# P-SV and P-P synthetic stacks

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## ABSTRACT

A method was developed for calculating converted-wave (P-SV) or compressional-wave (P-P) 'zero-offset' synthetic seismograms. The method is based on raytracing various offsets. The algorithm is based on the simplifying assumptions of horizontal homogeneous layers with constant time interval thicknesses, no amplitude attenuation and no multiples. Interval times are calculated, in the converted-wave case, by ray tracing a downgoing compressional wave and an upgoing shear wave. Exact values for phase and amplitude for each raytraced angle are calculated. By convolving with a Ricker wavelet, synthetic traces are generated for each offset. NMO and mute can be applied prior to stacking the traces into the P-SV or the P-P synthetic stack.

The algorithm was tested for an offset, mode-converted, VSP in South Alberta and a multicomponent seismic survey in West Central Alberta. Each set of seismic data correlated well with the appropriate synthetic stack. The P-SV synthetic stack, using either the full-waveform log or a sonic log and a Vp/Vs ratio, provided a reliable match between depth information from well logs and reflections observed in converted-wave seismic data. For the P-SV case, the Vp/Vs ratio strongly affected the traveltimes of events, while selection of NMO and mute had a more significant influence on the character of the synthetic stack. The P-P synthetic stack more accurately preserved the amplitude information than the P-P zero-offset synthetic when the events exhibited a significant amplitude variation with offset.

## INTRODUCTION

Events from surface seismic data in regions of flat or very gently dipping layers depict normal incidence reflections when positioned in their equivalent zero-offset locations. Events on seismic data are commonly tied to depth and lithologic information from wells by calculating synthetic seismograms. Compressional (P-wave) synthetic seismograms are calculated by integrating sonic and density logs into zero-offset, two-way, compressional wave traveltime, and computing reflection coefficients at normal incidence based on the impedance contrast derived from the integration of the well logs. The converted-wave (P-SV) case is complicated by the knowledge that at normal incidence, a compressional wave incident at the interface between two elastic media will not undergo mode conversion (Pilant, 1979). Methods for gathering, applying normal moveout corrections, and stacking mode converted data to produce zero-offset equivalent seismic sections have been developed and are in use (Fromm et al., 1985; Tessmer and Behle, 1988; Slotboom, 1990; and Eaton et al., 1990). Converted-wave (P-SV) data are displayed as conventional zero-offset stacked sections, even though the zero-offset converted-wave trace has no physical analogue. Therefore, in the P-SV case, the compressional wave method of generating the synthetic seismogram at normal incidence cannot be used.

Identifying events, establishing polarity on P-SV data, and correlating these to the P-P sections are fundamental tasks in understanding converted-wave data. The present technique available to interpreters uses the composite L-plot and requires VSP data (Gaiser et al., 1984). To better understand and interpret converted-wave data Geis et al. (1990) produced an L-plot using a full-waveform sonic log, VSP extracted traces for P-P and P-SV reflections and a P-P synthetic. These authors found significant differences in the reflectivity between the P-P and P-SV data in some intervals. The addition of a P-SV synthetic stack would enhance the interpretation of these data. By proving a reliable tool where VSP data is available as a check, a P-SV synthetic stack could be shown as a straight forward technique for matching well log information to P-SV surface seismic data, establishing polarity on P-SV data, modeling P-SV seismic data before acquisition, and correlating events between P-SV and P-P sections.

Full-waveform sonic logs are often unavailable for older wells and are not consistently run in new wells. Therefore, in addition to showing the reliability of the P-SV synthetic stack calculated using known S-wave velocities from the full-waveform sonic, it would be useful to compare it's validity when calculated using the P-wave sonic and an estimate of Vp/Vs.

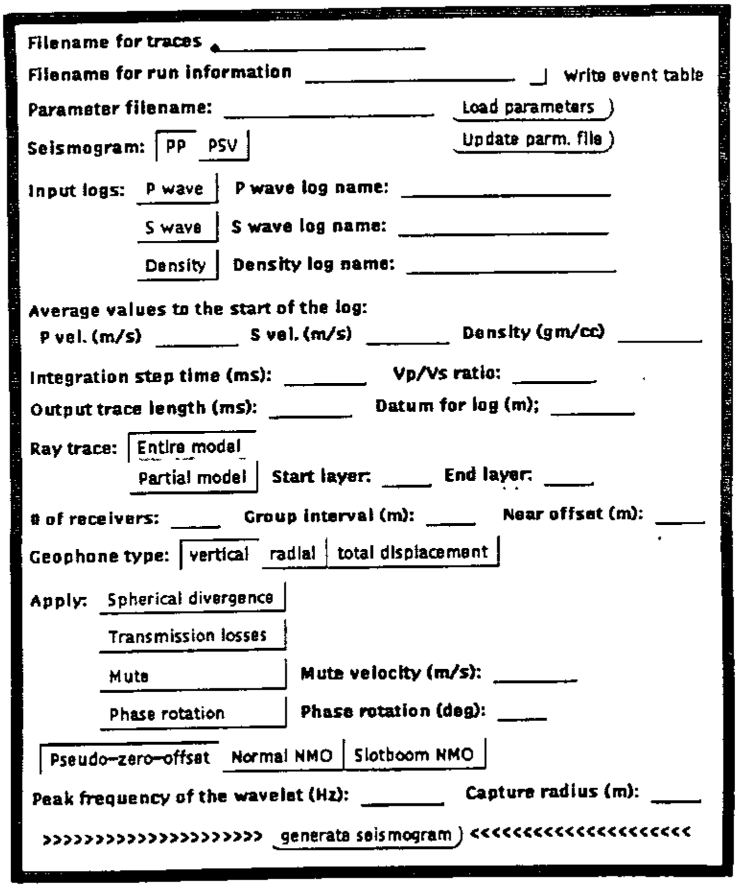


Figure 1. Interactive UNIX X window screen for PSV and PP synthetic stack program.

## METHOD

The method developed involves calculating converted-wave (P-SV) or compressional wave (P-P) synthetic seismograms at various source-receiver offsets and then stacking to produce a 'zero-offset' equivalent converted-wave synthetic seismogram. The algorithm is based on the simplifying assumptions of horizontal, homogeneous layers with constant time interval thicknesses, no amplitude attenuation and no multiples. Transmission losses through each layer and energy losses from spherical divergence can be accounted for.

The computer display for entering parameters and selecting options for use in generating a synthetic stack is shown in Figure 1. A P-wave sonic log is the only required log. If the S-wave or full-waveform sonic log is unavailable, then a Vp/Vs ratio must be input. If the density log is unavailable, then Gardner's equation (Gardner et al., 1974) is used to calculate density. As shown in Figure 1 and Figure 2, another required input to the processing flow is the geometry information, including number of traces, group interval, and near offset.

The next step shown in Figure 2, is the construction of a layered model comprised of constant zero-offset traveltime thicknesses which in the P-SV case are calculated using both the P-wave and S-wave velocities (i.e. $\delta Z/Vp+\delta Z/Vs=\delta t$ is equal to a constant where $\delta t$ is the chosen integration time ). Figure 3 shows the layered model ready to raytrace. Based on the input information, every layer is raytraced at each offset to determine the traveltime and the incident angle. Layers are raytraced by shooting rays and solving for the correct ray parameter by iteration using the bisection method.

Given the incident angle from raytracing, the exact reflection amplitude and phase is calculated from Zeoppritz's equations using the algorithm from Aki and Richards (1980). The Aki and Richards (1980) polarity convention is followed where P-P reflection amplitudes are assumed positive for velocity increases while P-SV reflection amplitudes are opposite and negative for velocity increases with depth. The reflection amplitudes are convolved with a phase compensated Ricker wavelet to produce a trace for every offset.

Before stacking, an NMO correction and a mute can be applied. In the P-SV case the choice is between conventional NMO and the P-SV moveout equation derived by Slotboom et al. (1990). The mute is applied next, based on a selected mute velocity; to preserve normalized amplitudes, muted traces are not stacked. Stacking is the final step and the typical output includes the offset traces in ascending order and the synthetic stack trace.

## RESULTS

### Rolling Hills example

The method of calculating a synthetic stack was tested on well logs from two areas. In the first area the full-waveform sonic from the study by Geis et. al. (1990), in the Rolling Hills region of Alberta was used. The Rolling Hills VSP was acquired using a P-wave vibrator, with an 8-100 Hz sweep, offset 325 m from the well. The full-waveform sonic log was recorded from 2700' (823m) to 6020' (1835m). A density log from the well was also available.

# FLOW CHART

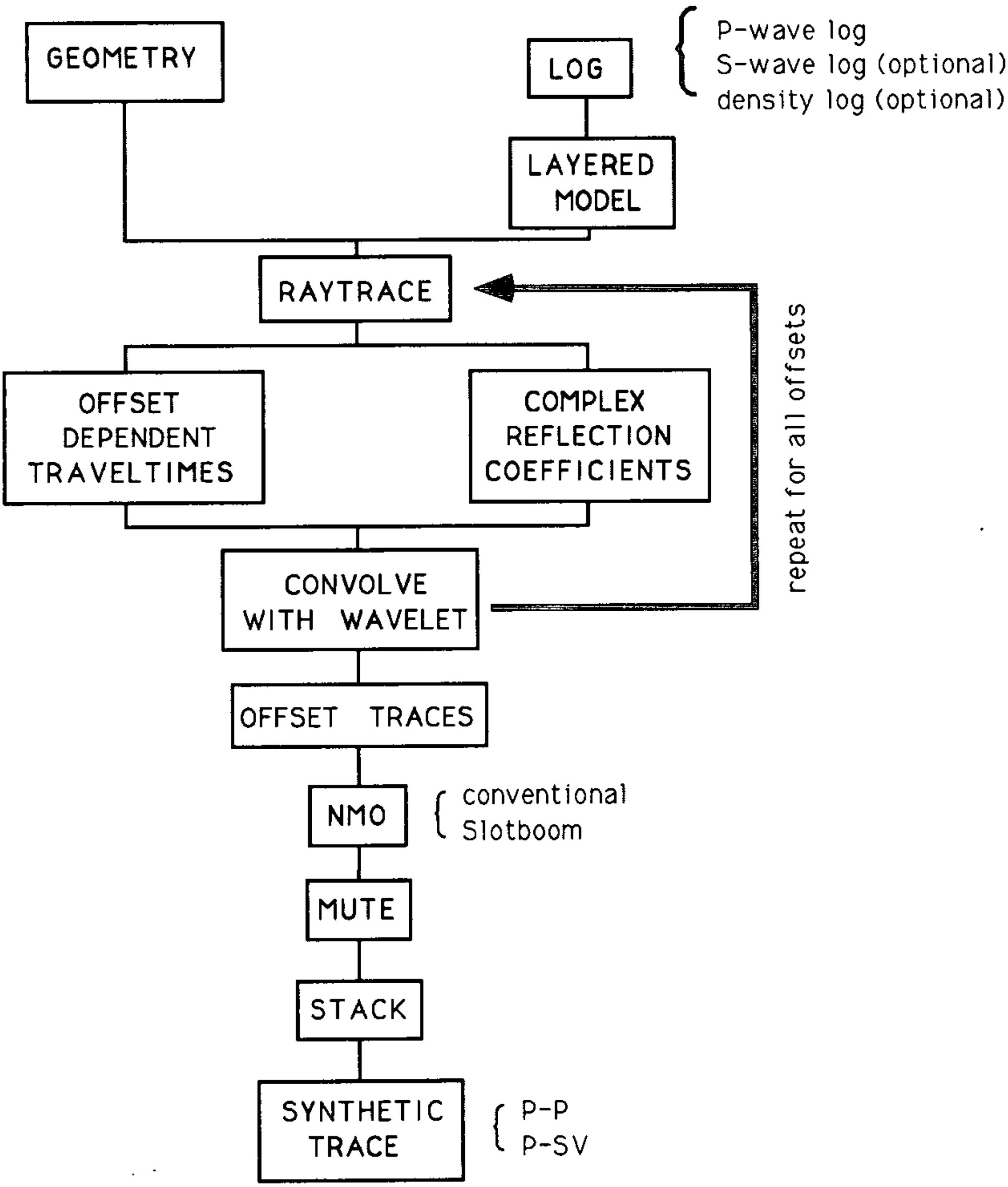


FIG. 2. Flowchart of the general steps followed to produce synthetic stacks.

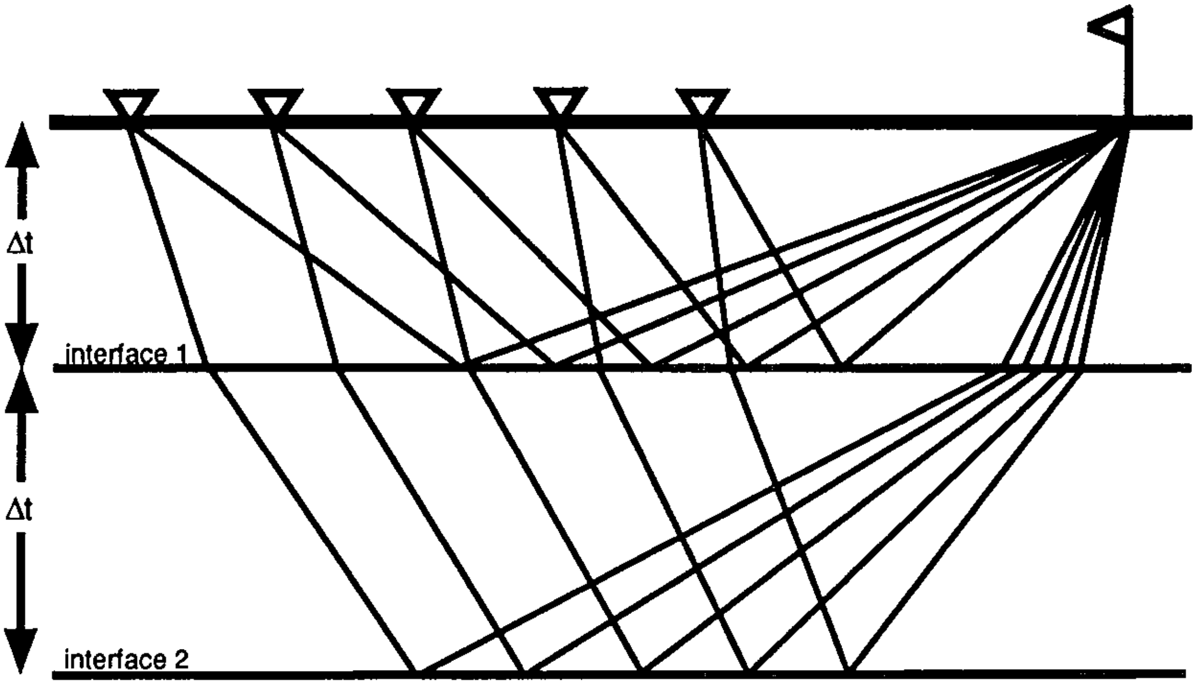


Figure 3. Model of constant traveltime layers raytraced at multiple offsets to produce traces for stacking into a P-SV synthetic stack.

Figure 4 compares the zero-offset P-P synthetic seismogram generated using GMA software, with the P-P synthetic stack and the VSP P-wave map. The P-P synthetic stack in Figure 4 was run using P-wave velocities from the full-waveform sonic log with Vp/Vs equal to 2.0 and was a result of stacking five offsets from 300 m to 500 m. The GMA zero-offset P-P synthetic was generated using P-wave velocities from the sonic log which was run over a longer interval than the full-waveform sonic log. The match between the zero offset synthetic and the synthetic stack is very close, as would be expected for the offsets under 500 m. Both synthetics match well with the VSP, demonstrating the reliability of the new method in the P-P case with a limited range of offsets.

In Figure 5, the VSP converted-wave map is compared with two P-SV synthetic stacks also generated by stacking five offset from 300 m to 500 m. The VSP converted-wave map was plotted in P-P time. The P-SV synthetic stacks were correctly plotted in P-SV time, but with a different time scale, allowing correlation of the events between P-P time and P-SV time. The first P-SV synthetic stack was generated using only the P-wave velocities from the sonic log and a Vp/Vs ratio of 1.85 based on results from Geis et. al. (1990). The middle P-SV synthetic stack was generated using the P-wave and the S-wave velocities from the full-waveform sonic log. Only very subtle differences are visible between the two P-SV synthetic stacks. The match between both P-SV synthetic stacks and the P-SV VSP is very good. In this offset-limited case, only a P-wave log and a single Vp/Vs ratio were necessary to produce a P-SV synthetic stack that closely matched the VSP.

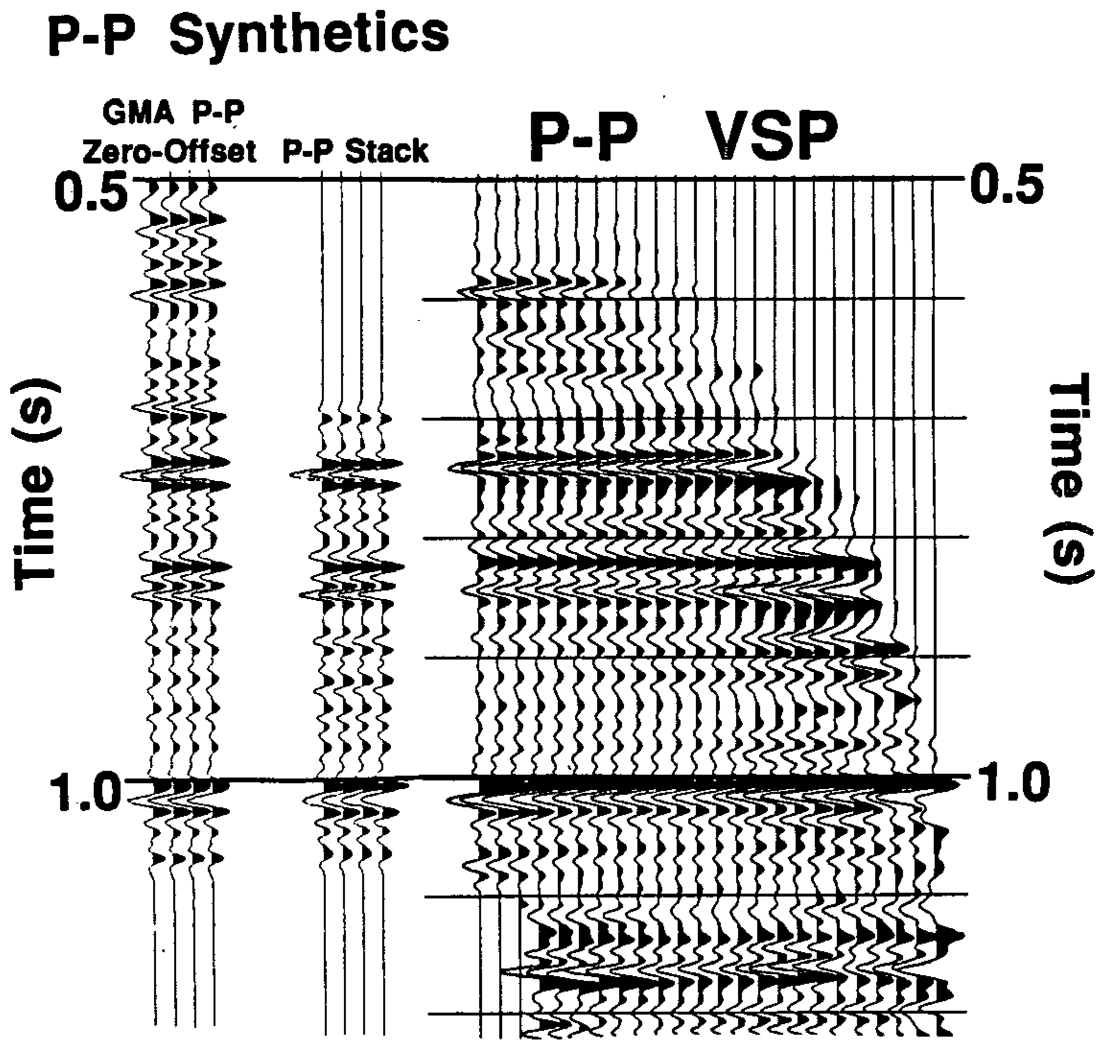


FIG. 4. GMA zero offset P-P synthetic seismogram and the P-P synthetic stack for five offset from 300 m to 500 m, compared with the P-wave map from the Rolling Hills VSP.

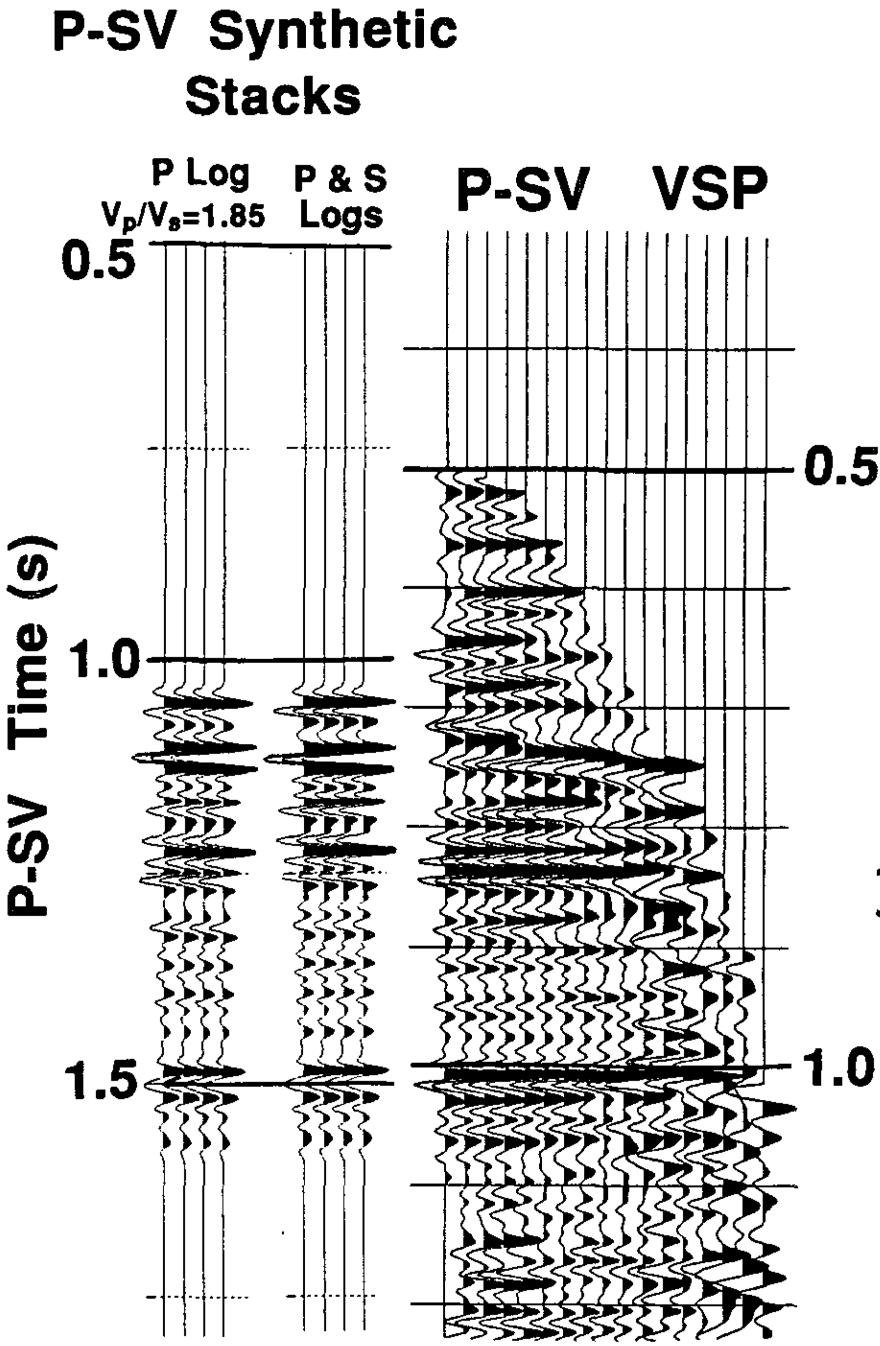


FIG. 5. The P-SV map from Rolling Hills compared to the P-SV synthetic stack created using a full waveform log (center), are a P-SV synthetic stack (left) created using the P-wave log only and an assumed Vp/Vs=2.

## Carrot Creek example

The second area was the Carrot Creek field in West Central Alberta, where a P-SV seismic line was originally processed by Harrison (1989). A second line, where a well is located, was processed and interpreted by Nazar and Lawton (1991). Only the P-wave sonic log was available for use. The Vp/Vs ratios, calculated by Nazar and Lawton (1991) by correlating the P-P section and the P-SV sections, ranged from 1.65 to 2.22, and averaged about 2.0. The energy source was a P-wave vibrator with a 10-94 Hz sweep. In each spread, there were 80 geophone groups with a far offset of up to 2500 m. The sonic log was recorded from 248 m to 2242 m. No density log was available.

Figure 6 shows three P-SV synthetic stacks all run with a Vp/Vs ratio of 2.0, a group interval of 125 m, a near offset of 0 m and a far offset of 2500 m. The first P-SV synthetic stack was run using the NMO equation from Slotboom et. al. (1990). The second stack was run using conventional NMO. Lower events in the zone of interest are no longer flat and the upper events are so distorted that a fairly severe mute above 1650 m/s was applied, and is shown in the third P-SV synthetic stack in Figure 6. The same conventional NMO and approximately the same mute were used in processing the Carrot Creek P-SV seismic section. Figures 7 and 9 use the same NMO and mute combinations to maintain consistency with the processed P-SV seismic data.

Figure 7 shows an excellent match between the P-P synthetic stack and the P-P seismic section, and also between the P-SV synthetic stack and the P-SV seismic section. Both the P-P and P-SV synthetic stacks were run with a Vp/Vs ratio of 2.0, a 125 m group interval, a 0 m near offset, a 2500 m far offset, a conventional NMO, and a mute of 1650 m/s. The synthetic stack is shown to be useful for tying P-P and P-SV sections, determining polarity, and interpreting events on P-SV sections.

Figure 8 shows first, a full P-P synthetic gather from zero to 2500 m, and then highlights the comparison of the P-P synthetic stack and the zero-offset P-P synthetic trace. The amplitude of several events on the gather can be seen to vary with offset. For these events there is a noticeable difference between the stacked trace and the zero-offset trace. If seismic data with long offsets has been processed to maintain true amplitudes, then the P-P synthetic stack will more accurately match the stacked P-P seismic section.

The two extreme Vp/Vs ratios of 1.65 and 2.22 were chosen and compared with a P-SV synthetic stack run using the more realistic ratio of 2.0 in Figure 9. The effect is to stretch or compress the synthetic stacks, leaving the character essentially unchanged. If the mute is constant and the Vp/Vs ratio is changed, there can be an indirect effect on character. The traveltime of events change, and therefore the amount of mute applied to the events can change, affecting the character. Even when an accurate value for Vp/Vs is unavailable, the P-SV synthetic stack still provides a reasonable match to the P-SV seismic section and can provide a check on the quality of the Vp/Vs ratio calculated using other methods.

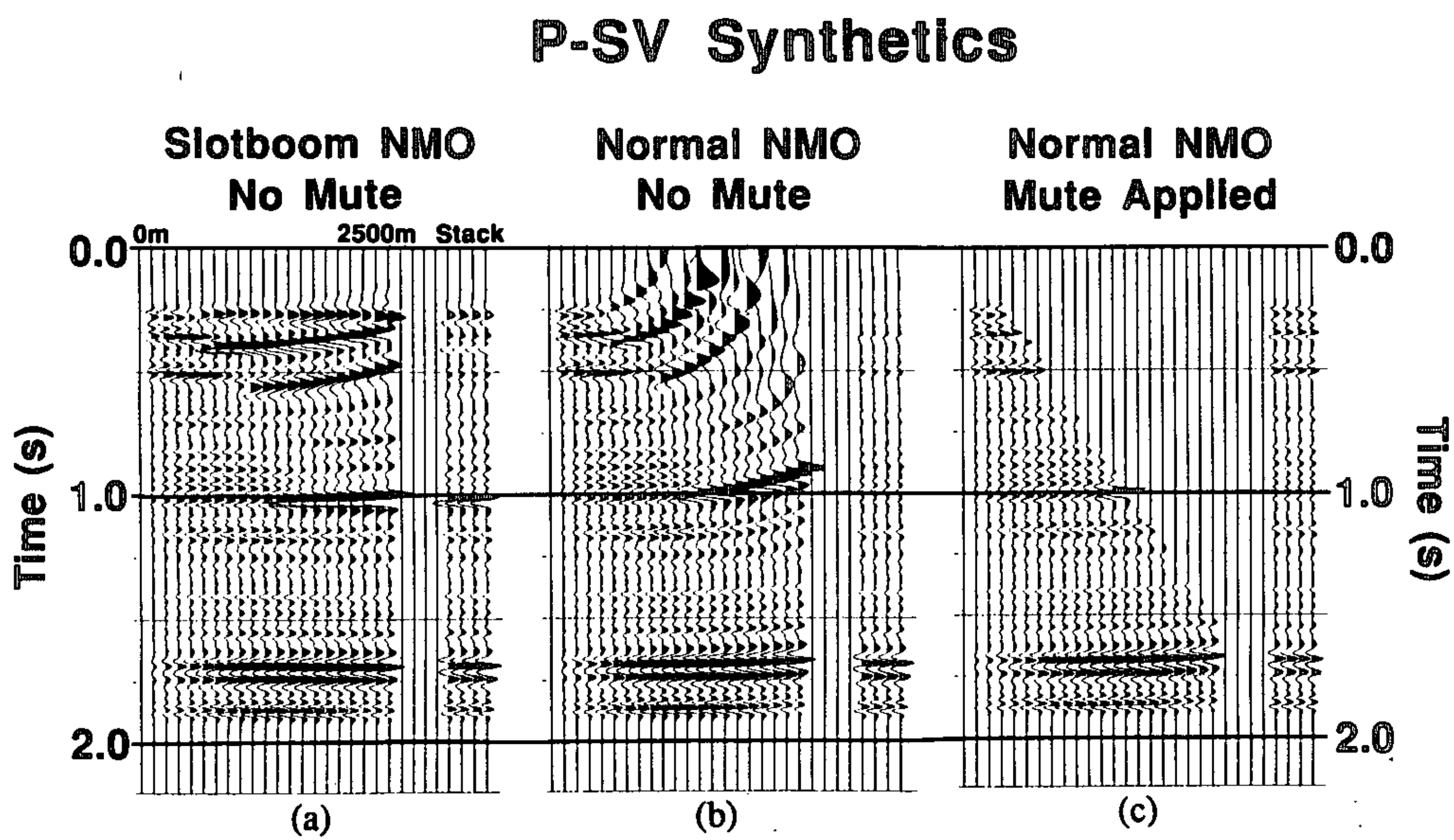


FIG. 6. P-SV synthetic gathers for offsets of zero to 2500 m. (a) with Slotboom NMO applied. (b) with normal NMO applied. (c) with normal NMO and mute applied.

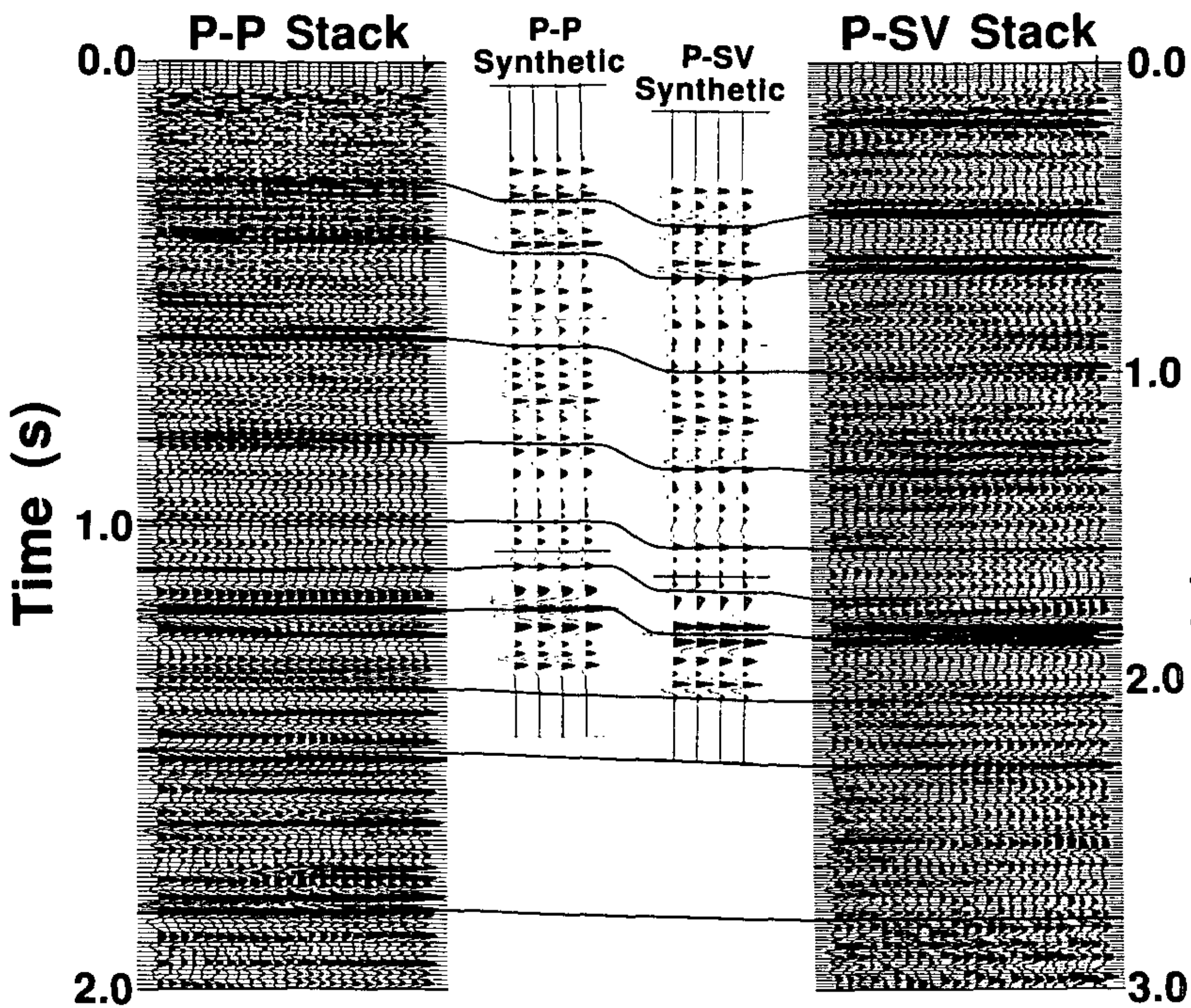


FIG. 7. Carrot Creek P-P section compared with P-P synthetic stack and P-SV section compared with P-SV synthetic stack (Nazar and Lawton, 1991).

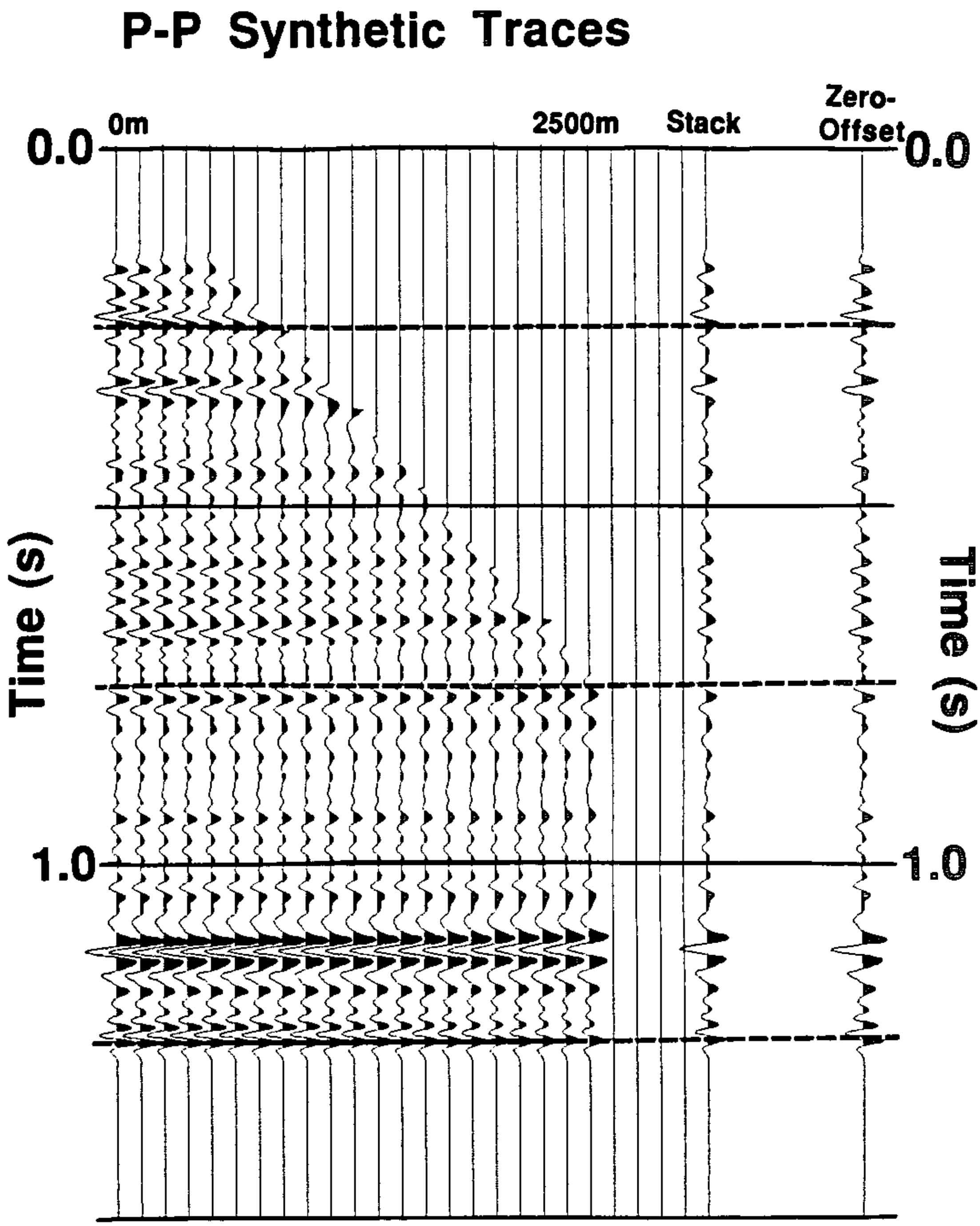


FIG. 8. P-P synthetic gather for offsets of zero to 2500 m and a comparison of P-P synthetic stack with the P-P zero-offset synthetic.

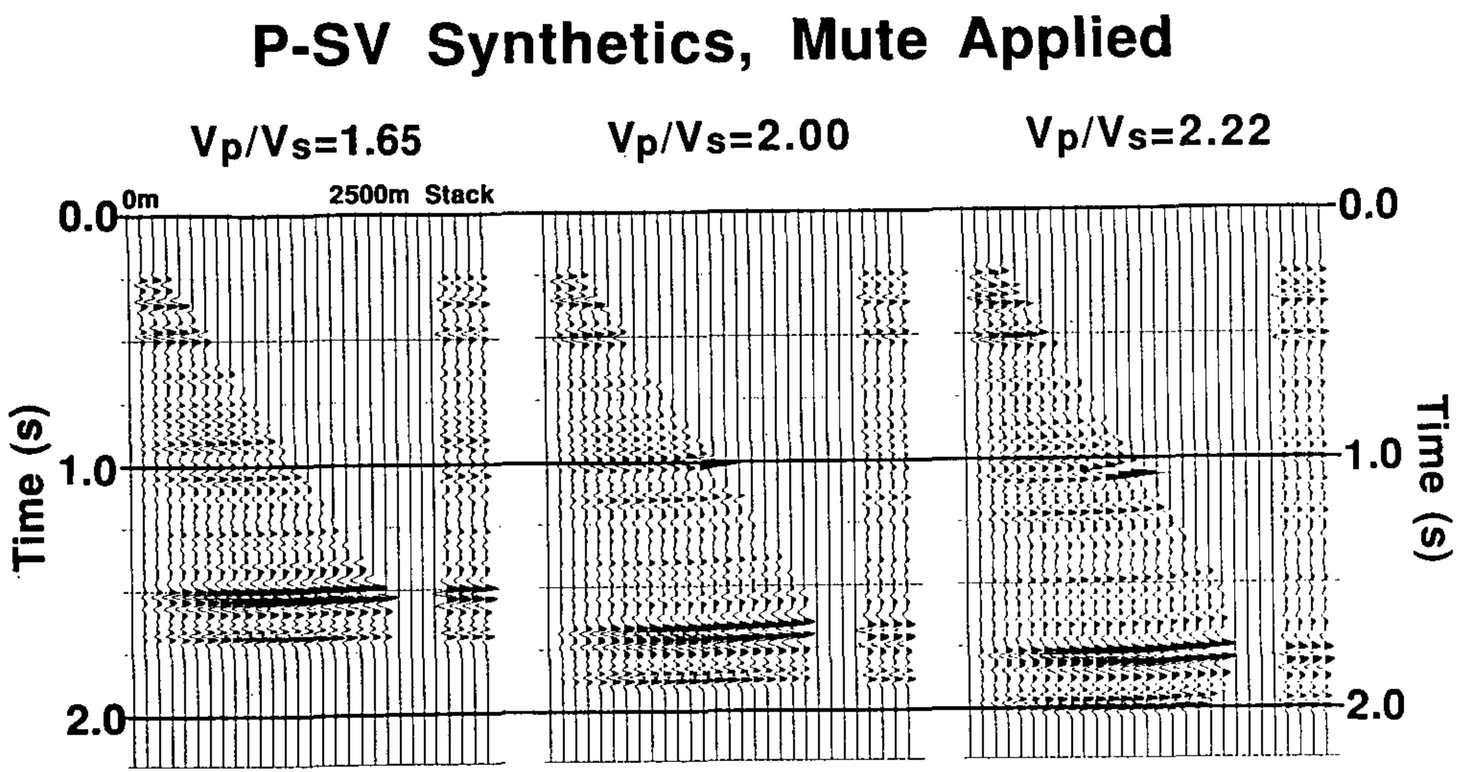


FIG. 9. Comparison of P-SV synthetic stacks using Vp/Vs of 1.65, 2.00 and 2.22 (left to right, respectively).

## CONCLUSION

At zero-offset, P-SV reflections do not physically exist and zero-offset P-SV synthetic seismograms can not be calculated using the same method as P-P synthetic seismograms. However, P-SV stack sections are the standard output of a P-SV processing stream and the P-SV synthetic stack presents a viable method for tying well log information to stacked P-SV seismic data. Several conclusions about this approach were drawn from this study:

1. A single Vp/Vs ratio was substituted for S-wave velocities in the calculation of the P-SV synthetic stacks, and the stacks still matched the P-SV seismic data very well.

2. The NMO and mute selected to create P-SV synthetic stacks had a very significant effect on the synthetic stack.

3. Changing the Vp/Vs ratio indirectly changed the character of P-SV synthetic stack if the mute was held constant, and directly changed the time position of events on the stack.

4. The accuracy of the time correlation between events on the P-SV synthetic stack and events on the P-SV seismic data could be used as a check on the calculated Vp/Vs ratio.

5. As should be expected, for offsets less than 500 m the P-P synthetic stack was found to very closely resemble the commonly used zero-offset P-P synthetic. For longer offsets of up to 2500 m there were slight character changes and amplitude differences between the zero-offset synthetic and the P-P synthetic stack.

## ACKNOWLEDGEMENTS

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