# Reflections on PS: An interactive discussion of problems and promise in converted-wave exploration

Don C. Lawton, Gary F. Margrave, and Robert R. Stewart

## ABSTRACT

Multicomponent seismic data are being recorded more often now than a decade ago, but the analysis and interpretation of the converted-wave (PS) data still lags that of P-wave data. Anecdotal evidence suggests that horizontal-component data are being recorded but not necessarily processed concomitantly with vertical-component data, except in some marine surveys. In other cases, the horizontal-component data are being shelved until value-added propositions are realized. This is due, to a considerable extent, to the many challenges that face the acquisition and processing PS-wave data and the current, immature status of joint P-wave and PS-wave interpretation methods. In this discussion, we will explore possible ways to make the PS data more useful.

## INTRODUCTION

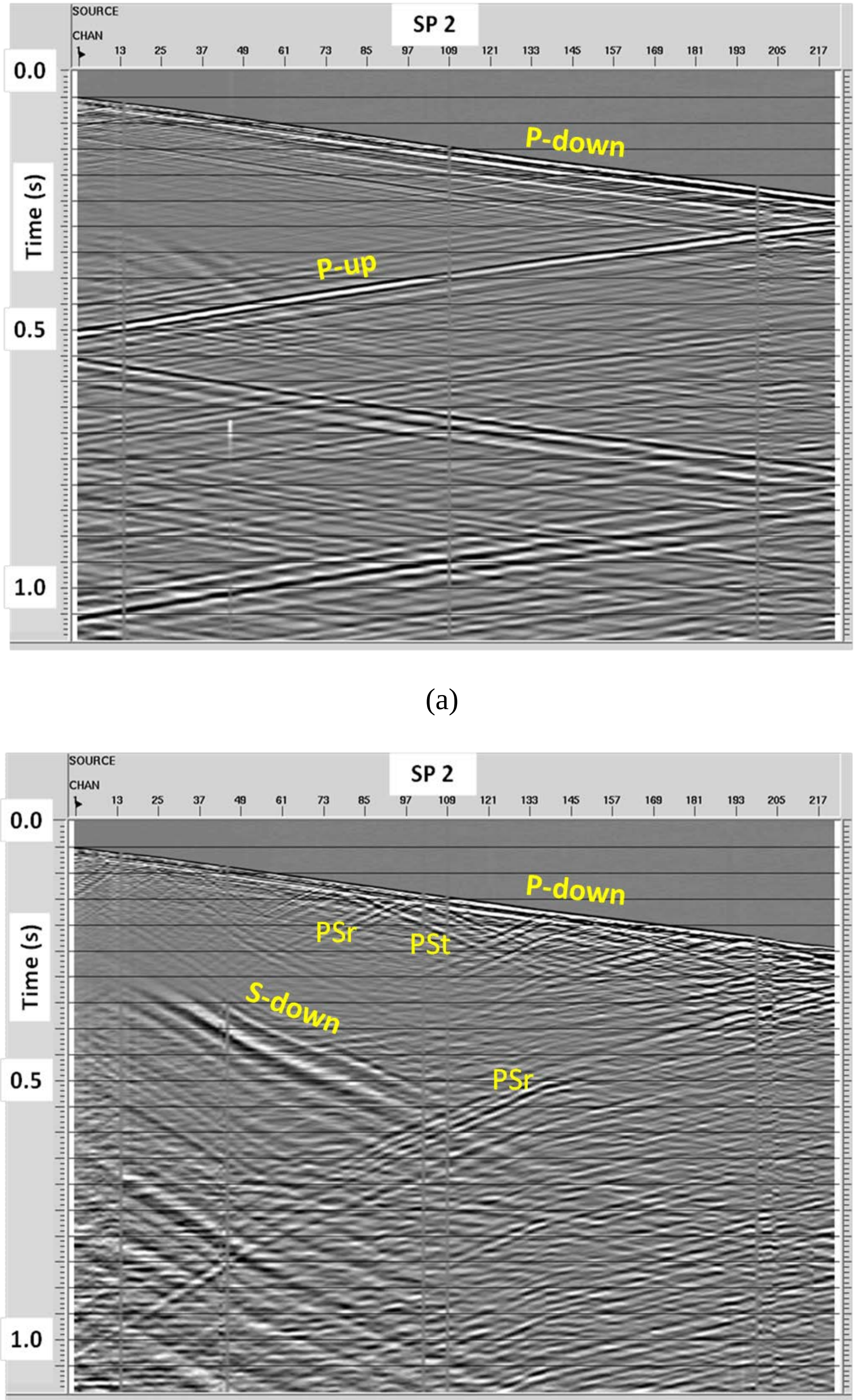
This paper is designed to provide motivation for a group discussion on the current status of multicomponent seismic data analysis and interpretation, particularly land converted-wave (PS) data. The goal is to review PS seismic data from acquisition through to interpretation, identify barriers to implementation of this technology and identify strategies and research topics to overcome them.

Acquisition issues include survey design, geophone coupling, efficacy of geophone orientation, group versus point receivers, low S-wave velocities in irregular and highly heterogeneous near-surface layers, source energy, and the free surface effect.

Key processing topics are receiver statics, velocity analysis, deconvolution, binning, migration/inversion, and anisotropy. Interpretation challenges are related to complexities in P-wave and PS-wave registration, differing elastic responses, differential S-wave versus P-wave attenuation, P-wave and PS-wave phase, PS-wave amplitude versus offset analysis and joint P-wave and PS-wave inversion, and anisotropy.

Figures 1 and 2 remind us that a surface or near-surface energy source excites very rich elastic wave-fields in the subsurface. The data shown in Figure 1 are the raw (with AGC) vertical and radial component shot gathers from an offset vertical seismic profile (VSP) recorded into a densely-sampled 3-component geophone array with a dynamite source. The source was offset 88 m from the well for this record and the geophone separation was 2 m. This dense receiver sampling allows easy observation of the many wave modes recorded, including down-going and up-going pure P and S modes as well as down-going and up-going PS modes. SP modes are not readily visible. Figure 2 shows the equivalent vertical and radial component gathers using an Envirovibe source at the same location as the dynamite source in Figure 1. While the dynamite source has much more energy than the EnviroVibe source, the latter generates a stronger direct down-going S-wave than the former, particularly visible on the radial component gather.

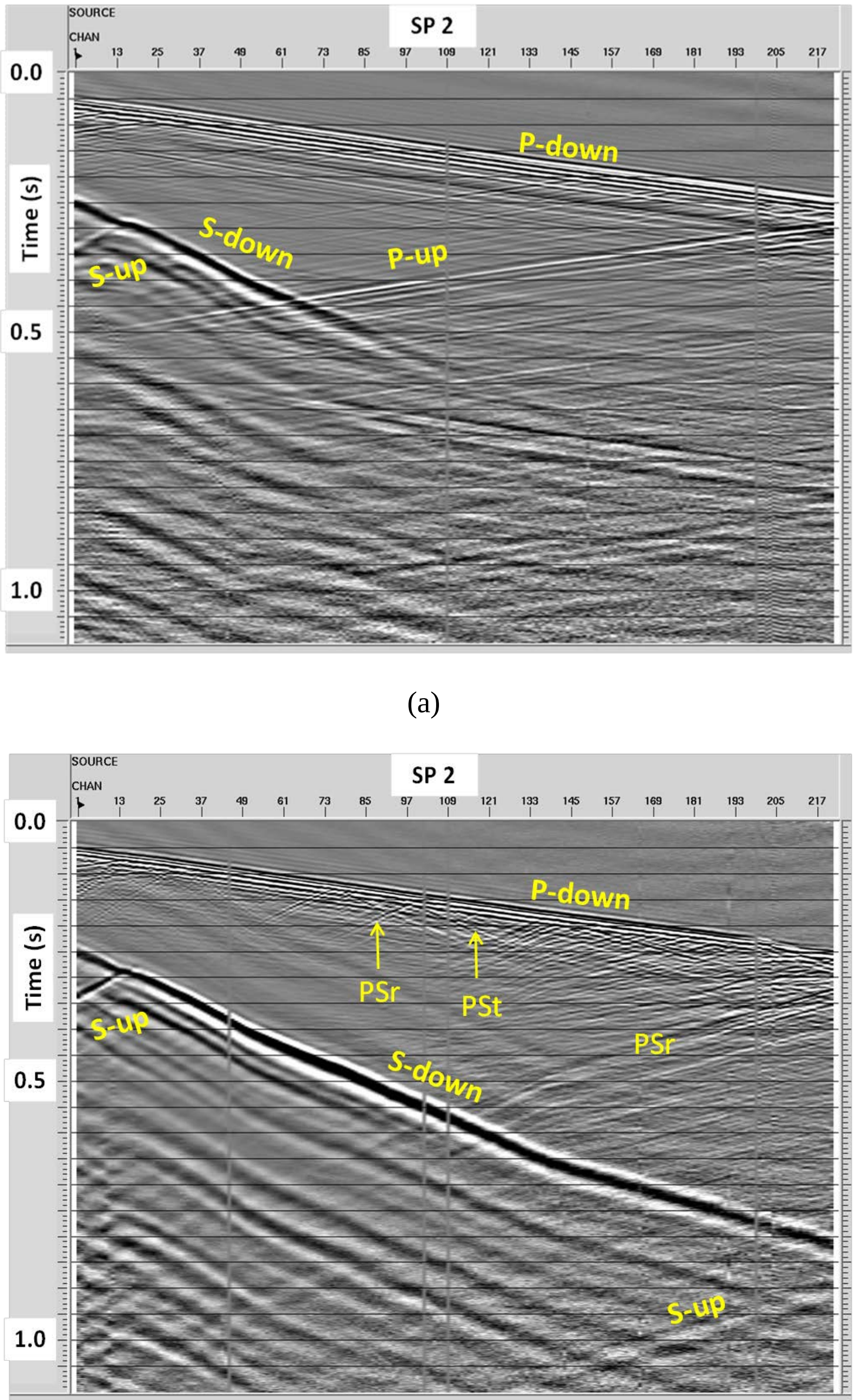
The VSP project and resulting data are discussed in more detail by Hall et al. (2012).




(a)

(b)

FIG. 1: Some wave modes identified in the (a) vertical and (b) radial component of a walkway VSP shot gather recorded with a dynamite source. PSr = P-S mode conversion upon reflection; PSt = P-S mode conversion upon transmission.




(a)

(b)

FIG. 2: Some wave modes identified in the (a) vertical and (b) radial component of a walkway VSP shot gather recorded with and Envirovibe source. PSr = P-S mode conversion upon reflection; PSt = P-S mode conversion upon transmission.

The following paragraphs provide some context for the discussion, along with some recommendations.

## Data acquisition

*Survey design.*

3D surveys that are designed for P-wave data are generally adequate for PS-wave surveys for deep targets, but PS imaging of shallow targets will be compromised by the asymmetry of PS-wave raypaths, with the PS conversion point moving toward the geophone as the reflector depth decreases. Since the trajectory of the conversion point with depth depends on Vp/Vs it may be difficult to predict shallow reflector illumination if Vp/Vs is not known *a priori*. PS fold maps based on bin hit counts will not provide a meaningful guide to final image quality because PS conversion points will not be bin-centred in most cases, even if Vp/Vs = 2.0. PS design should not be based on asymptotic PS conversion point binning as this also is unrealistic, particularly for large offset-to-target-depth ratios. In a 3D survey, large receiver line spacings may result in gaps created by the processing mute in the PS images of shallow reflectors. This might impact time-lapse analysis where shallow reflectors (i.e. above the reservoir) are used for calibration between baseline and monitor surveys.

*Geophones*

The quality of plants and orientation of 3C geophones is one of the most critical aspects of multicomponent seismic survey acquisition. It seems likely that poor geophone coupling does not affect all components of a 3D geophone equally. In fact, recent evidence (Manning 2012) suggests that vector fidelity of a 3C geophone may be increased with the simple artifice of a sandbag placed on top of it. The vertical component is relatively unaffected but evidence suggests better horizontal component data. Conventional geophones need to be precisely laid out in both a vertical and azimuthal sense and this requires careful work and quality control by the field crew, thus adding time and cost to the surveys. This overhead also discourages the use of multiple geophones per group and almost all multicomponent surveys are acquired with single-point receivers. MEMs devices (accelerometers) have in-built gravity-based tilt correction capabilities but still require precise orientation. Deterministic methods are starting to be employed to assess surface geophone orientation by analysis of first-arrival data (usually head-waves) on the horizontal components, but the free-surface effect and refractor cross-dip may impact the quality of such determinations.

*Near-surface heterogeneity*

Heterogeneity of the near-surface layers, particularly in Vs also favours the use of single-point receivers rather than geophone arrays as the intra-array static may be large (10s of milliseconds) and thus significantly attenuate the high frequency component of the recorded data (Hoffe et al, 2002). Rapid lateral variations in the depth and Vs velocity structure also create challenges for the calculation of weathering static corrections. Furthermore, in many environments, Qs in the shallowest weathering layers is very low and PS-wave data tends to have very low dominant frequencies, which impact both resolution and PP-PS registration.

There are three major changes underway in seismic acquisition systems: the use of MEMS sensors, cable-free nodes, and vastly more channels. These new systems are affecting both conventional and multicomponent acquisition. The promise for PS exploration is that more channels, closely spaced, will help solve many noise problems and increase the PS signal sharpness.

## Data Processing

### *Statics*

Rapid to extreme lateral variations in S-wave weathering static corrections are probably the most challenging aspect of PS-wave data processing. If the travel-times of shear head-waves are pickable, then standard static methods (inversion or tomography) can be employed to calculate the receiver static correction. However, this is rarely the case as shear head-waves are not easy to pick on most datasets. Some advances in surface-wave analysis have been made recently, with some promise for evaluating long-wavelength shear statics. Most standard approaches use the P-wave structure stack and common radial-component receiver stacks to extract the “optimum” receiver static solution. However, this method can be slow and tedious and output sections are not structurally independent from the P-wave data. Often, the S-wave receiver statics can be an order of magnitude larger than the P-wave shot statics and there may be no relationship in trend between these static corrections. Sometimes a bulk shift is applied to the S-wave static to avoid PS data being shifted to negative times. Is this the correct approach or would it be better to include the shallow S-wave velocity structure directly into velocity models for pre-stack imaging?

### *Deconvolution*

Since PP-wave and PS-wave data use a common source, it is reasonable to assume that the phase of the vertical and radial component data would be the same. However, due primarily to significance differences in Qp and Qs along the travel path, the amplitude spectra of the recorded wavefields are certainly not equivalent and the phase spectra may thus also be different. Also, stratigraphic filtering (i.e. the apparent changes in the wavelet due to the coda of multi-modes behind the first arrival) may well affect P and S wavelets differently. This will impact deconvolution of the data as interpreters would favour consistent phase between processed PP-wave and PS-wave processed data volumes.

### *Binning/Imaging*

In the absence of knowledge about interval Vp/Vs in the survey area, most PS-wave data are initially binned using an asymptotic conversion, assuming a global value for Vp/Vs. Depth-specific binning using DMO or pre-stack imaging requires multiple iterations to elucidate the optimum PS-wave stacking velocity. Binning is also influenced by velocity anisotropy, if present, either vertical or horizontal transverse isotropy (VTI or HTI). Perhaps all PS data should be processed with prestack migration?

*Shear-wave splitting*

HTI media will generate splitting of the upcoming wave field into fast (S1) and slow (S2) velocities. Layer-stripping is used to compensate for S-wave splitting commonly observed in the near-surface layers but the reason for this is still poorly understood. HTI anisotropy deeper in the sedimentary section is assumed to be caused by preferentially oriented fracture systems or the maximum horizontal stress being aligned in a particular direction. Detailed, shallow VSP studies are necessary to fully understand the variation in anisotropy with depth and to accelerate S-wave splitting analysis in surface multicomponent data.

A major change in seismic processing is the advent of very fast processing systems that can analyse and invert the full seismic wavefield. This is likely to have a major impact on PS imaging as we can begin to model the elastic wavefield and match it to the recorded data in their native domains.

## Data Interpretation

There is an urgent need to provide new approaches to the interpretation of multicomponent seismic data. At present P-wave and PS-wave data volumes are created and the interpreter essentially interprets each volume separately. The data can be integrated through derivative products such as Vp/Vs volumes but joint inversion methods are challenged by the differences in the amplitude spectra of PP and PS data.

*Dipole sonic logs and density logs*

It is very difficult to interpret PP and PS data as a joint dataset without consistent theoretical seismograms for modes. This requires a dipole sonic, preferably from surface casing to target, acquired somewhere in the area. Accurate seismogram construction also requires a corresponding density log. We should encourage such logging suites whenever 3C data are recorded.

*PP and PS Registration*

Integration of PP and PS data is currently undertaken through data registration of data volumes in time. This can be assisted with well log data, particularly dipole sonic logs, which enable PP and PS synthetic seismograms to be generated and tied to the PP and PS seismic data. We should move towards pre-stack depth migration for both PP and PS data volumes, which would then result in direct ties in depth. At present it is possible to produce quite robust interval P-wave velocities for computation of travel-times for the down-going P-wave-field, but determination of interval S-wave interval velocities is more difficult.

A significant step forward in PS interpretation has been the development of image analysis and overlay software systems. These can assist in rapidly registering and inverting PP and PS seismic data.

*Attenuation*

Attenuation of S-wave energy results in PS sections tending to have lower dominant frequencies than PP sections. Compressing PS section so PP time improves the apparent vertical resolution but often it is still difficult to register the sections. Figure 3 shows registration between PP and PS sections (Nicol and Lawton, 2012) and this is clearly not a simple task.

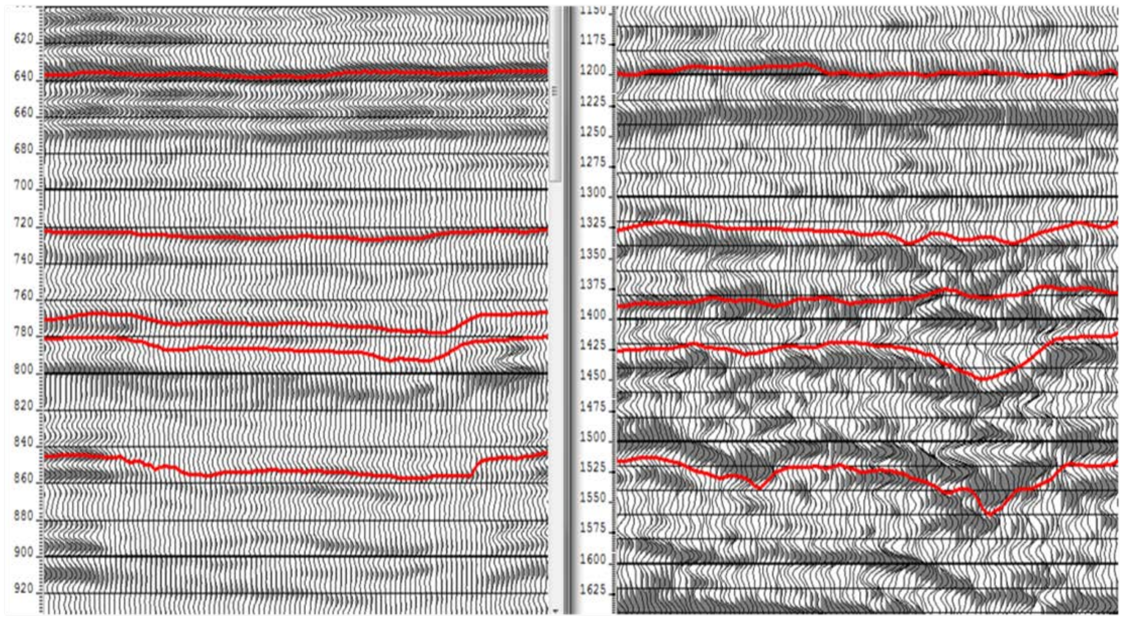



FIG. 3. Registered PP (left) and PS (right) sections

When we record the PS events near their point of origin (the conversion point), we generally find that they have the same temporal frequency as the P-waves – as they should according to theory. Because of this, the PS events often have significantly higher resolution or shorter wavelengths than the P-waves. This is key in many VSP cases as shown in a reservoir porosity study (Figure 4).

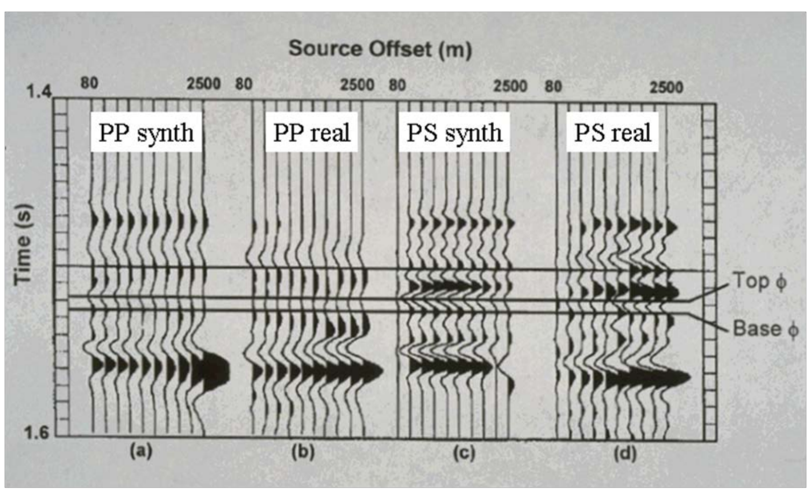



FIG. 4. Converted-wave VSP data can have more activity and better resolution than the PP counterpart (Coulombe et al., 1996).

It is clear though that the S-wave band is reduced somewhere in the near-surface as we can see from a Cold Lake example (Figure 5).

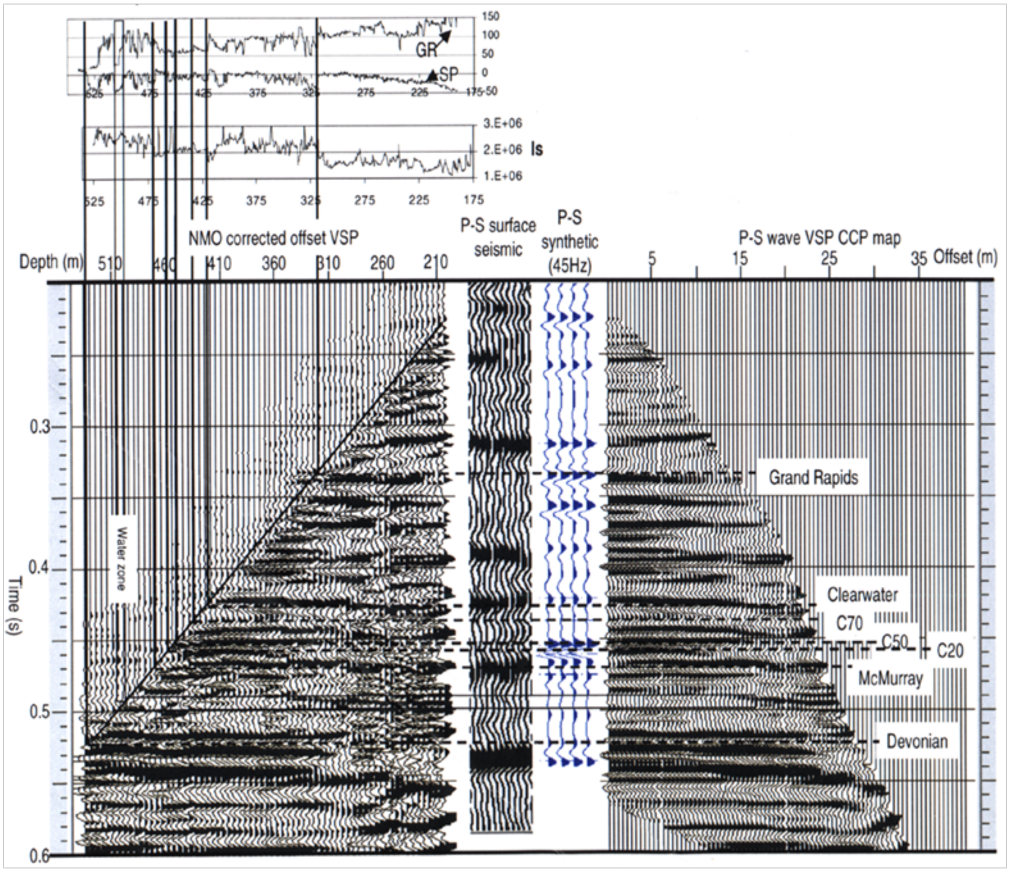
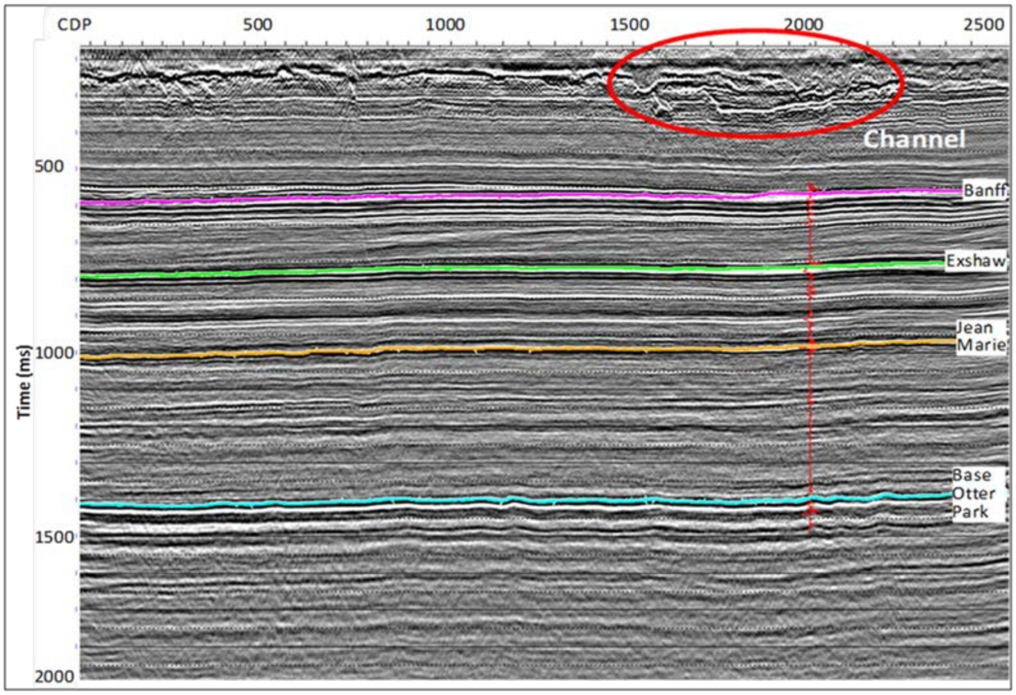



FIG. 5. Composite borehole and surface seismic plot from Cold Lake, Alberta area shows the remarkable S-wave frequency loss between in situ measurements (VSP CCP map and P-S synthetic seismogram) and a P-S surface seismic section (Sun, 1998).

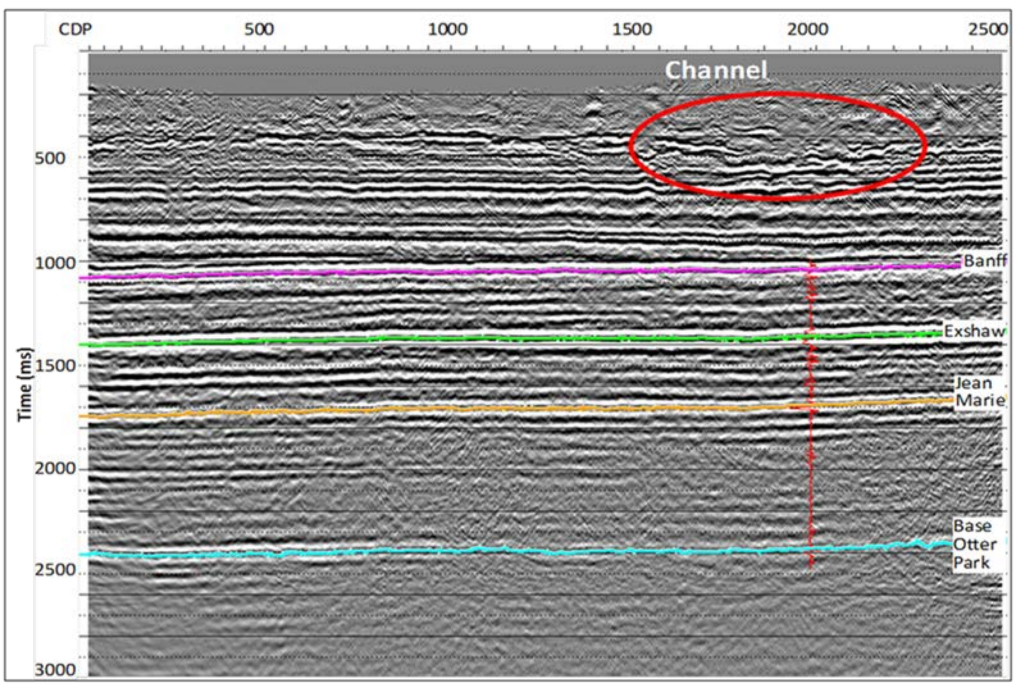
One reason for this loss of band is attenuation. The shorter wavelengths of the S-wave are at first an advantage, but as attenuation is a loss per wavelength over a given distance, shorter wavelengths are attenuated more. The rock quality with respect to S-waves (Qs) can be lower than that for P-waves (Qp). This gives an additional penalty to S-wave propagation.

## Some recommendations

For multicomponent seismic surveys, record a high-fold 2D line along one or more receiver lines in a 3D survey. This will yield information about the near-surface velocity structure which is important for PP-wave and PS-wave event registration. Figure 6 shows 2D PP and PS sections (Zuleta and Lawton, 2012) where a complex shallow channel system is present.




(a)




(b)

FIG. 6 (a) PP section; (b) PS section, imaging a complex shallow channel that is impats PS processing. From Zuleta and Lawton (2012).

An in-line PP section from a 3D survey was extracted along the same line as the 2D line shown in Figure 6. In the 3D data (Figure 7), this channel feature is not imaged, as seen in the PP data. The equivalent section from the same in-line from the PS volume is not yet available, but it is unlikely that the shallow channel will be imaged in that volume either.

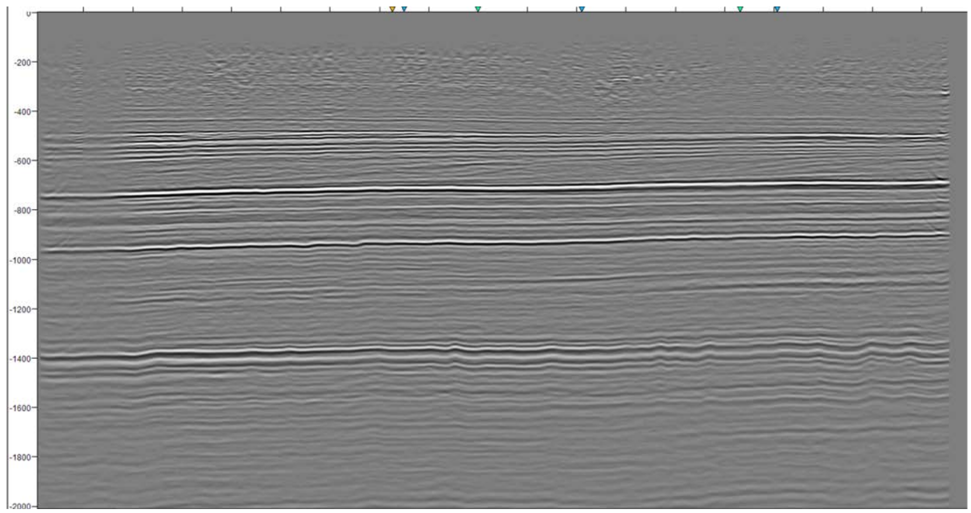


FIG. 7. PP in-line section from the 3D volume, extracted to match the 2D line shown in Figure 4.

If PS statics are data-limiting in the survey area, then recording an SH refraction survey along receiver lines is recommended. Depending on line access, these can be done quite quickly and SH first arrivals can be used to calculate receiver S-wave static corrections. However, there is no guarantee that S-wave statics corrections will be azimuthally isotropic and this is an important topic to be researched. Figures 8 and 9 show first-break travel time picks for vertical and transverse components of shot gathers for vertical (P) and transverse (SH) sources respectively (Zuleta and Lawton, 2012). The first breaks are quite easy to pick and yield S-wave static corrections to datum that are much larger than the P-wave statics at the same stations (Figure 10). These analyses .yield the complex velocity structure of the near-surface layers in this area, and confirm the high Vp/Vs values from shallow dipole sonic log data in the area (Figure 11). This information is critical for precise time to depth conversion, or in the development of interval velocity models for time and depth imaging.

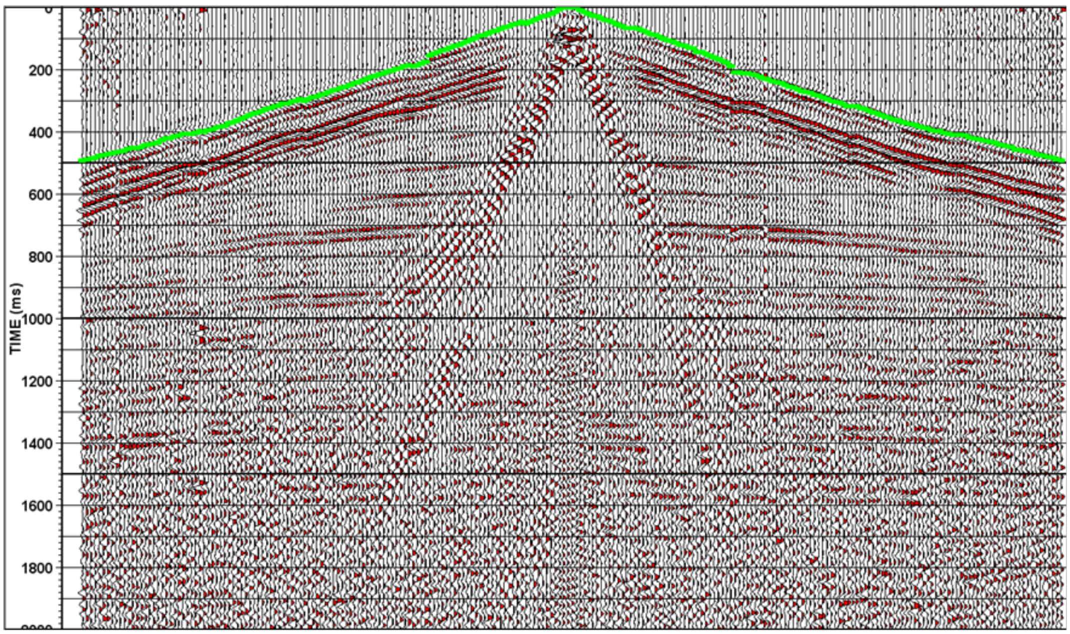



Fig. 8. Vertical component shot gather with P-wave first arrivals picked. From Zuleta and Lawton (2012)

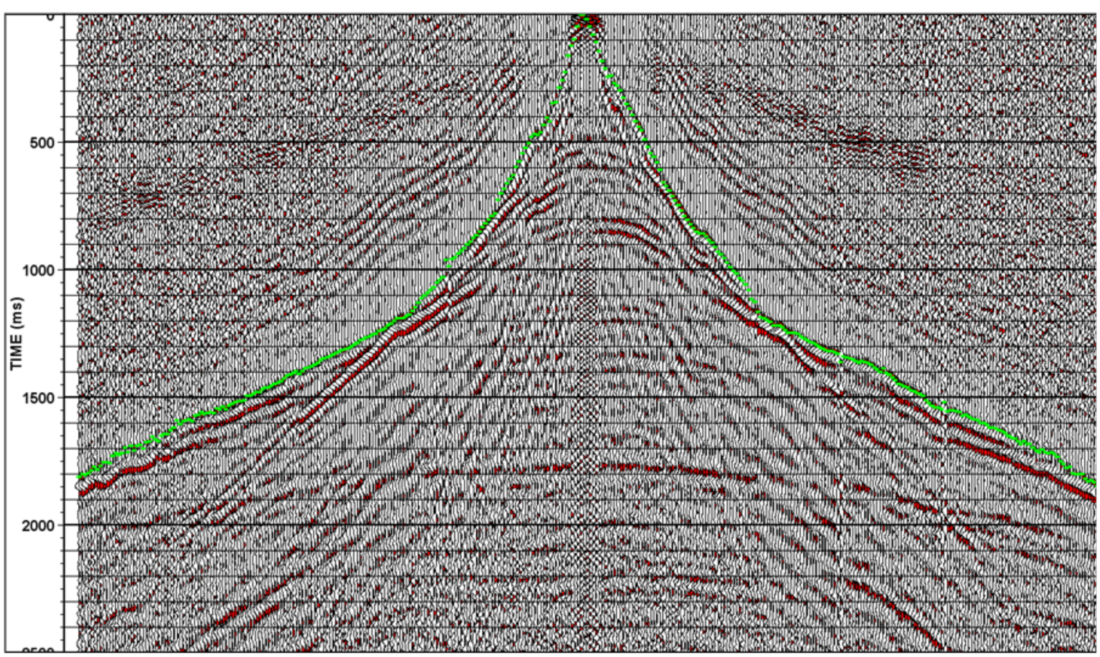



FIG. 9. Transverse component shot gather with SH-wave first-break pick times picked. From Zuleta and Lawton (2012)

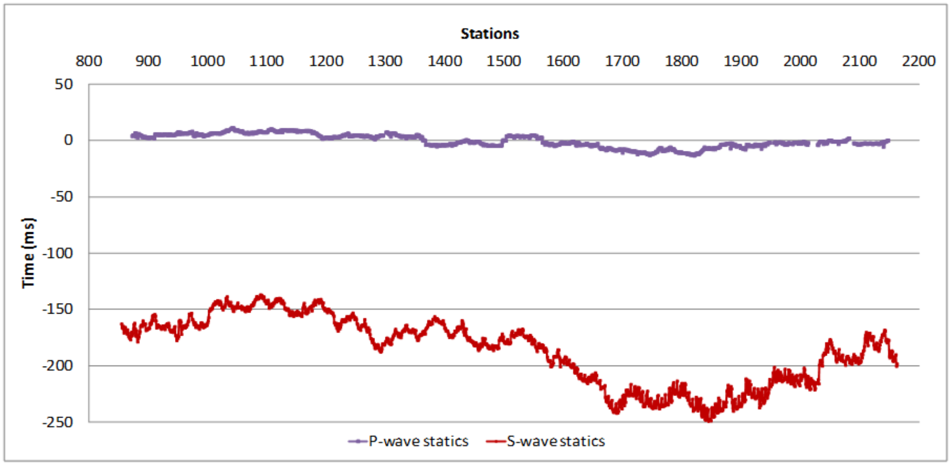



FIG. 10. Datum receiver static corrections for P-wave data and SH-wave data, illustrating the large difference in static values. From Zuleta and Lawton (2012).

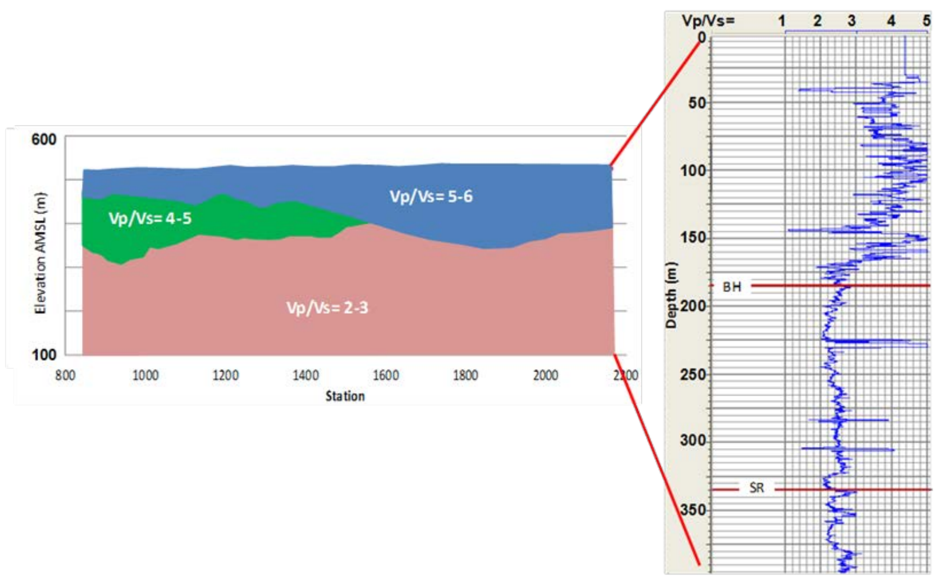



FIG.11. Shallow Vp/Vs from analysis of P-wave and SH-refraction data and dipole sonic data from a nearby well. From Zuleta and Lawton (2012).

Within the area of a 3C-3D survey, including buried 3C receivers in a sparse grid may be beneficial. Burying geophones below the near-surface weathering layers will likely enable higher bandwidth PS-wave data to be recorded by these geophones provided that the receiver ghost notch lies outside the spectral bandwidth. Depths between 20 and 50 m may be required and vertical arrays of 3C geophones could be considered for deeper holes (mini VSPs). This approach may yield higher PS bandwidth and fewer statics problems that recording with surface geophones. Figure 12 shows a very nice example of an up-going converted wave captured in the VSP (Hall et al., 2012). The broadening of the event at shallow depths will be used to determine Qs of the shallow section; it also illustrates that good PS energy can be recorded.

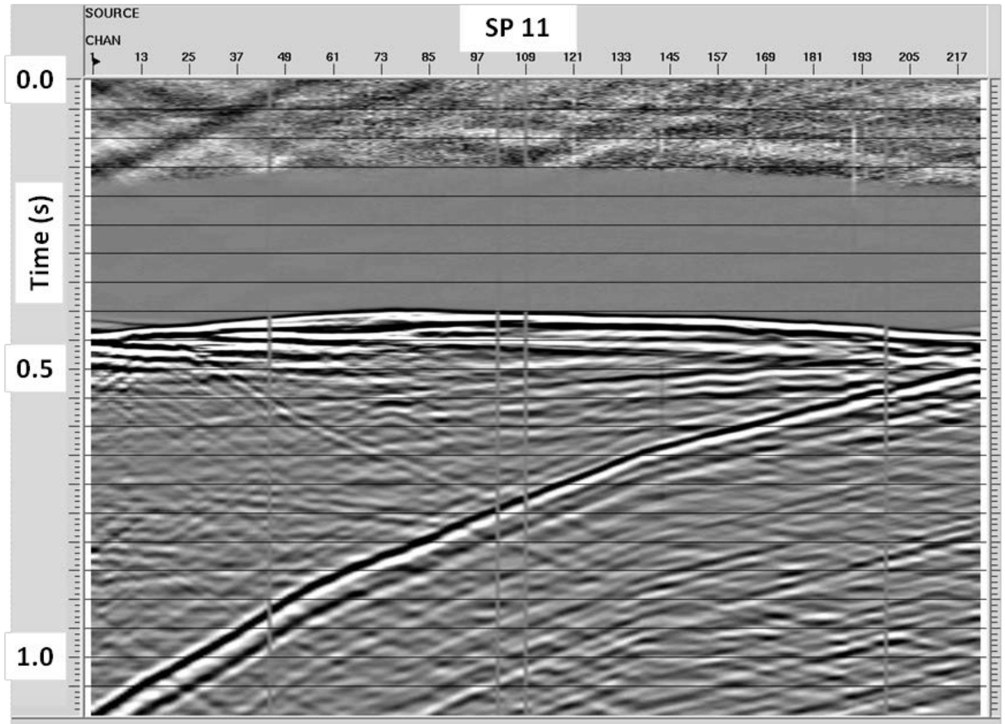



FIG. 12. Radial component of an offset VSP survey showing a high amplitude up-going PS-wave. Dynamite source.

.Finally, for precise PP and PS registration, the formation tops in both PP and PS volumes need to be tied to the seismic data very carefully through the use of synthetic seismograms. It cannot be assumed that a zero-crossing for a PP event will correspond exactly with a zero crossing in the PS event for the same formation top. Figure 13 shows this process for a PP and PS registration process, as discussed by Nicol and Lawton (2012).

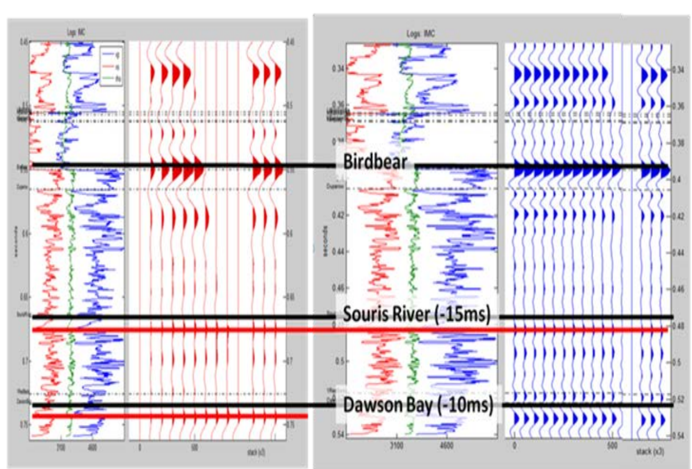



FIG. 13. PP and PS registration through PP and PS synthetic seismograms

## ACKNOWLEDGEMENTS

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