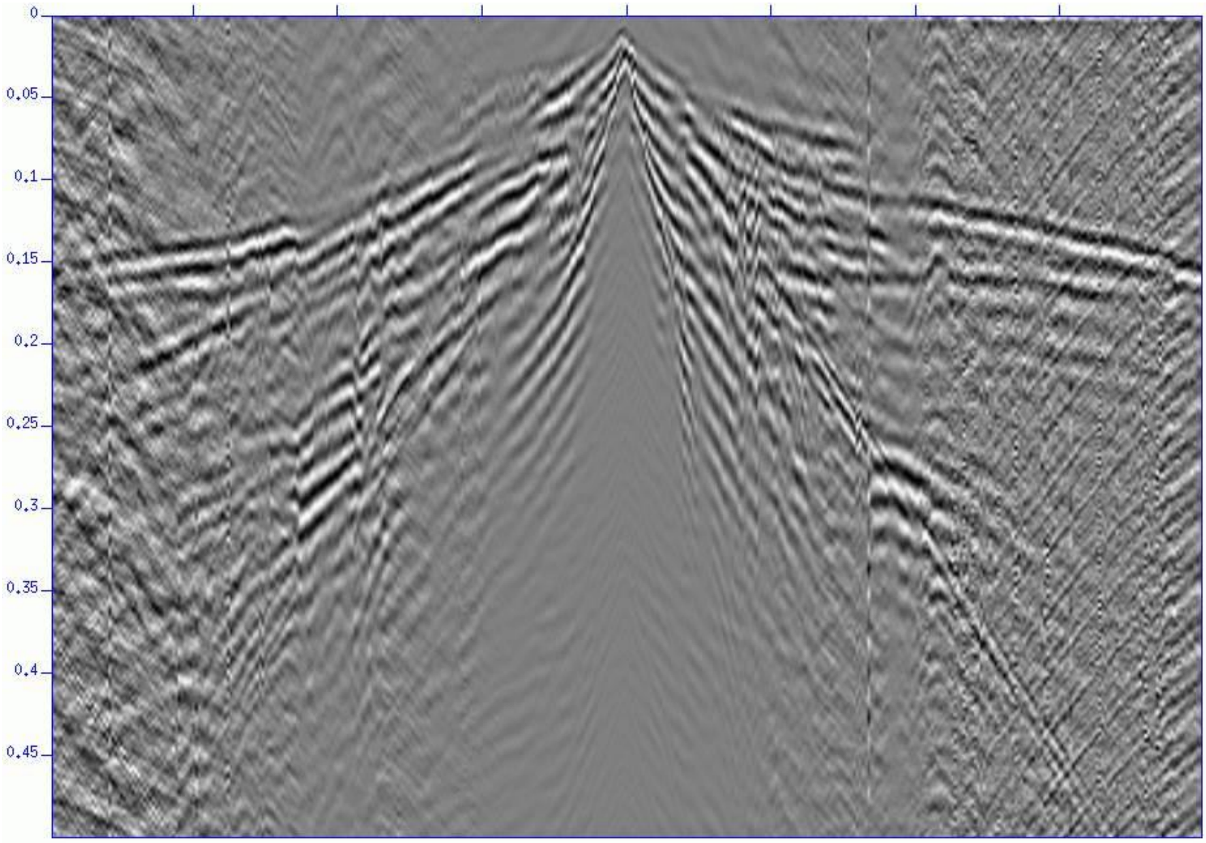

Figure 19. Combined pseudo-random record, generated by stacking three pseudo-random sweeps with carrier frequencies of 60Hz, 90Hz and 150Hz.

S-wave source

To generate a shear-wave at the surface, the ground needs to be deformed in a horizontal direction, i.e. parallel with the surface of the earth. A shear-wave source can be as simple as hitting a railway sleeper with a sledge hammer at one end or the other. A vehicle is commonly parked on top of the sleeper to increase coupling with the ground. However, from a health and safety perspective, it is desirable to remove manual handling of the sledge hammer from the system.

The S-wave source tested here achieves this by using a pneumatic piston, similar to the vertical piston. However, the piston is oriented horizontally, rather than vertically. Figure 20 shows a front-view of the shear-wave generator with a vehicle parked on top to increase coupling with the ground. Figure 21 shows the pneumatic control unit on the back of the service vehicle.

Figure 20. Pneumatic shear-wave generator.

Figure 21. Pneumatic shear-wave generator.

For shear-wave surveying, this source is oriented in the crossline direction and the piston is fired both ways at least once per shot point. Subtracting the shot records from opposite directions cancels out much of the unwanted P-wave noise, while enhancing the desired S-wave signal. The pneumatic shear-wave generator offers the same technical and logistical advantages and disadvantages as the pneumatic vertical piston.

Figure 22 and Figure 23 show two crossline component shot records acquired at the same ground location but from the source fired in opposite directions. The desired energy is on the crossline component. Because the energy is fired from opposite directions, the polarity of the two crossline component shot records is reversed. This is demonstrated by the event at approximately trace 130 (offset 120m), time 0.3s on Figure 23 where the polarity is positive. On Figure 22, the same event is negative.

This event represents the refraction off the base of weathering. Compare this to e.g. Figure 6 where the same event at the same offset (trace 320) appears at time~0.15s. This demonstrates the slower propagation velocity of S-waves and their projection later in time on shot records. As mentioned earlier, this means that S-wave reflections tend to be better separated from surface noise. S-wave reflection imagery from this survey have been published in Strong (2015).

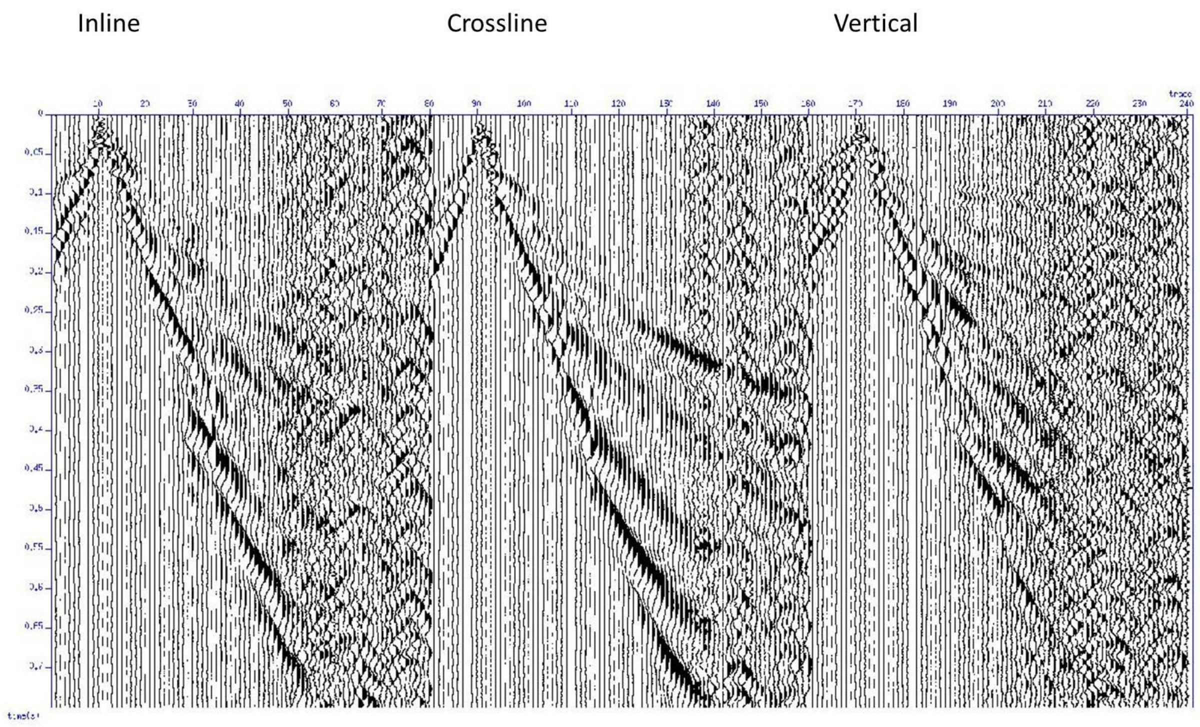

Figure 22. Crossline 3C shot record acquired during production survey.

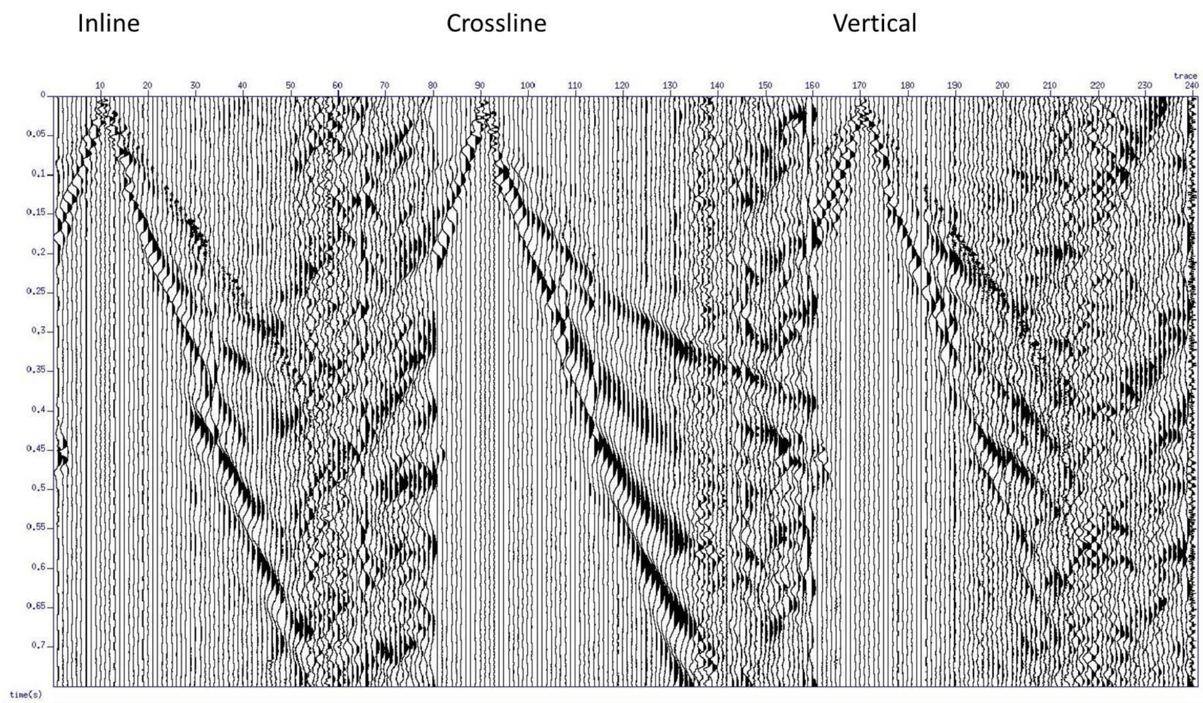

Figure 23. Crossline 3C shot record acquired as part of production survey.

PROCESSING

Processing of ultra-shallow P-wave data, converted-wave or S-wave data can be more challenging than processing larger-scale seismic data in many circumstances (e.g. Steeples, 1998; Steeples and Miller, 1998). One of the major reasons relates to the physical properties of the near-surface, particularly in Australian Basins where the weathering layer is deep. However, the additional information gathered from these different surveys enables a fuller image of the near-surface to be developed. V_P/V_S ratios can provide information relating to rock properties (e.g. rock strength, Poisson's Ratio, Young's Modulus). The multi-channel analysis of surface waves (MASW) technique, which analyses the dispersive properties of surface-waves, requires broadband recording as well as tight spatial sampling. The success of processing a near-surface dataset is contingent not only on the survey design but the types of sources used.

CONCLUSIONS

Velseis has implemented and tested several P- and S-wave sources for use in the near-surface environment. Preliminary tests suggested the preferred P-wave sources were Mini-SOSIE, Bigfoot and jackhammer. Comparisons between these sources at specified intervals along the production line showed that Mini-SOSIE possesses the optimum combination of signal penetration and bandwidth for the ground locations tested. For this particular survey, Bigfoot offered the simplest option in terms of logistics. The pneumatic S-wave source was successfully used for the production S-wave survey.

These sources have been used for production work in the Surat Basin but would be equally applicable for use in the Bowen Basin.

ACKNOWLEDGEMENTS

The authors would like to thank Steve Hearn for his technical advice and John McMonagle for observing the acquisition of the data.

REFERENCES

Cunningham, A.B., 1979, Some alternative vibrator signals: *Geophysics*, **44**, pp1901-1921.

Garotta, R., 2000, Shear waves from acquisition to interpretation: SEG Distinguished Instructor Short Course, 3, Society of Exploration Geophysicists, Tulsa, OK.

Hearn, S., Kay, M., Dixon, O., 1991, Evaluation of P- and S-wave sources for shallow seismic reflection: *Exploration Geophysics*, **22**, pp169-174.

Meulenbroek, A., 2015, Integrated reflection and refraction processing of an ultra-shallow seismic survey: Extended Abstract, 24th ASEG conference and exhibition, Perth.

O'Brien, P.N.S., 1960, Seismic energy from explosions: *Geophysical Journal of The Royal Astronomical Society*, **3**, pp29-44.

Peet, W.E., 1960, A shock wave theory for the generation of the seismic signal around a spherical shot hole: *Geophysical Prospecting*, **8**, pp509-533.

Pugin, A., Brewer, K., Cartwright, T., Pullan, S., Didier, P., Crow, H., Hunter, J., 2013, Near-surface S-wave seismic reflection profiling – new approaches and insights: *First Break*, **31**, pp49-60.

Steeples, D,W., 1998, Shallow seismic reflection section – Introduction: *Geophysics*, **63**, pp1210-1212.

Steeples, D.W., Miller, R.D., 1998, Avoiding pitfalls in shallow seismic reflection surveys: *Geophysics*, **63**, pp1213-1224.

Strong, S., 2015, Can near-surface velocity structure be improved via dispersion analysis of conventional reflection data? Extended Abstracts, 24th ASEG conference and exhibition, Perth.

Strong, S., Hearn, S., 2004, Numerical modelling of pseudo-random land seismic sources: Extended Abstracts, 17th ASEG conference and exhibition, Sydney.