Analysing the Pikes Peak multi-offset VSP dataset

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ABSTRACT

As part of a continuing long-term study, a multi-offset VSP survey was shot in a test well at Pikes Peak, Saskatchewan during September 2000. Three-component data was recorded at a series of six offsets with an average lateral source-receiver separation of 90m. The data has a high signal-to-noise ratio, and the zero-offset data has already been found to tie well with a 2D seismic line conducted nearby (Xu, 2001). However, the dataset is still a challenging one, especially with regards to processing the farther offsets. High-frequency noise and static shifts due to tool-clamping problems initially suggested spurious geological information, while up-going arrivals on the farther offsets revealed important new subsurface velocity information. This dataset emphasizes the importance of survey and borehole information combined with quality control of each processing step for the ultimate accuracy of the seismic image and accuracy of the rock properties derived from the data.

INTRODUCTION

In late 2000, a multi-offset VSP survey was shot in Pikes Peak, Saskatchewan. The data collected are of good quality, with no tube waves and little surface noise and a high signal-to-noise ratio. However, this does not mean there are no challenges or potentially misleading features in the data. Survey and borehole information, together with quality control of first-break picking are vital starting points for the processing flow. If unusual first arrivals are not checked against borehole and survey conditions or for subtle but wholly artificial static shifts, the accuracy of the seismic image and understanding of the subsurface may be adversely affected. In this paper, the preliminary analysis used to explain two features of the Pikes Peak data set, a pattern of high-frequency noise contaminated traces and up-going first arrivals on the greater lateral source-receiver offsets will be described, finishing with how this information will be used to guide the rest of the processing flow.

ACQUISITION

Pikes Peak is a heavy oil field in North Saskatchewan owned by Husky Energy Inc. It has been subject to long-term, in-depth research to more accurately characterize the reservoir. As part of this research, a multi-offset vertical seismic profile survey was run in a test well (141/15-06-050-23W3M) just prior to shut-in. The well was chosen because it had not been used for reservoir steaming, and it passed through all the major area formations (Dey, 2000). It was also fully cased, with 17.8 cm diameter casing for its entire length, and a second, 24.5 cm diameter casing from the surface to 107.9 m (IHS Accumap, 2000a), providing a fairly consistent surface for borehole tool-clamping.

The VSP survey was carried out by Schlumberger Canada in September 2000. Data was collected with a five-level Array Seismic Imager (ASI) tool using three-component receivers at 15m spacing. The clamping mechanism was a set of rotatable permanent magnets (Schlumberger, 2001). The energy source was a Vibroseis truck running a linear sweep from 8 to 200 Hertz. Shot positions were at 23m (processed as and referred to in the rest of this paper as 'zero-offset'), 90m, 180m, 270m, 360m, and 450m. Sixty-six unique levels were recorded at a depth interval of 7.5m from a maximum depth of 515m to a minimum of 27m. The sampling interval was 0.001s for a total recording time of 2.999s.

PROCESSING SOFTWARE

Two VSP processing packages are being used to process and analyse the Pikes Peak data set: DSISoft from the Downhole Seismic Imaging for Mineral Exploration (DSI) Consortium in Ottawa, and Seislink from Baker Atlas Inc. DSISoft is a Matlab-based package freely distributed under the Gnu public licence. It may be downloaded from the DSI Consortium website at http://www.cg.nrcan.gc.ca/dsisoft/. The DSI package was chosen to process the 23m offset data and for preliminary analysis of the farther offsets for its ability to run on a PC workstation and with a view to continuing code development. The complete processing of the farther offsets will be done in Seislink, a UNIX-based package, in order to take advantage of its robust migration tools.

PRELIMINARY PROCESSING AND OVERALL DATA QUALITY

The process of vertical stacking revealed that the shallowest five levels had been recorded twice, and that there were occasional dead traces due to recording problems. After culling and sorting, the vertical stacking bins contained from five to fourteen traces. Trace summation was followed by removal of a strong DC bias on all traces by an arithmetic mean algorithm. Overall, the offset datasets have a high signal-to-noise ratio, although the 90m offset suffers from section wide high-frequency noise below roughly 0.5 seconds.

Figures 1, 2, 3, and 4, the vertical and radial components for the zero and 180m offsets, illustrate two of the first striking features of the Pikes Peak data set. Despite the change in borehole diameter from 24.5cm to 17.8cm at 107.9m, there is no obvious change in received seismic energy. It is somewhat surprising that there are no tube waves on any of the offset records due to this significant change in borehole diameter. The ASI tool has successfully excluded them, along with the surface noise in the area of the borehole. The four figures also illustrate the presence of strong shear wave events. The shear wave events in Figures 1, 2, and 4 are probably due to energy generated by the vibrator. This is also a bit surprising, as this event represents strong shear energy in the vertical direction from a conventional Vibroseis source. Figure 3 shows both a source-generated shear event and one that is probably due to the subsurface geology. However, as explained in the next section, these figures also reveal two features that can deceive an unwary data processor.

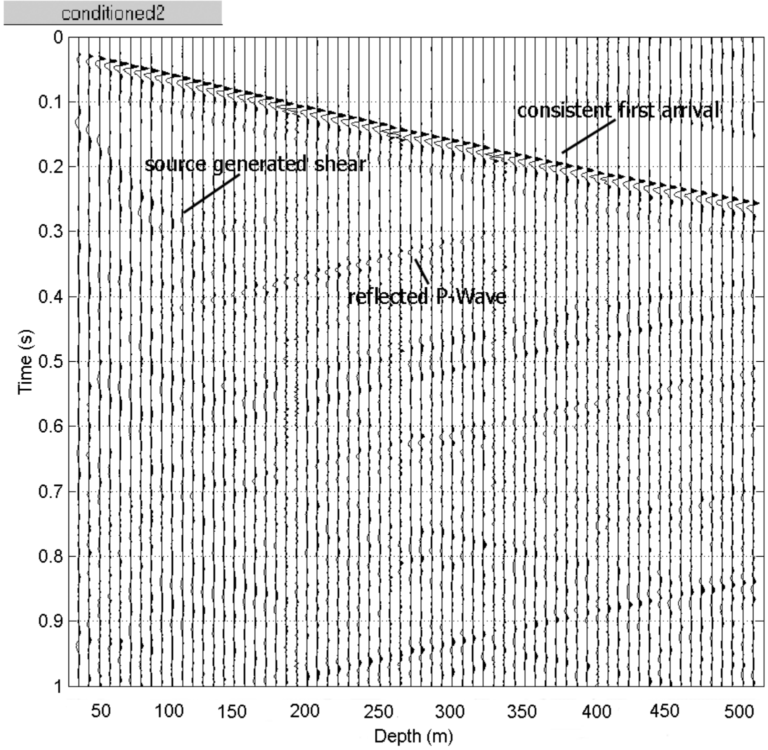

FIG. 1. Vertical component of the zero-offset data.

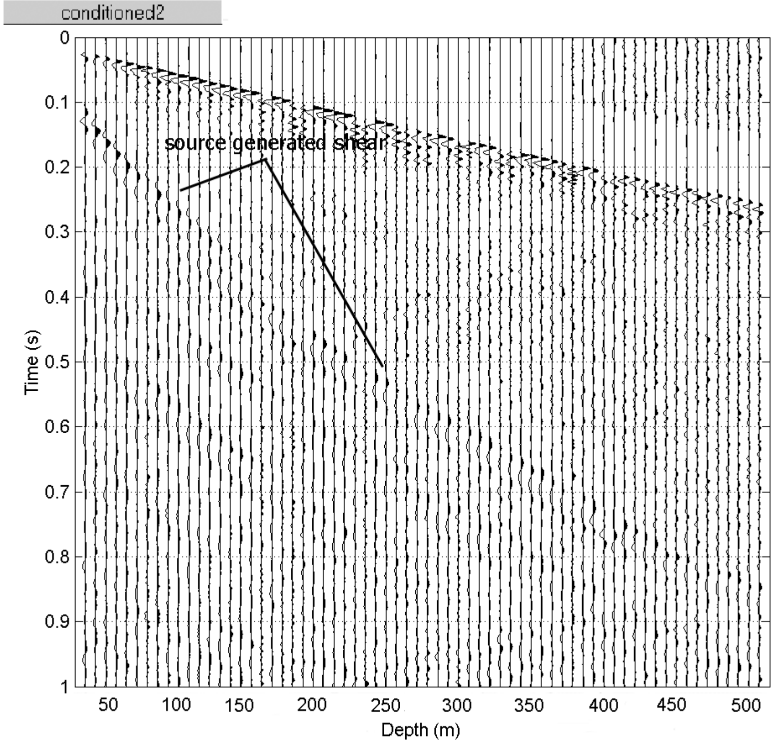

FIG. 2. Radial component of the zero-offset data.

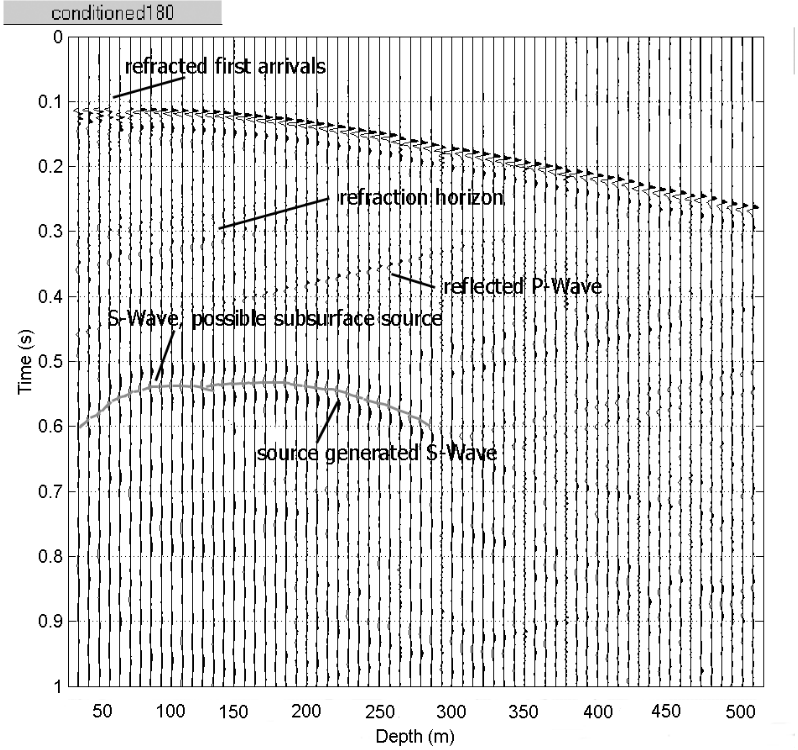

FIG. 3. Vertical component of the 180m offset data.

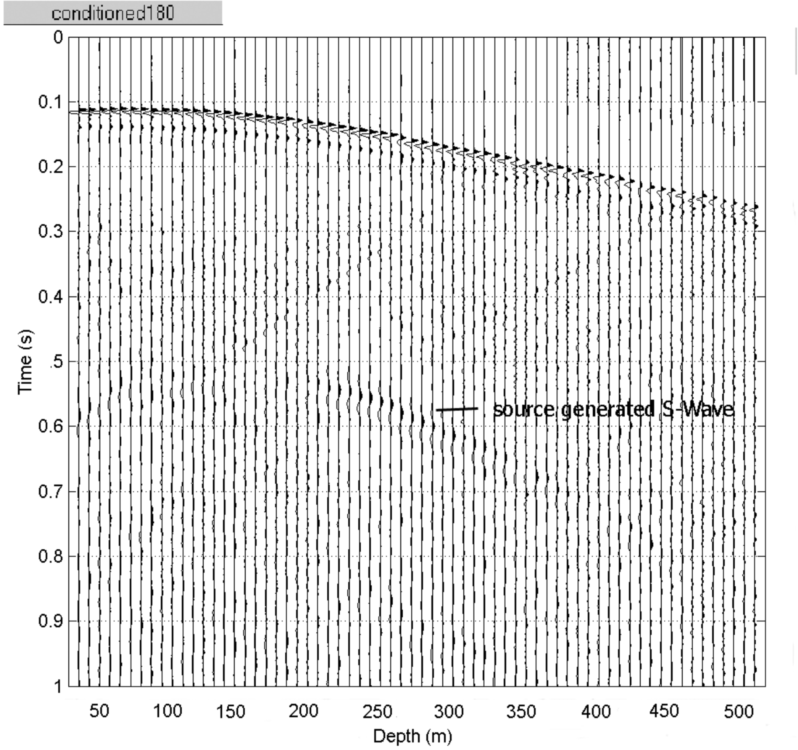

FIG. 4. Radial component of the 180m offset data.

PROCESSING CHALLENGES IN THE PIKES PEAK DATASET

1) Borehole-Tool Coupling Issues

The vertical component of the zero-offset data also reveals a regular pattern of high frequency noise contamination (on traces 21, 22, 31, 32, 41, 42, 51, and 52). More convincing frequency-depth plots of the ungained zero-offset vertical and radial components are in Figures 5 and 6. The problem traces fall in the depth interval 177.2m to 470.0m, well below the region of doubled casing (surface to 107.9m). The ten-trace separation between pairs of contaminated traces shows the problem is due to tool-clamping issues rather than poor casing cement. A schematic of the tool move pattern in Figure 7 identifies the first receiver with the coupling problems. The first receiver is sometimes noisy in VSP surveys simply because it is at the top of the sensor package, but this type of high-frequency ringing is a signature of poor receiver-borehole wall coupling.

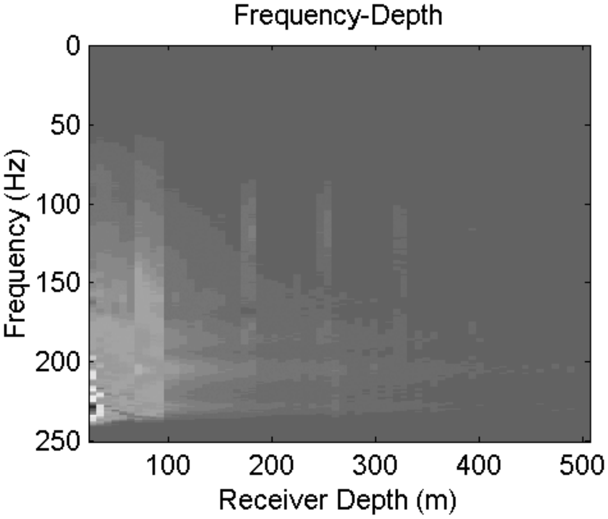

FIG. 5. Frequency-depth plot of the ungained vertical component of the zero-offset data.

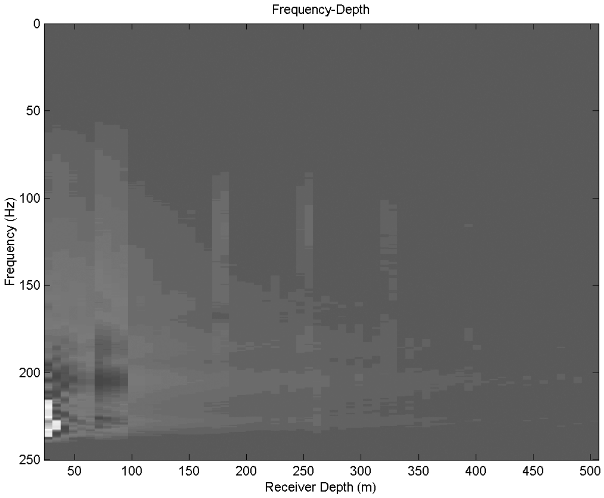

FIG. 6. Frequency-depth plot of the ungained radial component of the zero-offset data.

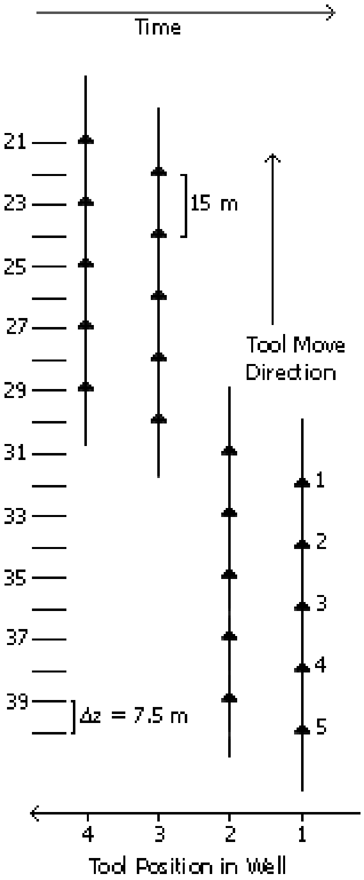

FIG. 7. Tool move pattern used for the Pikes Peak VSP survey. At position one, the tool records data at levels 32, 34, 36, 38, and 40. It is then moved 7.5 m, and detects data at levels 31, 33, 35, 37, and 39. After raising the tool 67.5 m (position 3), the sequence begins again.

At the start of the VSP survey at Pikes Peak, wax build-up in the well caused the ASI tool to become temporarily stuck at the bottom of the recording interval. Accordingly, there are no ringing traces for that section of the recording range. Figure 8 consists of a diagram showing how the magnetic clamping system actually contacts the borehole wall. Like most clamping systems, it uses two contact points. Anything that may prevent one or both points from settling firmly against the borehole wall may lead to high-frequency ringing with each shot. Unfortunately, as in this dataset, the ringing often falls within the seismic frequency band and cannot be filtered without damaging the data. A potential solution in future borehole tools is to use a three-point contact system for at least the first receiver, creating a tripod that maximizes stability on many irregular surfaces. Of course, the only way to deal with clamping problems at the join between two different casing diameters or borehole washouts is to clamp the receiver above or below the join or washout if possible. Finally, the lack of high frequency noise on the traces recorded above 177.2m reflect a combination of the high-amplitude, low-frequency shear event and the cleaner well bore.

First-break picking made apparent a small but important static shift between each group of ten traces that creates four false velocity spikes when the velocity-depth curve is calculated. The static error, ranging from 1.5 to 3.5 milliseconds, may be due to time delays during recording, tool response, or inaccuracies in the depth measurements. The static shifts were corrected using a combination of curve fitting to determine the best correction and the handstatics algorithm in DSISoft.

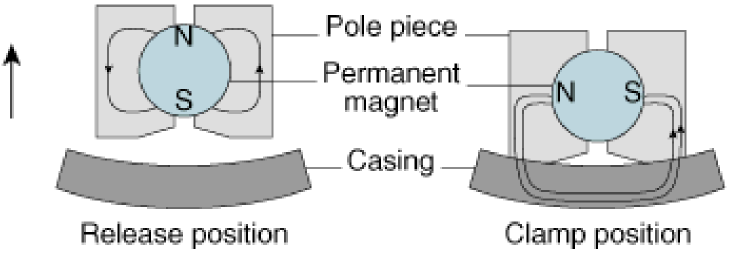

FIG. 8. The magnetic clamping system used by the ASI tool. (From the Schlumberger Canada Corporate Website, 2001.)

2) Up-going First Arrivals at Offsets Greater Than 90m

A second complication appears at 180m offset, when first breaks with reversed polarity relative to the others begin to appear on the vertical components. The decreasing arrival times for the reversed polarity arrivals together with their polarity indicate they represent up-going energy. Figures 9, 10, and 11, a series of plots of all components from 90m, 180m, 270m, 360m, and 450m offsets show the increasing number of up-going arrivals with lateral source-borehole distance on the vertical components. The scalloped trend of the first breaks on the farther offsets suggests the presence of two refracting layers in the subsurface. Approximate depths to these layers were picked where possible, for the results in Table 1. Only the depths for the second refractive layer fall within the region covered by the sonic log, which extends from 113.6m to 521.3m (IHS Accumap, 2000b).

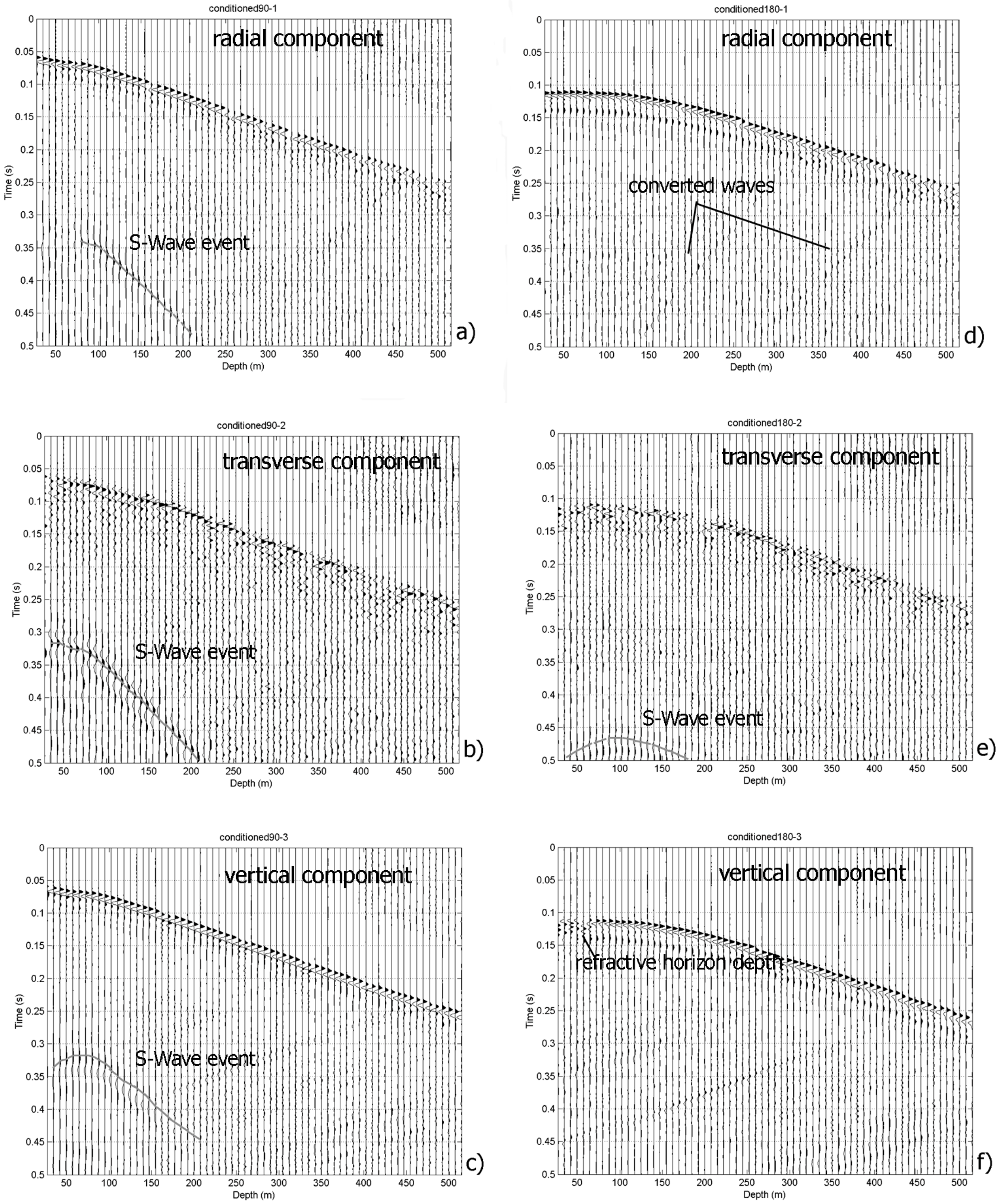

FIG. 9. Radial, transverse, and vertical components for the 90 m and 180 m offsets.

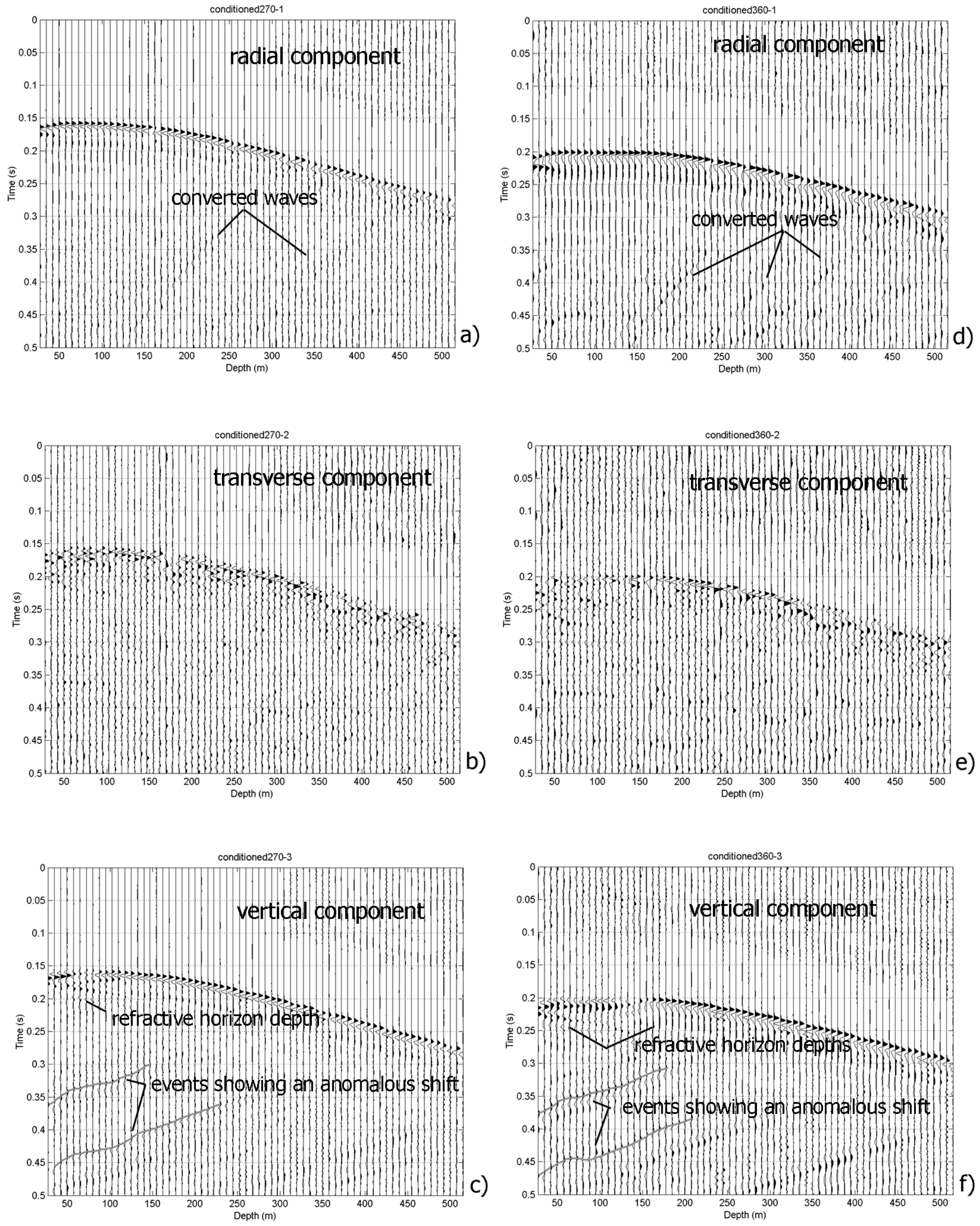

FIG. 10. Radial, transverse, and vertical components for the 270 m and 360 m offsets.

The rot3c module in DSISoft was used to rotate the original horizontal components to radial and transverse positions. In particular, notice the first breaks arriving at deeper receivers before shallower ones on the vertical components in Figure 11c (traces 11 to 17) and on the radial components in Figures 10a and 10c, the strong shear events still visible on Figure 9a, b, c, and e, and the converted waves on Figure 9d and Figure 10a and d. Perhaps more intriguing than any of these are the highlighted events on Figure 10c and d. The slight dogleg in each picked event suggests an unexpected high-velocity stratum at approximately 80m depth.

	Offset (m)	Approximate Depth (m)
Refractive Horizon 1	180	57.27
Refractive Horizon 2		-
Refractive Horizon 1	270	72.39
Refractive Horizon 2		-
Refractive Horizon 1	360	57.27
Refractive Horizon 2		147.01
Refractive Horizon 1	450	64.71
Refractive Horizon 2		162.12

Table 1. Approximate depths to refractive layers.

Dillon and Thomson (1984) described the geological and tool conditions under which polarity reversals and inverted arrival times may occur:

a) Clamping a receiver in a low-velocity formation just above a high-velocity formation. Refracted head-waves may have shorter arrival times than direct waves that must travel through the low velocity medium. The resulting trend of the head-wave first breaks may be curved in the presence of layers and gradients. A curved trend is seen on the Pikes Peak dataset.

b) Moving a receiver into the high-velocity medium in the same geological conditions as (a) can then result in inverted direct arrivals, deeper receivers receiving data prior to shallower ones, as best seen in Figure 10f and 11c.

Note that in these scenarios an important implicit assumption is being made about the borehole where the data are being recorded: that its casing does not change in a way that may alter the traveltimes of the arrivals. Although the casing conditions are different between the surface to 109.7m interval and the remainder of the well, this assumption has not been violated at Pikes Peak. Figure 1 demonstrates this via the phase consistency of its first arrivals. If the casing had had any significant effects on the data, those effects should have been visible at any offset.

The velocity-depth curve calculated from the zero-offset data in Figure 12 (static and corrected for the actual lateral source-borehole offset) show two distinct gradients. A faster gradient in the 27.0m to 109.7m interval, and a more gradual, curved gradient for the rest of the recording interval. As noted in the Acquisition section, from the surface to 109.7m there is a second, narrower casing within the first. However, the gradient actually reflects the transition from low-velocity, unconsolidated near-surface to more consolidated material in the subsurface.

The pre-survey modelling used to determine the best recording interval and source spacing was based on the sonic log. Neither the velocity information from the check shot survey data nor the sonic log suggest the presence of any high velocity layers in the geology of the correct thickness for the effects observed on the data (Newrick et al, 2001) in the deeper subsurface. One of the goals of continued processing is to confirm or rule out whether the up-going first arrivals represent turning waves rather than head waves.

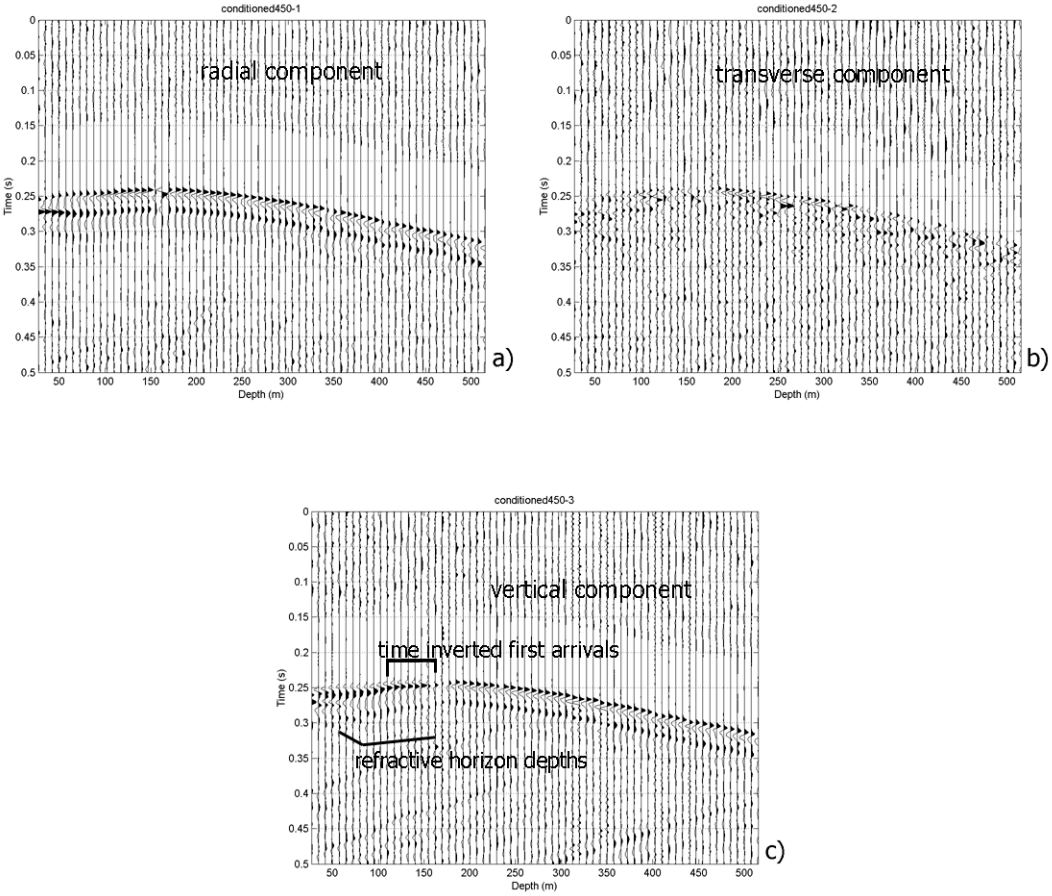

FIG. 11. Radial, transverse, and vertical components for 450m offset.

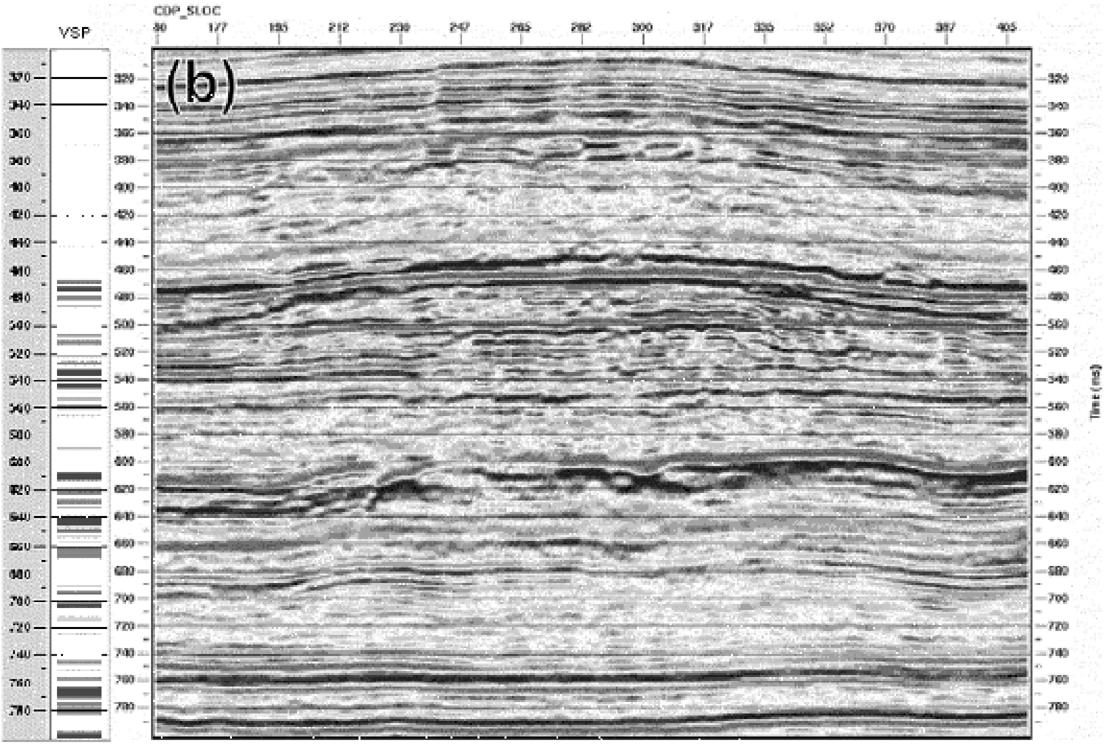

FIG. 12. The zero-offset VSP corridor stack (left) versus data from the nearby 2D seismic line (right). (From Xu, 2001.)

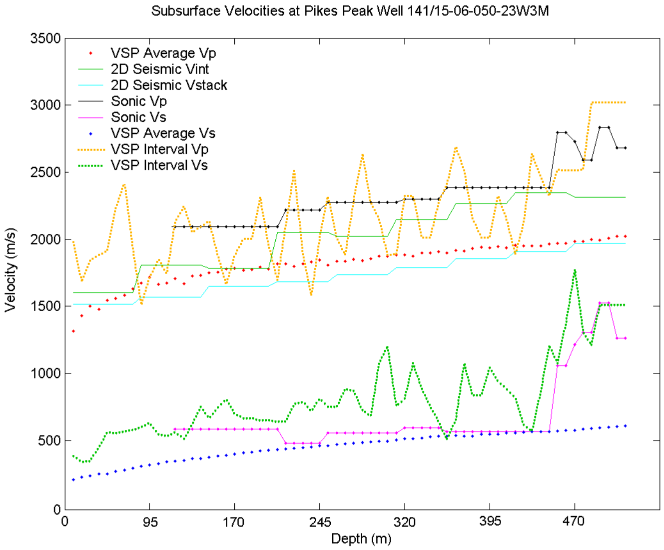

FIG. 13. Average, interval, stacking, and sonic velocities versus depth for the zero-offset data. The VSP average velocities were calculated from the first break times and distance between the receiver and the source, corrected for the 23 m lateral offset. The VSP interval velocities were calculated using a version of the Dix equation, including correction for the lateral offset.

CONCLUSIONS

The Pikes Peak multi-offset VSP dataset is an important and informative one. It is a strong reminder to the data processor to gather as much information as possible about the survey and borehole conditions, as well as quality checking headers, traces, and first-breaks. The zero-offset data correlates reasonably with the 2D surface seismic data collected near the well in March 2000, as can be seen in Figure 12. The high signal-to-noise ratio of the offset data, ranging from a minimum of 24.85dB to a maximum of 25.93dB suggests two things. First, the ASI tool has effectively compensated for the regular static shifts by blocking tube wave and surface noise. In the case of a VSP survey run in a well in a high activity, high surface noise area without provisions to block tube waves, the signal-to-noise ratio may range from 4.8 to 15.5dB (Simmons Jr., 1999). Second, a properly designed velocity model may allow successful migration of both the traces affected by up-going first arrivals and those that are not. The VSP data also illustrates the potential value of modelling software that can calculate turning ray-paths accurately.

Even before the more detailed analysis required to determine the causes of anomalous data shifts, actual refractor depths, or whether the farther offsets have been affected by turning waves or head waves, important subsurface information has been revealed by the data. Figure 13 shows the average and interval VSP velocities from the zero-offset data, together with interval and stack velocities from the surface seismic and blocked curves from the sonic log. As expected, the average P and S velocity curves from the zero-offset VSP data are incorrect. The velocities are both too low and too smooth compared to the sonic data and the surface seismic interval velocities. The two high velocity layers visible towards the end of the well (between approximately 350m and 500m) aren't evident at all on the average velocity curves.

However, the VSP interval velocity curves are more promising, as they do have two distinct high-velocity segments near the end of the well. There is also a suggestive region of high-velocity between 57m and 95m, which includes the suspected depth of the first refracted layer.

FUTURE WORK

The VSP data from Pikes Peak contains important shear- and compression-wave data on all offsets and almost all components. P-P and P-S images from the fully processed offset data should provide more detailed subsurface information. To that end, processing of the data is continuing, including development of velocity models that include the effects of the various refraction events for the best migration result. Among the issues that will be addressed during the continued processing and modelling are: determining the actual cause of the up-going arrivals on the farther lateral offsets, confirmation of the shallow refractive horizon depths, and finding the cause of the anomalous shifts so evident in Figure 10c and f.

The final velocity models may also be compared to those used by Xu (2001) to estimate Q-values for the region, and perhaps explain the negative Q-factor estimates for shallower depths. An additional area of follow up is on raytracing software for pre-survey data modelling, specifically implementing more accurate turning wave calculation.

ACKNOWLEDGEMENTS

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