PS Logger®

Enhanced P- and S- Wave Acquisition Using a Dual-Sensor Hydrophone-Geophone Architecture

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Engineering Technical Review
ETR-PSL-003

Executive summary

This report demonstrates why integrated hydrophone and geophone acquisition within the PS Logger® delivers measurably superior seismic data quality compared to single-receiver systems, particularly in offshore environments.

The physical basis for the tool is briefly laid out in terms of seismic source and relevant wave dynamics and related back to receiver-type, thereby describing the method by which the dual-receiver system allows for separate P-wave and S-wave recording channels from the hydrophones and geophones, respectively. The receivers are considered in terms of their sensitivity to different sources of noise with a focus on their use offshore, where low-frequency noise often renders single-receiver data unusable.

Case studies are used to illustrate some of the impediments to seismic data collection using single-receiver (geophone-only) tools, highlighting the merits of the dual-receiver system (specifically with regard to obtaining P-wave velocity measurements): increasing data quality and yield, reducing interpretation time, improving confidence in derived velocity profiles and enhancing overall operational efficiency. The presented case studies demonstrate that, while geophone-only systems can deliver acceptable P-wave measurements under ideal conditions, offshore environments frequently introduce low-frequency and platform-related noise that significantly degrades geophone signal quality. In such settings, hydrophones are essential to reliably capture compressional (P-wave) arrivals due to their relative insensitivity to these noise sources. Indeed, in some scenarios, acquisition of usable P-wave velocity data may even be impossible without a hydrophone channel.

Even where geophone-derived P-wave velocities are technically obtainable, the associated data quality metrics are often inferior, reducing confidence in velocity measurements and necessitating additional processing effort to mitigate signal contamination. By contrast, hydrophone data consistently exhibit higher clarity and stability, enabling more straightforward velocity determination and reducing the need for manual intervention. The hydrophone channel is also inherently more compatible with automated picking algorithms, supporting faster, more repeatable processing workflows.

Overall, the integrated use of geophones and hydrophones within the PS Logger® represents a technically robust and operationally efficient solution for offshore seismic data acquisition, delivering higher data quality, improved reliability, and greater confidence in both P-wave and S-wave velocity measurements compared with geophone-only systems.

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Contents

1 Overview

This document briefly summarises the relevant physics and lays out the advantages of the combined geophone/hydrophone receiver system.

2 Seismic source

Traditional borehole tools using combined source and receiver configurations (sondes) relied on a straightforward monopole tool, emitting a radial pressure pulse within a fluid-filled borehole, allowing measurement of compressional and shear velocities. In slow formations (e.g. where the formation shear velocity is less than the fluid compressional velocity), monopole sources fail to generate a refracted shear wave, prohibiting measurement of shear velocity. Dipole sources address this by inducing the flexural mode in the borehole, which travels at the formation shear velocity (although not technically a shear wave), and therefore can be used to measure compressional and shear velocities in fast or slow formations.

The dipole source works as follows: a hammer hits the internal wall of a steel cylinder, generating a positive pressure field on the struck side, and a negative pressure field on the opposite side. For a perfect dipole, this change is perfectly simultaneous, and the opposing pressure changes are exactly opposite magnitudes. In practice, it is impossible to create a perfect dipole – there is a momentary imbalance before the non-struck side catches up with the struck side (Figure 1). This momentary imbalance generates a monopole in the borehole fluid, i.e. a radially equal pressure field. As such, the PS Logger® has both monopole and dipole source components, with distinct frequency spectra, i.e. the ranges of frequency of vibration they cause of the borehole wall are different: the dipole causes relatively low-frequency movement (1 to 2kHz) compared to the monopole component (up to 10s of kHz).

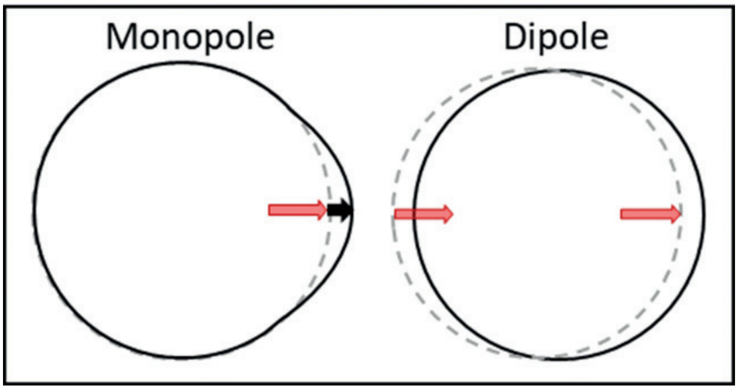

Figure 1 – Illustration of monopole and dipole source components.

3 Wave propagation and measurement

Geophones within the PS Logger® are specially configured to register lateral movement of the borehole wall, i.e. side-to-side displacement. Hydrophones are sensitive to pressure changes in the borehole fluid.

Consider a slow formation (therefore we can ignore refracted S-waves) and idealised conditions (perfect radial symmetry of the borehole, perfect tool alignment, formation homogeneity):

1. *Monopole-induced P-wave:* the initial monopole causes a radially-symmetrical compressional fluid wave to strike the borehole wall, generating refracted P-waves which travel up and down the borehole wall. The pressure field is radially symmetrical – this means that the propagating waves would register clearly on a hydrophone but not on a geophone. The measured frequency will be a result of the (relatively high) monopole source frequency spectrum and the borehole/formation conditions. If the hammer direction is reversed, the hydrophone-measured signal is identical.

2. *Dipole-induced P-wave:* the subsequent dipole also generates P-waves but these have a radially-asymmetrical pressure field: if there is a positive pressure on one side of the borehole, there is a negative pressure on the other side of the borehole. There will be slight displacement of the borehole fluid as a result of volumetric expansion/contraction, equal and opposite between two the sides, therefore, a small signal will register on a geophone but not on a hydrophone. The measured frequency will be a result of the (relatively low) dipole source frequency spectrum and the borehole/formation conditions, with a relatively low amplitude. If the hammer direction is reversed, the geophone-measured signal is mirror-imaged.

3. *Dipole-induced flexural wave:* Additionally, the dipole excites the flexural mode, “bending” the borehole. There will be a significant lateral movement of the borehole wall, and hence of the borehole fluid, equal and opposite between the two sides, therefore, a large signal will register on a geophone but not on a hydrophone. The measured frequency will be a result of the (relatively low) dipole source frequency spectrum and the borehole/formation conditions, with a relatively high amplitude. If the hammer direction is reversed, the geophone-measured signal is mirror-imaged.

It is important to note that the amount of compressional energy resulting from the monopole component is significantly larger than that of the dipole component: the monopole source produces volumetric compression, resulting in effective transmission of energy directly into P-waves; the dipole source produces shear motion, primarily transferring energy to S (flexural) -waves, where P-waves are a secondary effect, receiving much less energy. Therefore, monopole-induced P-waves are much stronger than dipole-induced P-waves, which are registered by the hydrophones and geophones, respectively. As such, the hydrophone channel allows much clearer recording of P-wave signal than the geophone channel. Note, because the monopole component of the source is triggered first, the monopole-induced P-wave arrives just before the dipole-induced P-wave, although both travel at the same velocity. By reversing the direction of the hammer within the seismic source, the directionality of the pressure fields is also reversed.

In practice, idealised conditions never apply, and there will frequently be some cross-over registered between the P/hydrophone and S (flexural)/geophone channels, however, the sensors are not optimally configured to measure this cross-over. Additionally, **the descriptions of relative amplitude of the recorded signals on the geophone receiver are indicative only**: in some formations, dipole-induced flexural motion will be more strongly attenuated than dipole-induced compressional motion, leading to the dipole-induced P-wave having a greater amplitude on the geophone than the flexural wave even though the flexural wave has more initial energy.

4 Geophones versus hydrophones

4.1 Configuration

Geophones are composed of a magnet housed within a coil. When subject to vibration, relative movement between the magnet and the coil generates a proportional voltage (the signal). Within the PS Logger®, the near and far geophones are specially configured to register lateral movement of the borehole wall.

Hydrophones are made from piezoelectric material, which generate a voltage when subjected to pressure variations. Within the PS Logger®, the near and far hydrophones are sensitive to pressure changes in the borehole fluid, resulting from infinitesimal radial contraction/expansion of the borehole.

Table 1 – Wave types and their sensitive receivers (idealised conditions)

Wave type	Borehole deformation type	Hydrophone	Geophone
Monopole P-wave	Radially symmetrical contraction/expansion	✔	X
Dipole P-wave	Radially asymmetrical: contraction of the borehole on one side, expansion on the other	X	✔
Dipole S (flexural)-wave	Lateral movement	X	✔

4.2 Sensitivity

The sensitivity of the geophones and hydrophones to excitation is a function of:

a) the type of movement registered;
b) the natural mechanical response of the individual components to vibration;
c) the bandpass filters applied to the recorded signals.

Table 1 shows that the hydrophone and geophone receivers are optimally designed to register the monopole and dipole signal components respectively, and given that these components have distinct frequency spectra, the two receiver types have different fundamental natural responses (Figure 2), and different applied bandpass filters (Figure 3). Figure 2 shows that the natural response of the hydrophone component is approximately five times higher than that of the geophone component, which corresponds to the range of source frequencies given in section 1. These natural responses are supplemented by bandpass filters implemented within the system electronics resulting in unique responses of the two receiver types to excitation. From Figure 3 it can be seen that the geophone receivers are more sensitive to offshore noise frequencies.

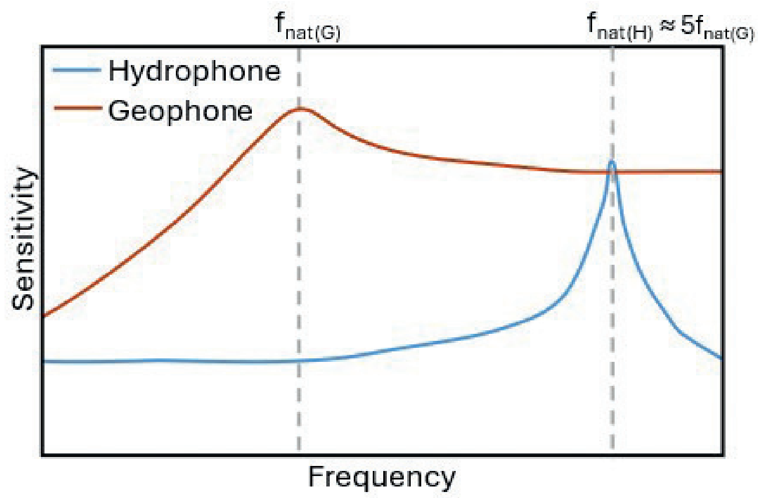

Figure 2 – Natural response of receiver components. Note, actual values obscured for retention of proprietary information.

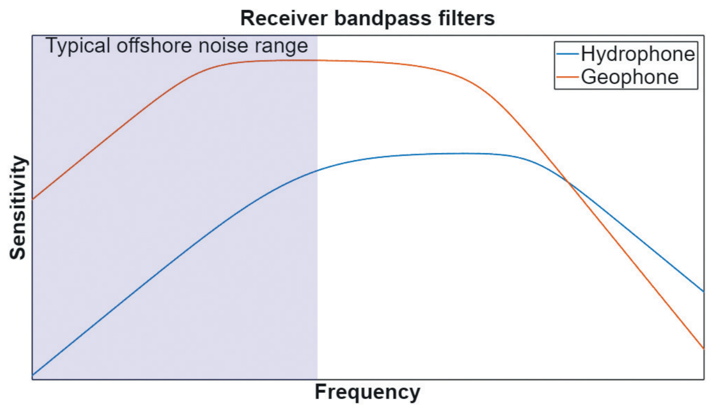

Figure 3 – Bandpass filters applied to different receiver types. Note, actual values obscured for retention of proprietary information.

5 Data overview

In the following section, PS Logger® data are presented in the context of P-wave velocity measurement. Six channels of data are presented: geophone left near, geophone right near, geophone left far, geophone right far, hydrophone near, hydrophone far. The data illustrate the practical manifestation of the theoretical wave dynamics explained in section 3, and highlight issues regarding data collection using diverse examples. Where appropriate, picked arrivals are shown, distinguishing between the different wave-types.

5.1 Textbook data

Figure 4 illustrates high-quality data capture from the PS Logger®, fitting the description in section 3 and in Table 1, showing the dipole-induced P-wave arrival (dash-dot line), with low amplitude compared to the dipole-induced shear (flexural) arrival (dotted line), on both the near and far geophone channels. The monopole-induced P-wave arrival is clear on the near and far hydrophone channels (dashed line) and arrives slightly earlier than the dipole-induced P-wave. Fourier analysis shows the dipole-induced P-wave to oscillate near the dipole source centre frequency (indicating approximately 1.4kHz), whereas the flexural wave is oscillating at a much lower frequency (approx. 0.5kHz), and the monopole-induced P-wave in the range of 8 – 12kHz. In the example shown, velocities are V_S = 222m/s, $V_{p(dip)}$ = $V_{p(mono)}$ = 1563m/s. The observed offset in P-wave arrival time between the different types (monopole and dipole) is 0.2ms. In this example, given the clear separation between dipole-P and shear (flexural) signals on the geophone, and the lack of noise, both the geophone and hydrophone -obtained signals yield clear P-wave arrivals.

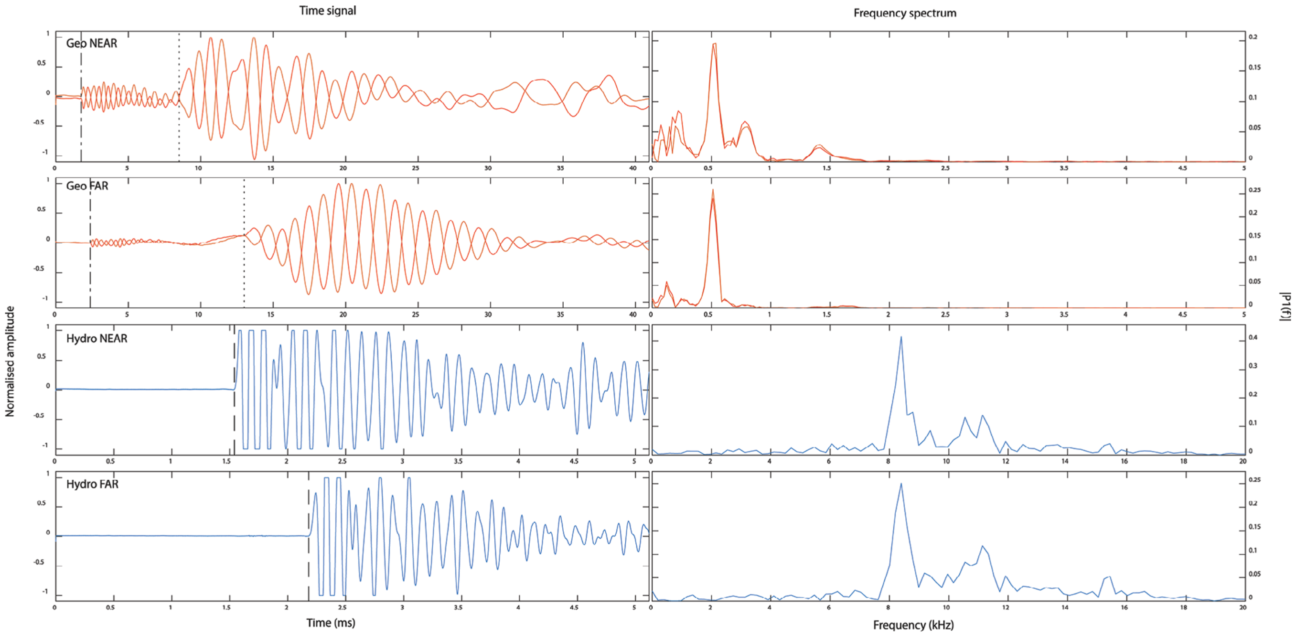

Figure 4 - High-quality PS Logger® data and accompanying Fourier analysis. Dash-dot line = dipole-P arrival; dotted line = shear (flexural) arrival; dashed line = monopole-P arrival.

5.2 Low dipole-P amplitude

Figure 5 illustrates very low recorded amplitude of dipole-induced P-wave, such that it is very difficult to accurately identify the onset of the P-wave from the geophone channel. On the hydrophone channel, monopole P-wave signal is of high amplitude, resulting in unambiguous P-arrivals on both the near and far channels. Flexural wave arrival times are clear from both geophone channels. In this example, recorded velocities are V_S = 472m/s, $V_{p(mono)}$ = 1810m/s.

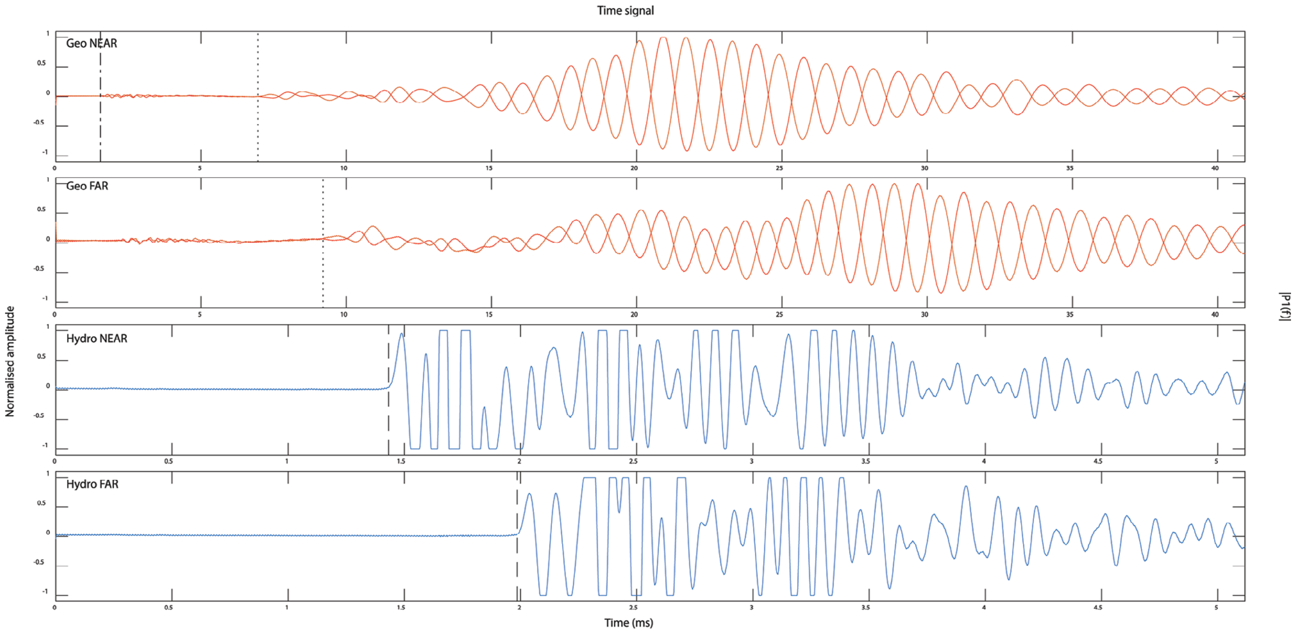

Figure 5 – PS Logger® data showing low dipole P-wave amplitude on geophones. Dash-dot line = dipole-P arrival; dotted line = shear (flexural) arrival; dashed line = monopole-P arrival.

Although the gains could be increased, the closeup of the geophone channels shown in Figure 6 shows that dipole P-wave signal is of such low amplitude that the P-wave arrival cannot be accurately identified on the far trace, further obscured by the presence of low amplitude noise on the trace, and poor reversals between left and right hammer shots on the far geophone channel.

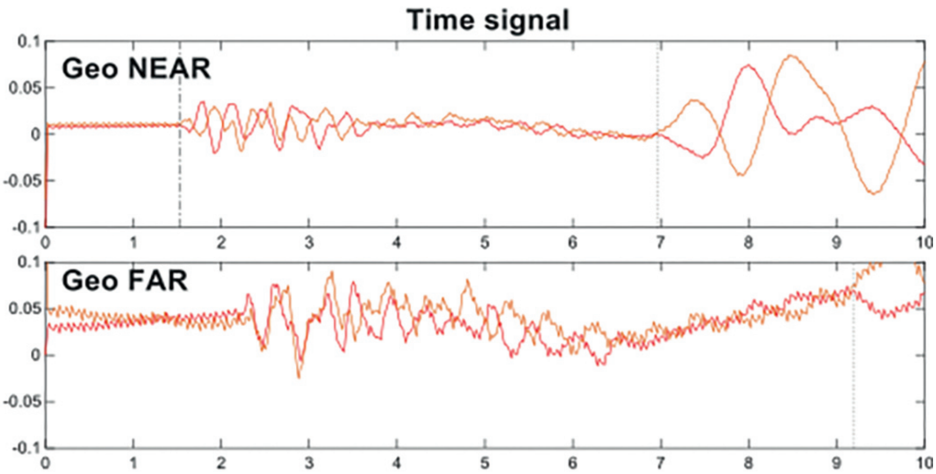

Figure 6 – Closeup of near and far geophone channels. The first peak/trough (dipole P-wave) cannot be accurately identified from the far geophone channel due to noise and poor reversal between left and right hammer shots. Dash-dot line = dipole-P arrival; dotted line = shear (flexural) arrival; dashed line = monopole-P arrival.

5.3 Overlapping signals

The following example (Figure 7) illustrates poor separation between signals on the near geophone, which, combined with a broad first peak, makes it difficult to identify the onset of the dipole P-wave on the near geophone, whereas the monopole P-wave onset is clear from both hydrophone channels as the point of first deflection. Here, V_S = 1471m/s, $V_{p(mono)}$ = 2778m/s.

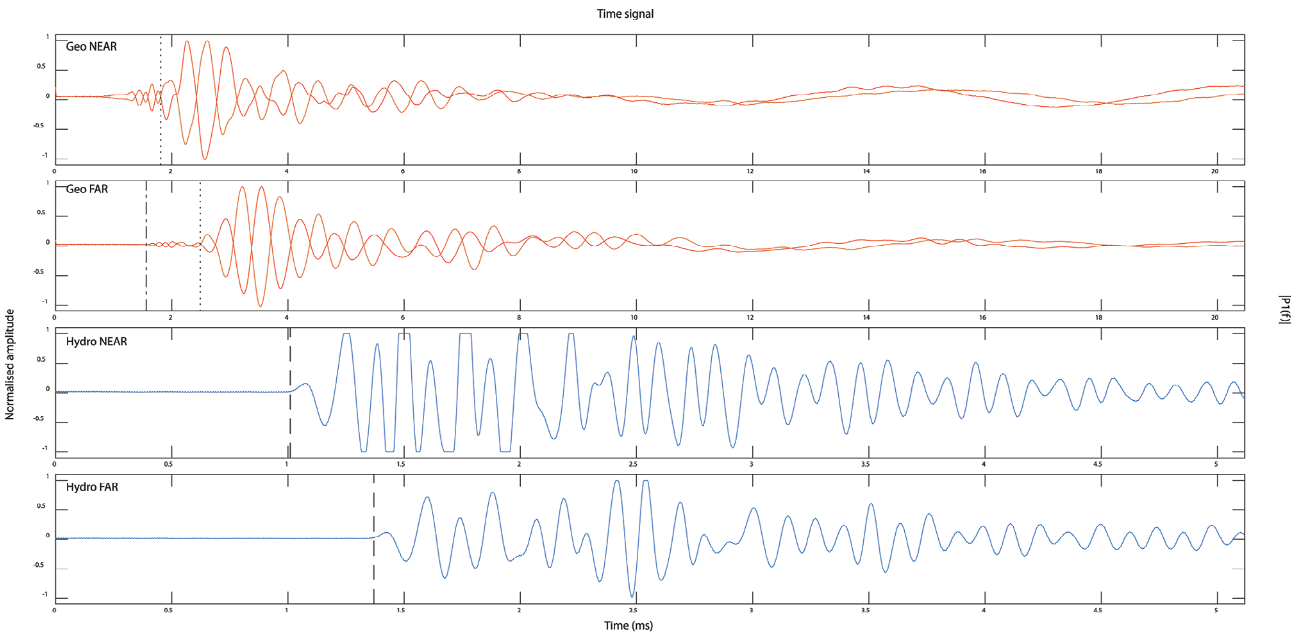

Figure 7 – PS Logger® data showing overlapping dipole P-wave and shear (flexural) wave signals on the geophones. Dash-dot line = dipole-P arrival; dotted line = shear (flexural arrival); dashed line = monopole-P arrival.

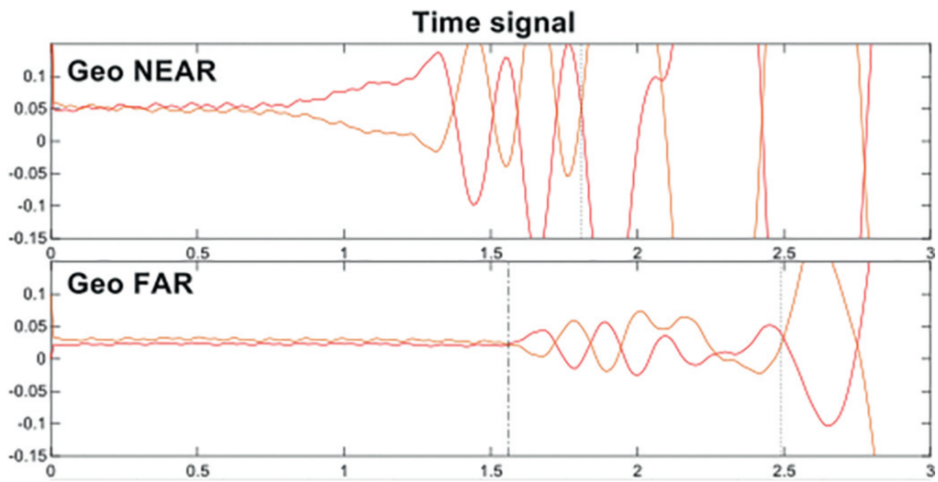

Figure 8 – Closeup of near and far geophone channels. The first peak is broad, and it is not clear where the point of first deflection lies. Dash-dot line = dipole-P arrival; dotted line = shear (flexural) arrival.

The use of a 2m filter tube rather than a 1m filter tube would separate out the dipole-P and flexural signals on the geophone, however, this usually impacts signal-to-noise ratio (SNR) which, given the low dipole P-wave amplitude would likely result in the dipole P-wave signal being lost.

5.4 Noisy signal

The most significant issue affecting the use of geophones to infer P-wave velocity is their sensitivity to noise. Signal amplitude (and hence SNR) is key to obtaining useable data. Multiple sources of noise affect the PS Logger®, which may be either ambient or transient, as detailed in Table 2, which highlights the fact that in offshore environments noise mitigation measures are limited.

Table 2 – Sources of noise affecting PS Logger® data

	Ambient		
Environment	**Source**	**Impact on data**	**Mitigation**
Land	General environmental background	Generally insignificant	Not required
Offshore	Vibration from generators, engines, air-conditioning and other motorised devices onboard. The noise can propagate to the probe via the winch cable directly, through platform legs, through metal casing or be transmitted through a drill ship hull directly to the seabed	Significant	Drill ship: not possible Jack-up: non-essential motors can be switched off
	On drill ships vibrations from thrusters and propellers which are used to maintain position. This propagates through the sea layer directly to the seabed	Significant	Not possible
	Noise from waves striking the borehole casing. Where two or more layers of casing are deployed impacts can also occur between them	Significant	Not possible
	Wind noise on the winch cable where it runs over the sheave wheel can vibrate the probe in the borehole. The resulting noise is-low frequency and high-amplitude	Significant	Temporarily tying off the cable to isolate the down hole section
	Transient		
Land	Traffic (moving vehicles or idling engines)	Significant	Minimise traffic as much as possible
Offshore	Shipping passing the borehole can produce strong low frequency noise from its propellers. This can happen at distances of a kilometre or more depending upon the size of the ship and local seabed factors	Significant	Wait until ship has passed. Keep repeating shots until clean data are obtained
	Concurrent operations on platforms and drill ships can produce transient noise in the data. Operations such as stacking drill pipes, craning equipment about the drill deck or repairs involving hammering	Significant	Activities should be controlled as much as possible. Keep repeating shots until clean data are obtained

The following examples illustrate sensitivity of the geophones to external noise obscuring the dipole-P arrival, usually worst on the far receiver due to reduced SNR; monopole-P arrival is clear from the hydrophone channels.

5.4.1 Low-frequency noise

The example shown in Figure 9 highlights some of the issues of logging in slow, unconsolidated offshore materials. On the near geophone channel, the dipole P-wave arrival (oscillating at approx. 1.5kHz) and shear (flexural) arrival (0.5kHz) are relatively clear, however, on the far geophone channel, the presence of low-frequency noise (under 0.5kHz) makes it impossible to resolve either arrival. The frequency spectrum of the far geophone shows very little signal at 1.5kHz, indicating that the dipole-P signal amplitude is extremely low. The monopole P-wave arrivals are clear from the hydrophone channels as the point of first deflection, yielding $V_{p(mono)}$ = 1869m/s.

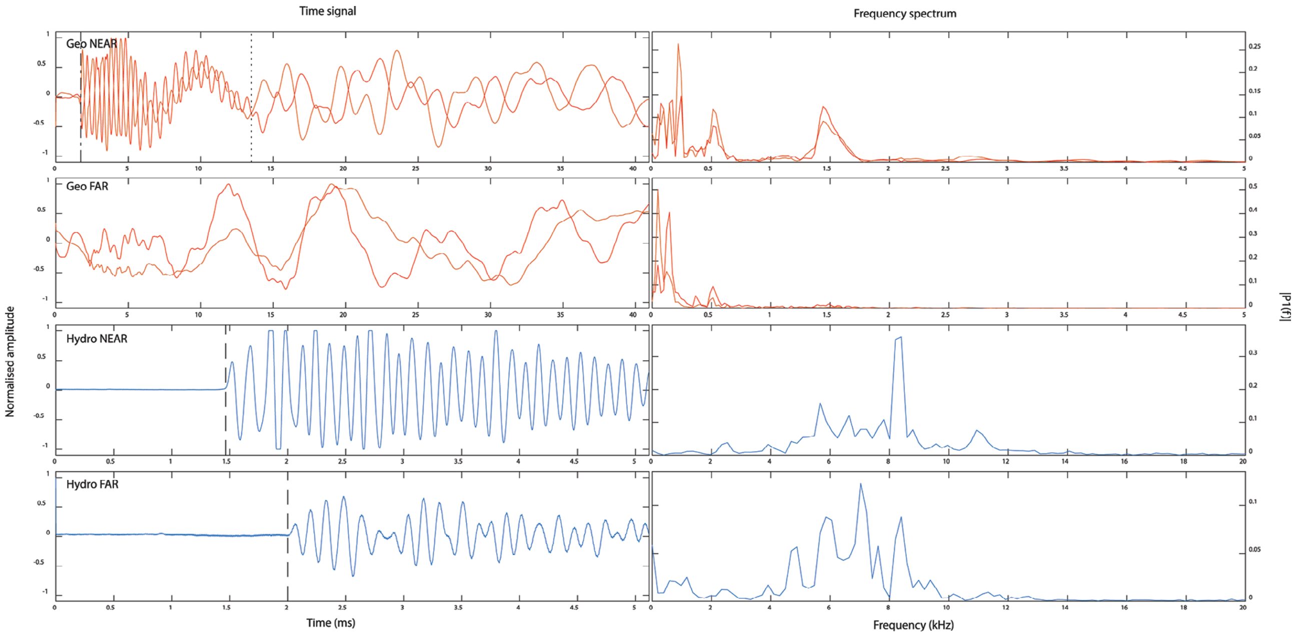

Figure 9 – PS logger data example show low-frequency noise present. Dash-dot line = dipole-P arrival; dotted line = shear (flexural) arrival; dashed line = monopole-P arrival.

5.4.2 High-frequency noise

A second example of unconsolidated offshore sediments, shown in Figure 10, demonstrates higher frequency noise obscuring the geophone signals. Again, dipole P-wave and shear (flexural) arrivals are obtainable from the near geophone signal but cannot be resolved with any certainty from the far geophone. Monopole P-wave arrival times are unambiguous from the near and far hydrophones, yielding $V_{p(mono)}$ = 2210m/s, despite there being no clear peak in the frequency spectrum for the monopole P-wave. This is because compressional waves are non-dispersive (i.e. different frequency components travel at the same velocity).

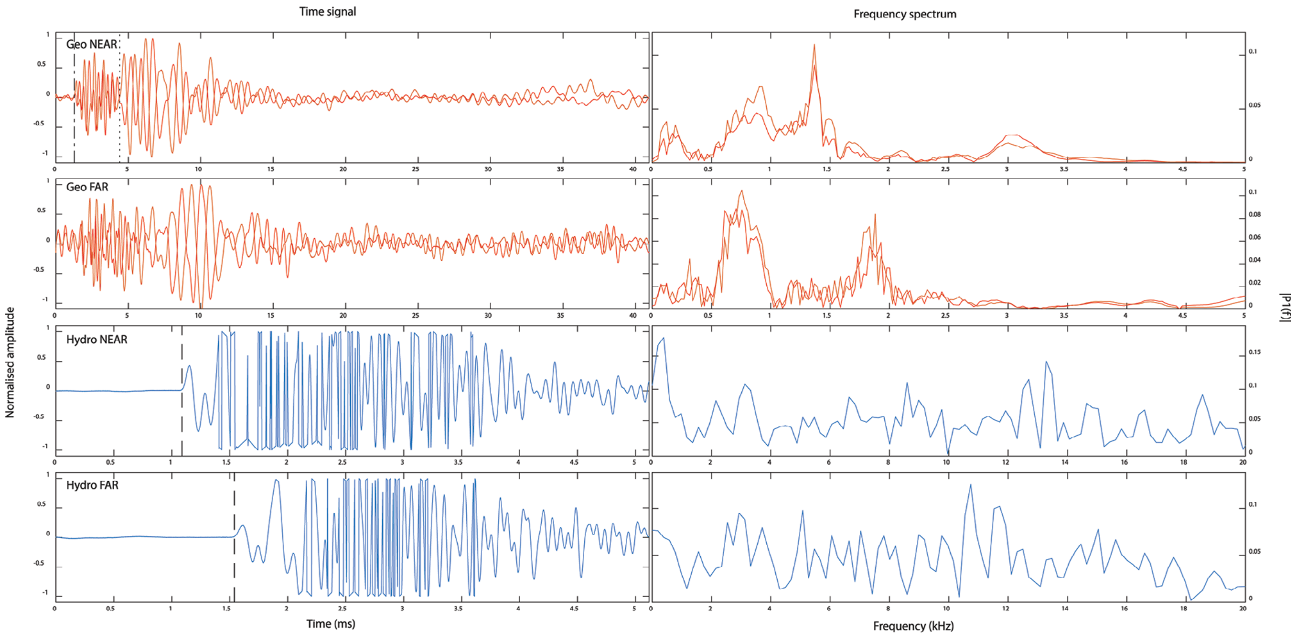

Figure 10 – PS Logger® data example showing high-frequency noise present. Dash-dot line = dipole-P arrival; dotted line = shear (flexural) arrival; dashed line = monopole-P arrival.

5.4.3 Dipole P-wave velocity from poor-quality data

In very poor-quality data, it can be (difficultly) possible to register the dipole P-wave arrival on both near and far geophones, allowing P-wave velocity to be measured from the geophones.

In the following example, noise has obscured the geophone signal such that the shear (flexural) signal cannot accurately be resolved from either the near or far channels (Figure 11). From a closeup image (Figure 12), it can be seen that the dipole P-wave arrival appears on the near geophone channel (clear from both left and right hammer shots), but it is harder to make out on the far geophone: only the right signal shows the arrival clearly. Again, the monopole P-wave arrivals are clearly visible on the hydrophone channels, yielding $V_{p(mono)}$ = 1587m/s. Although the monopole P-wave arrival could have been taken as the point of first deflection, here the first peak has been taken, for clarity.

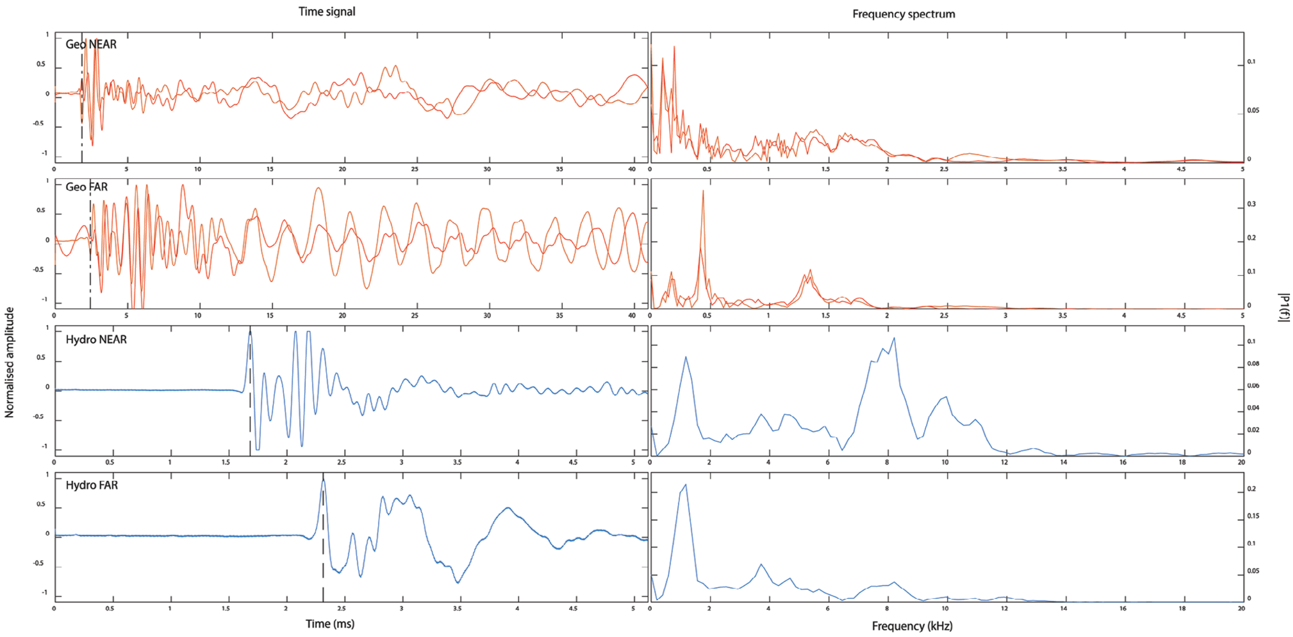

Figure 11 – PS Logger® data example showing distorted geophone signal. Dash-dot line = dipole-P arrival; dashed line = monopole-P arrival.

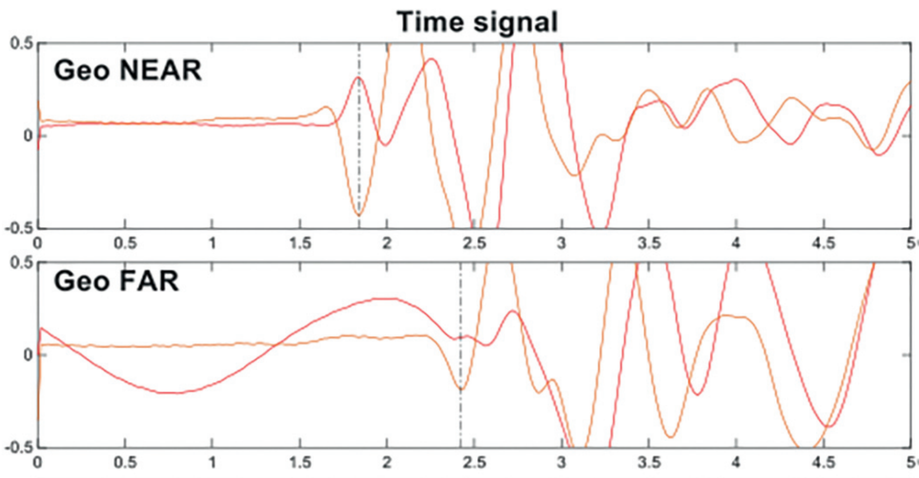

Figure 12 – Closeup of geophone channels for previous example. Dash-dotted lines denote dipole P-wave picks, clear from left and right signals on the near geophone, but right only on the far geophone.

Figure 13 shows another example of offshore data, where the near geophone data are of excellent quality, showing clear dipole P-wave and shear (flexural) arrivals, oscillating at frequencies of approx. 1.5kHz and 0.2kHz, respectively. The far geophone yields much poorer data quality, however, from a closeup of the far geophone channel (Figure 14), the dipole P-wave arrival can be seen, although the first peak is erroneous and should be ignored. P-wave velocity is much more easily obtained from the hydrophone channels, yielding $V_{p(mono)}$ = 1646m/s.

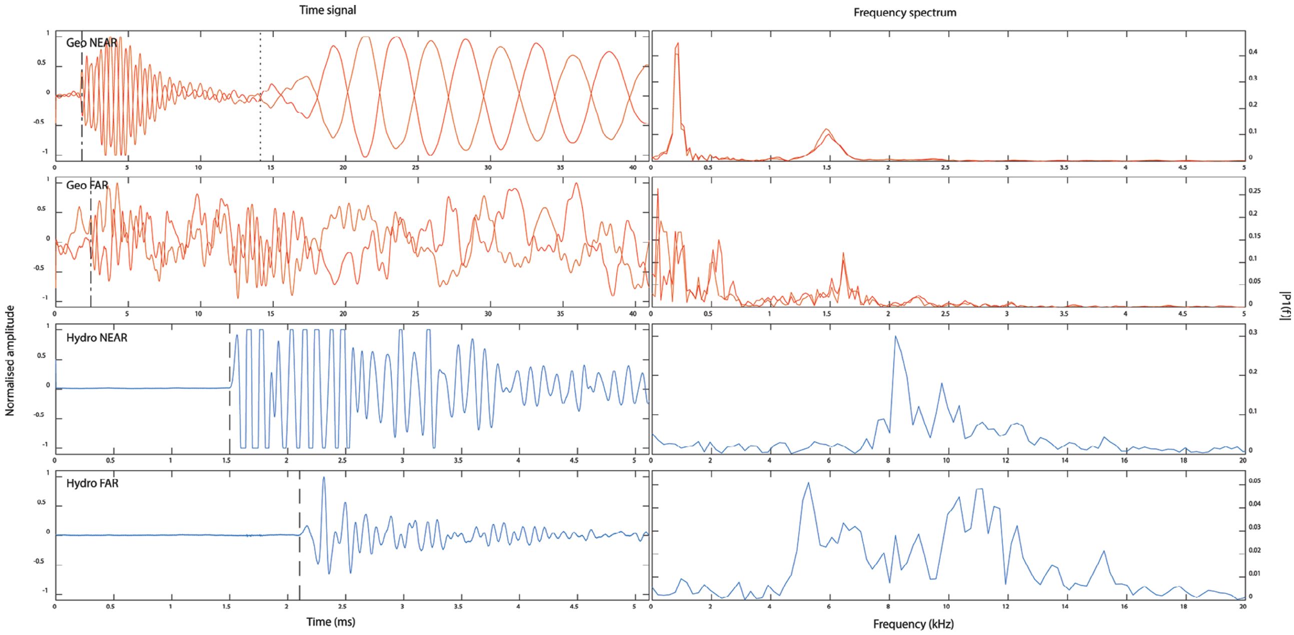

Figure 13 – PS Logger® data example showing distorted far geophone signal. Dash-dot line = dipole-P arrival; dotted line = shear (flexural) arrival; dashed line = monopole-P arrival.

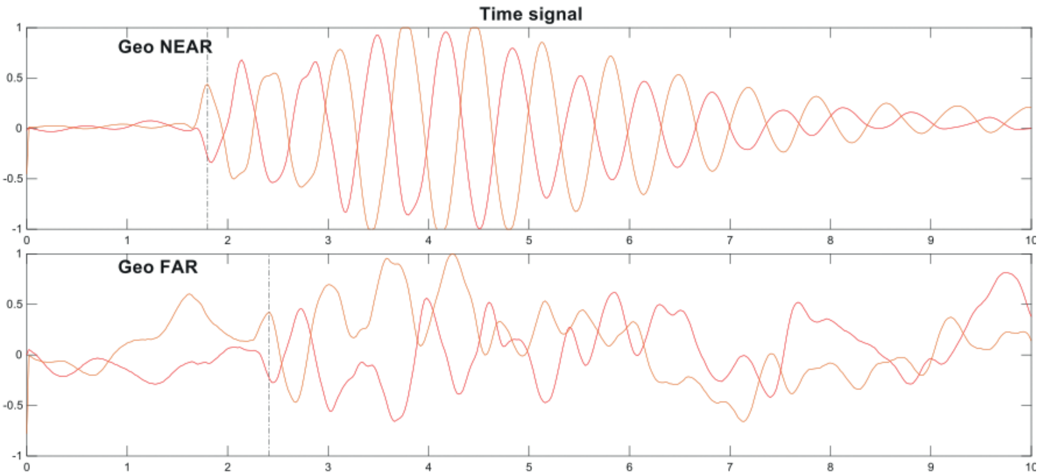

Figure 14 – Closeup of geophone channels for previous example. Dash-dotted lines denote dipole P-wave picks, clear on the near geophone, but heavily obscured on the far geophone.

5.4.4 Offshore depth profile

The previous examples all show data obtained at a discrete depth, in order to highlight some of the common data recording issues. Figure 15 and Figure 16 show a sample of PS logger results from an offshore project, recorded at depths between 17m and 22m. Where possible, the shear (flexural) arrivals have been picked on the geophone channels, but it is obvious that data quality is poor. Dipole P-wave arrivals have not been picked from the geophone channels, but it can be seen that this would be largely impossible due to the combination of offshore noise and low dipole P-wave amplitude. The hydrophone data are of high quality and suffer only minimally from noise distortion (for example at 19m depth, where the monopole P-arrival has been picked at the first peak, rather than the first deflection). For this dataset, $V_{p(mono)}$ is in the range of 1750-2000m/s, and Vs in the range of 250-500m/s. Figure 17 presents an overview for this dataset, and highlights the relatively high sensitivity of the geophones to offshore noise, compared to the hydrophones, resulting in data gaps on the geophone channels (in terms of V_S). It can be seen that in the top 9m of the borehole, geophone data quality is so poor that it no useable data are obtained. In offshore environments, especially on drill ships, poor-quality geophone data output may render the top 10-15m of data unusable.

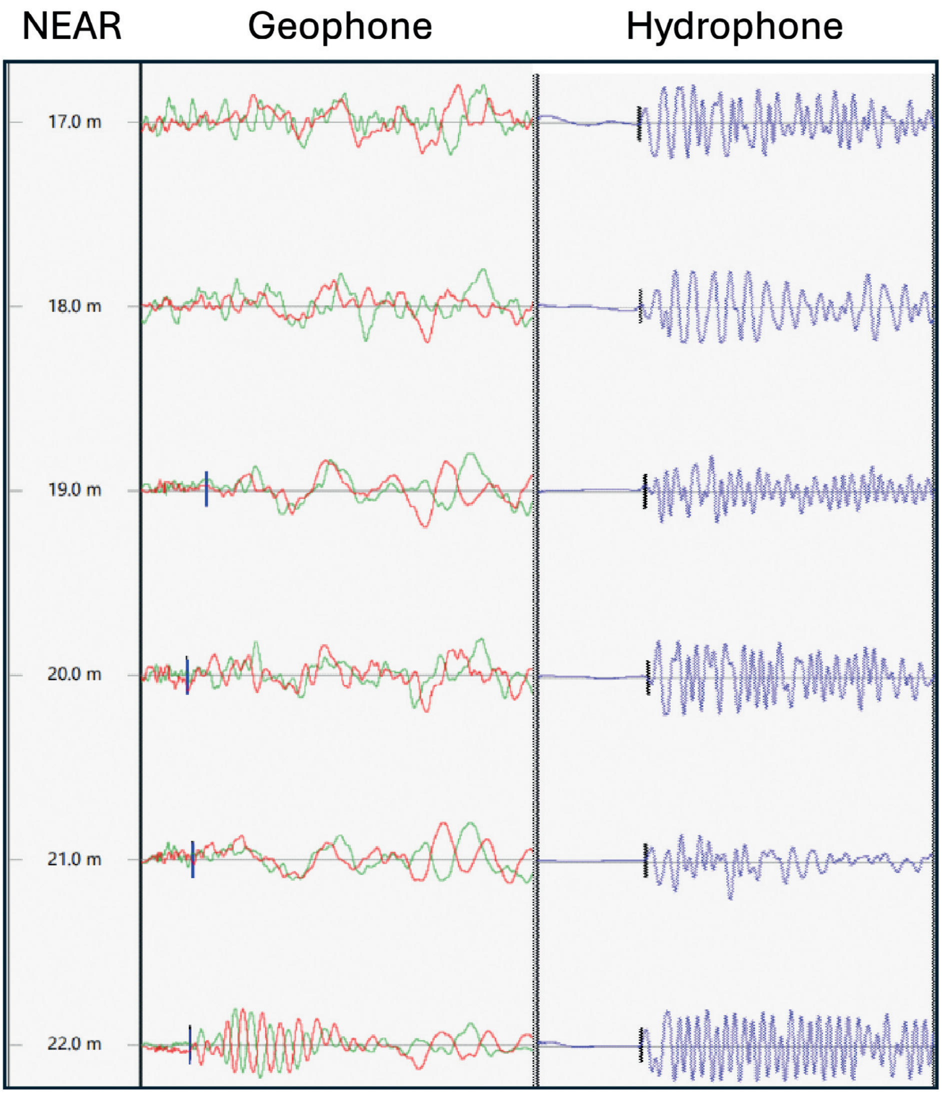

Figure 15 - Near geophone and hydrophone channels. Note, timescales are different between left and right. Picks shown pertain to shear (flexural) arrivals on the geophone, and monopole-P arrivals on the hydrophone.

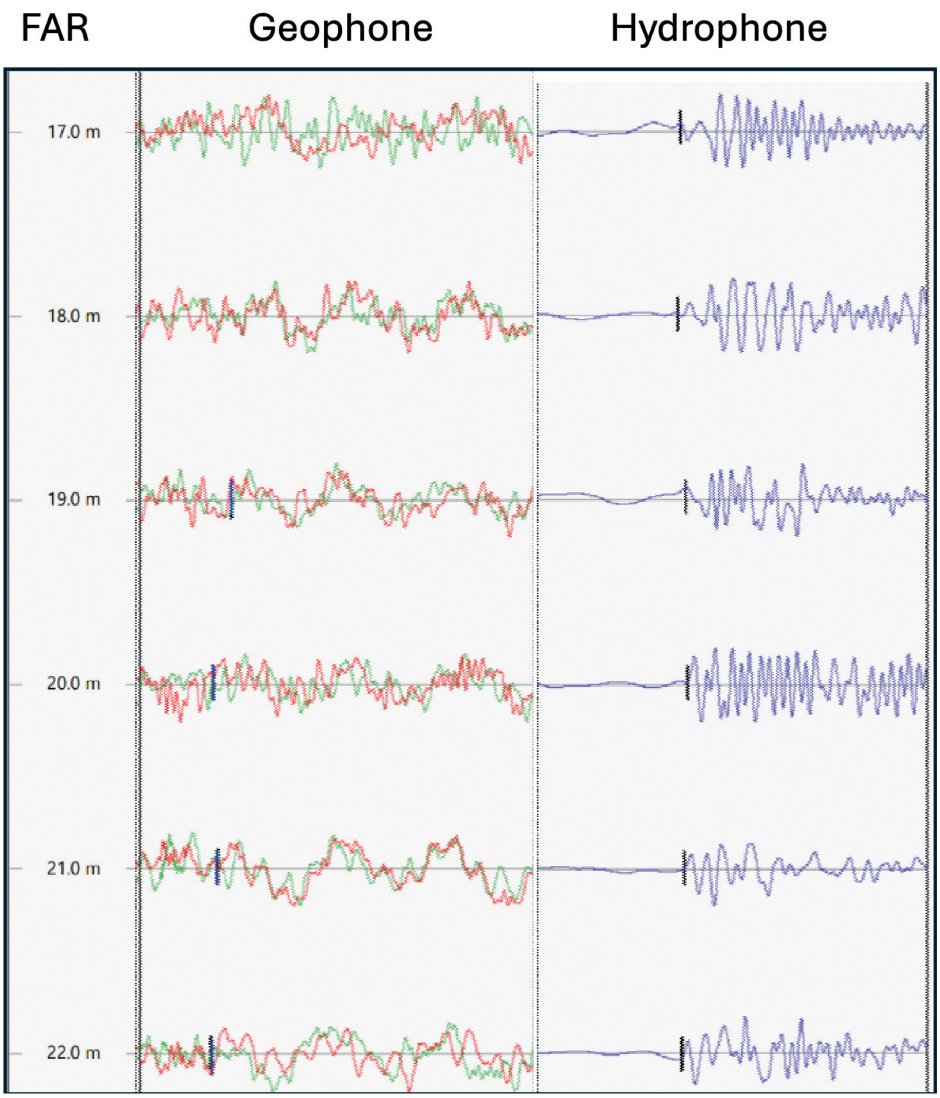

Figure 16 - Far geophone and hydrophone channels. Note, timescales are different between left and right. Picks shown pertain to shear (flexural) arrivals on the geophone, and monopole-P arrivals on the hydrophone.

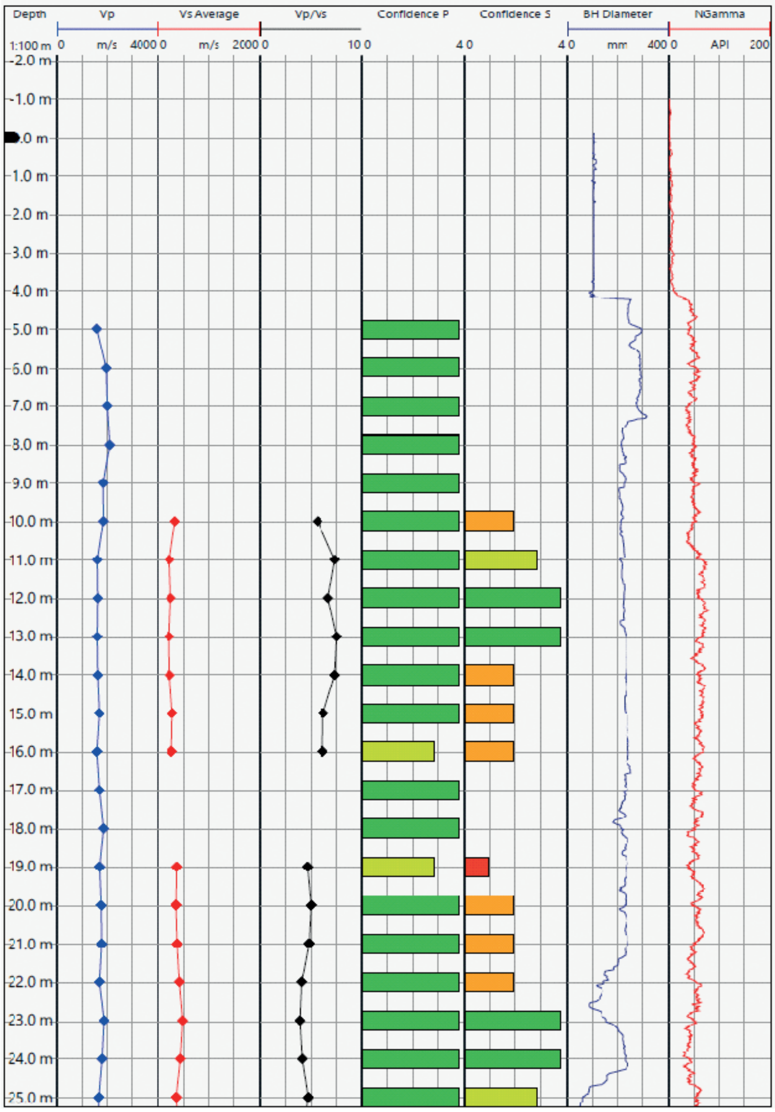

Figure 17 – Data summary for Figure 15 and Figure 16, illustrating greater yield and quality of P-wave channels (hydrophones) compared to S-wave channels (geophones). Note gaps in S-wave data, especially near the surface.

6 Discussion

As explained in this report, the dipole-induced P-wave can register on the geophone, generally with a small amplitude compared to the flexural signal which may be large enough to allow P-wave velocity to be measured – this is the basis of the geophone-only model. This is problematic when looking at less consolidated materials, as the weak dipole-induced P-wave signal is strongly attenuated. In such cases, the monopole-induced P-wave registered on the hydrophones provides a clear P-wave signal, as the initial energy content is much higher.

6.1 Mitigation of geophone recording issues

Under optimal conditions, textbook data clearly register the wave dynamics detailed in section 3. In these circumstances, P-wave velocity can be accurately derived from the geophone channels with minimal inconvenience. More commonly, however, additional steps are required:

1. Poor separation between dipole-P and shear (flexural) signals may be overcome by different sampling frequencies, and/or the use of 2m filter tubes;
2. Low dipole-P amplitude can mitigated by increasing the signal gains;
3. Additional frequency filters can be applied to noisy offshore data.

These mitigating actions, however, can only have limited success given the intrinsically low energy (and amplitude) of the dipole-P signal, and overlap between the dipole source operating frequency and offshore noise. In all cases, it is more straightforward to obtain P-wave velocity from the hydrophone channels.

6.2 P-wave velocity data quality

Even in very poor-quality offshore data, it can sometimes be possible to pick the dipole P-wave arrival, as shown in section 5.4.3. Increasingly, data quality metrics are important in quantifying confidence in seismic data. Therefore, where tenuous P-wave arrivals have been picked from geophone data, quality metrics will be correspondingly poor, undermining confidence in the picked data. As can be seen from Figure 17, data confidence is high across the range of hydrophone data, where geophone data confidence is poor. P-wave velocities obtained via hydrophone receivers are likely to always have higher quality metrics than those obtained via geophone receivers, given a) high energy of the monopole P-wave, and b) relative insensitivity of the hydrophones to offshore noise.

6.3 Automation

Some stakeholders employ automatic picking algorithms for selection of P-wave arrival times, which may, for example, identify the signal's point of first deflection, or first peak. This report has shown that hydrophone P-wave data more are compatible with such methods, given the relative insensitivity to extraneous noise and high amplitude signals, compared to geophone P-wave data.

7 Conclusion

The PS Logger® is unique in that it is optimally configured to make recordings of shear (flexural) velocity using geophones, and of compressional velocity using hydrophones, offering advantages over geophone-only models. This report has discussed the physical basis for the advantage of hydrophones in obtaining P-wave velocity, and demonstrated, using real data, issues regarding the use of geophones to obtain P-wave velocity.

The following conclusions have been drawn:

1. Under ideal conditions, geophone signals can be used to measure P-wave velocity, however, in offshore environments, hydrophones are essential given their relative insensitivity to offshore noise. In such environments, it may be difficult or even impossible to record P-wave velocity without a hydrophone-obtained signal. Typically, geophone data from the top 10-15m of offshore boreholes logged from drill ships are not usable due to noise distortion;
2. Even where P-wave velocity can be obtained from the geophone signal, data quality metrics are likely to be poor, undermining confidence in the data, where hydrophone data quality is consistently high;
3. Measurement of P-wave velocity from the geophones involves additional effort in order to mitigate signal issues, whereas it is straightforward to measure from the hydrophone signal;
4. Hydrophone data are more compatible with automated picking algorithms;
5. Hydrophone data are more robust, and provide data even when geophone signals are unusable, reducing data gaps.

8 Further research

1. Stoneley wave monitoring in the RG borehole using the hydrophone receivers. This will likely involve changes to the applied bandpass filters, and sampling frequencies;
2. Development of PS Logger® model (tilt, eccentricity, rugosity, fractures, anisotropy, near field/far field radiation, external noise).