Acquisition and preliminary analysis of the Castle Mountain shallow VSP dataset

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ABSTRACT

As part of the 2006 geophysics field school for the University of Calgary Department of Geology and Geophysics, a shallow VSP survey was conducted by students in two water wells at the Castle Mountain Ski Resort near Pincher Creek in southwestern Alberta. The wells were drilled in unconsolidated sand and gravel to total depths of about 37 and 42 meters, ending a meter or so into shale bedrock. A 7.3 kg sledge hammer source was used with a pressure-proofed clamping 3C geophone and an eight-element hydrophone array as the downhole sensors. A Geometrics R60 seismograph recorded data at various source offsets from the wellhead. Both P and S events were present on the data. Using picked arrival times and source-detector separations, apparent velocities were estimated to lie between 1100 m/sec to 2000m/sec for the P wave, and between 350m/sec to 400 m/sec for the S wave. A more accurate P-wave velocity versus depth profile around one of the wells was obtained by modelling the arrival times using a refracting boundaries ray-tracing program. Future processing of the data will attempt to identify reflections from the overburden/bedrock interface for VSP/CDP imaging.

INTRODUCTION

The University of Calgary Department of Geology and Geophysics held its 2006 geophysics field school near Castle Mountain in the Pincher Creek, Alberta, area. One activity, carried out by students, was the acquisition of VSP data around two vertical water wells on property owned by the Castle Mountain Ski Resort. The exercise occurred over a period of two weeks in August and September, and, in addition to introducing students to basic VSP field procedures, it resulted in an interesting dataset that may prove useful for evaluating the groundwater potential in the immediate vicinity of the ski lodge.

Figure 1 is a plan map of the immediately environs of the ski lodge showing the locations of the two wells, which are designated the Lodge Well and the Duplex Well. The Lodge Well is about 43 meters deep, while the Duplex Well is about 32 meters deep. Both wells are drilled through sand and gravel down to the shale bedrock. Both wells are cased with steel casing at the top and screened sections at the bottom, allowing inflow of groundwater. The inner diameters were about 20.3 cm for the casing, and 17.8 cm for the screen.

Along the cased parts of the wells, a bentonite seal was forced around the casings to prevent vertical groundwater flow. At the time of the field school, the static water levels were about 6 meters below ground level in the Lodge Well, and about 5 meters below ground level in the Duplex Well. Figure 2 contains some details regarding the construction of the wells and the geological materials they encountered.

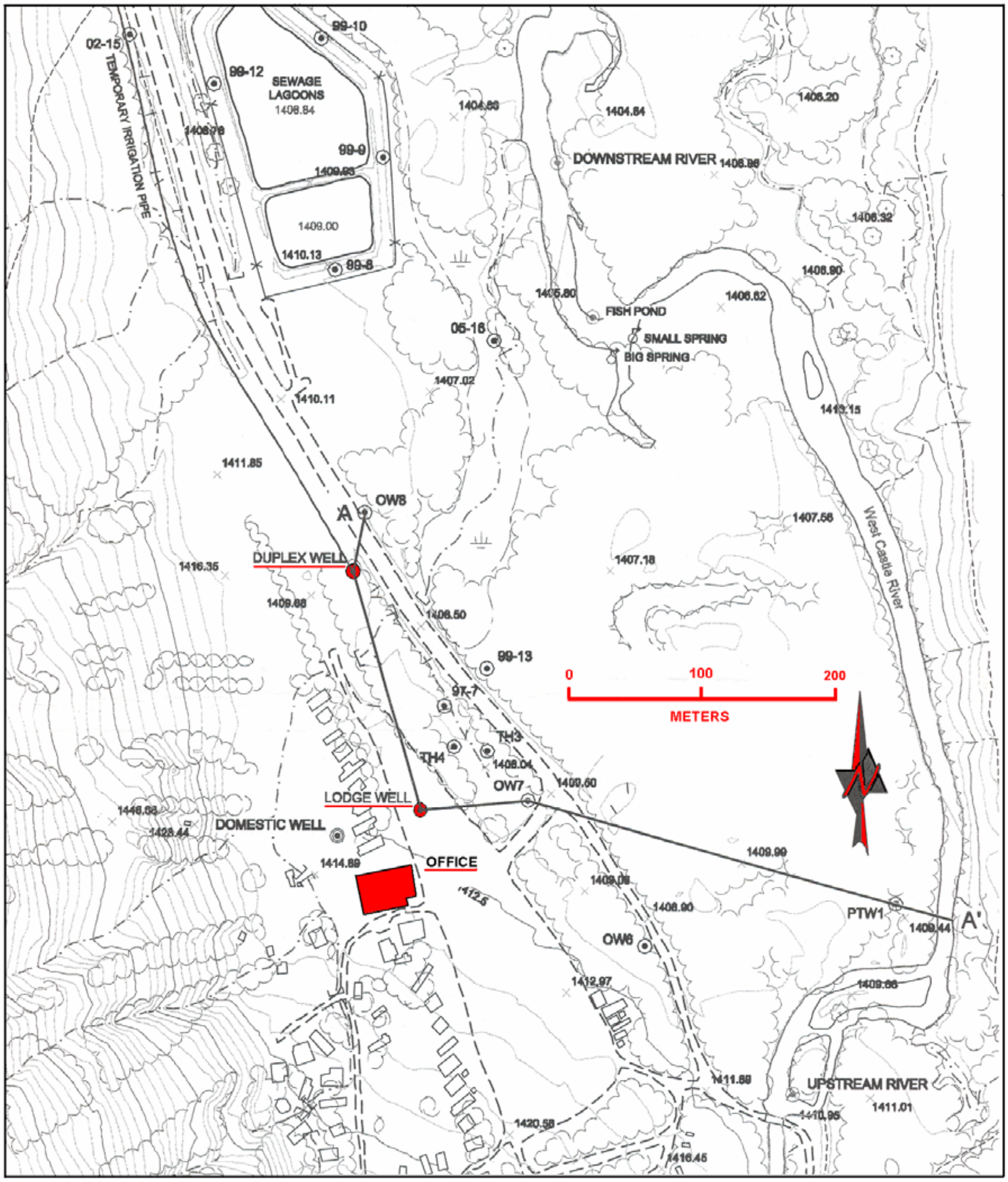

FIG. 1. Property map of the Castle Mountain Ski Resort. VSP surveys were held near the Lodge Well and the Duplex Well.

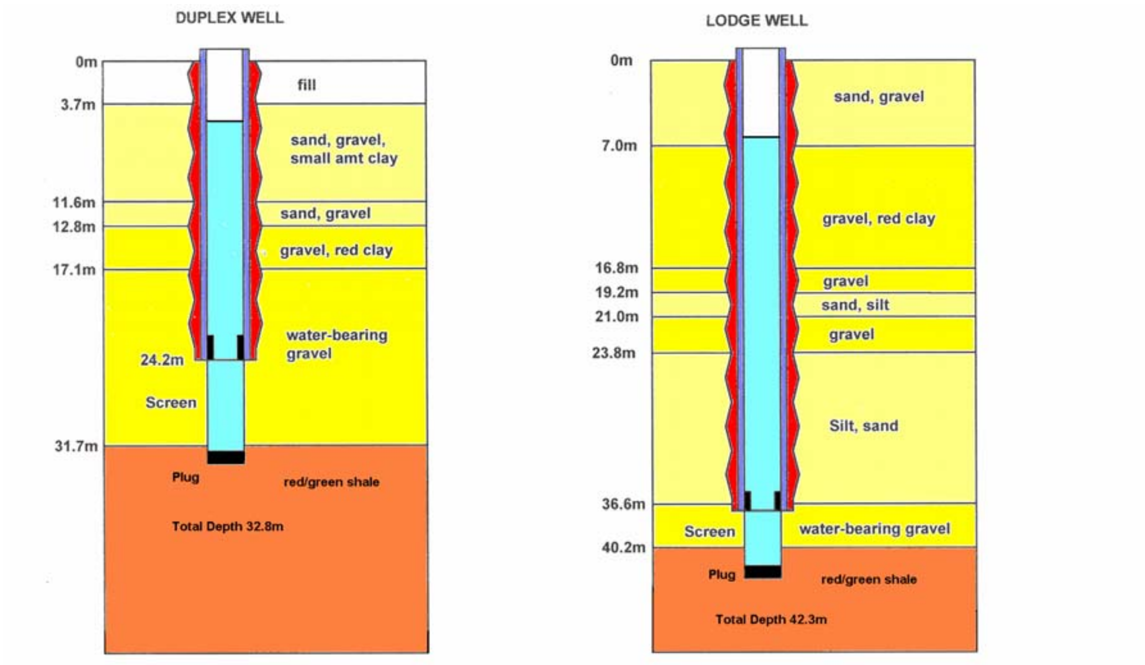

FIG. 2. Vertical section showing the construction of the Duplex and Lodge Wells. The red material around the outsides of the casings is a bentonite seal used to prevent vertical groundwater flow.

In the first half of the 2006 Field School, VSP surveying was done in and around the Lodge Well over two days in the last week of August. In the second half, VSP surveying was done in and around the Duplex Well over two days in the first week of September. Although VSP surveying was done using both wells, we will address only the Lodge Well survey, leaving discussion of the Duplex Well survey to a future report.

FIELD ACQUISITION

Field acquisition procedures for VSP surveys are described in Hardage (1985). Figures 3 and 4 show the two geometric configurations used for the VSP experiment. Figure 3 is the fixed source offset scheme; recording is done with the surface source at a fixed distance from the wellhead and detectors at many depths down the hole. Figure 4 is the walk-away scheme, where a detector is kept at fixed depth in the well, while recording is done with surface shot locations at many offsets along a line laid out in a SE to NW direction. Stations were measured in at 1 m intervals from -31 m (SE end) to +31 m (NW), with the well located at 0 m.

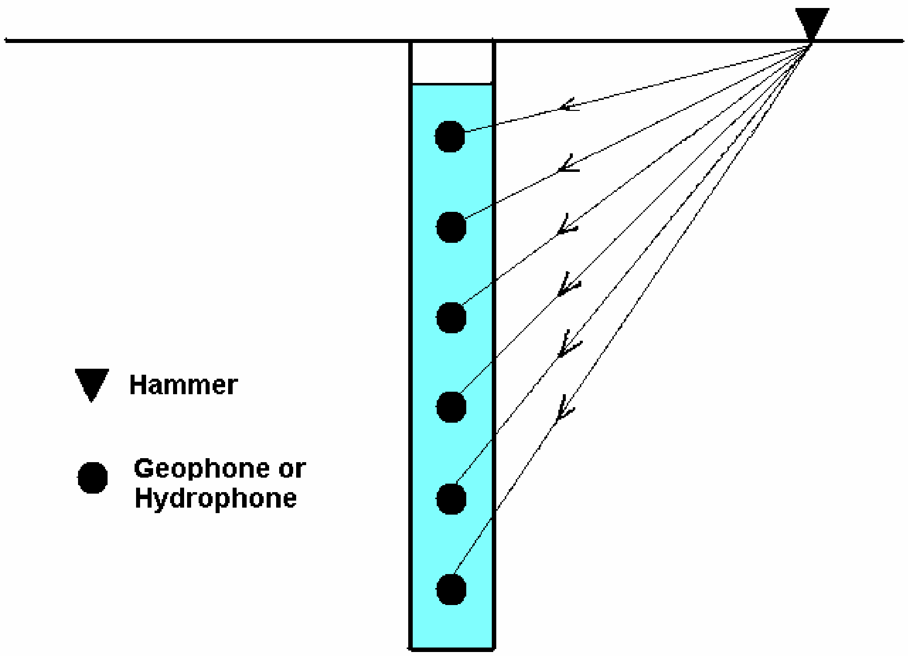

FIG. 3. Depth profile shooting with fixed source offset.

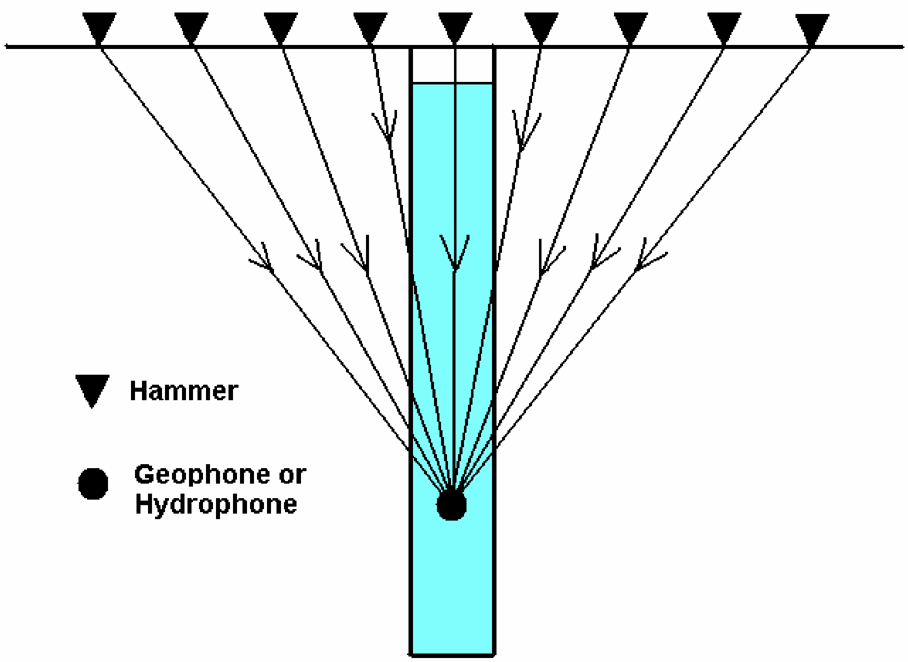

FIG. 4. Source walk-away profile with fixed downhole detector.

The source was 7.3 kg sledge hammer striking an aluminum cylinder with its serrated base set into the ground. We used a Geostuff BHG-2 clamping 3-C geophone as well an array of eight hydrophones as the downhole sensors. Channels 1 to 3 of a Geometrics Strataview R60 seismograph were used to record the VSP seismograms. The 57 remaining channels of the seismograph were connected to surface 3C geophones. Nine 3-C geophones were placed at stations -20 m, -18 m, …, -4 m; another ten 3C geophones were placed at +2 m, +4 m, … +20 m. The surface seismic data from the field school will not be considered in this report.

Separate ends of conducting wires attached to the metal head of the sledge hammer and the aluminum strike cylinder. The metal head striking the aluminum cylinder closed the triggering circuit of the seismograph, initiating digital sampling of the detector outputs. This arrangement provided a reliable zero time.

Source points (hammer locations) were restricted to the 0 m station (at zero-offset) and odd-numbered stations ranging from -31 m to +31 m. The downhole geophone and the hydrophone array were lowered down into the Lodge Well by guiding the attaching cable over a sheave wheel (or pully) mounted over the wellhead. The top of the sheave wheel was 1.1 m above ground level. All geophone and hydrophone depths in this report have been corrected for the sheave wheel elevation, and so are referenced to ground level. The downhole geophone occupied depths ranging from 3 m to 42 m at one-meter intervals. Hydrophones were installed, below water level, at 1 m depth increments from 10 m to 42 m. We recorded with a sampling rate of 0.5 ms, a record length of 0.512 seconds, and a high cut filter of 500Hz.

FIELD RESULTS

Hydrophone recorded VSP

Figures 5, 6, and 7 are hydrophone-recorded VSPs with source offsets of 0 m, 15 m and 19 m from the wellhead. The gathers for the 0 m and 15 m offsets have interpolated traces plotted between the integral depth positions.

The hydrophone VSP with 0 m source offset appears to have lower signal levels than does the hydrophone VSP with 15 m and 19 m source offsets. The following explanation may account for this observation. Hydrophones respond to water pressure in the well, which in turn responds to forces acting perpendicular to the walls of the well. At 0 m offset, the hammer blow right at the wellhead generates a P-wave with vertical particle motion parallel to the well wall. In the vertical propagation direction, the particle motion then is always parallel to the well wall, and so will not affect the water pressure very much. Consequently, the hydrophone output should be weak for the zero-offset source. At a non-zero source offset, both P and S waves impinge on the well wall with particle motions that have components perpendicular to well wall. In this case, the incident seismic energy will cause changes in water pressure in the well that can be sensed by hydrophones.

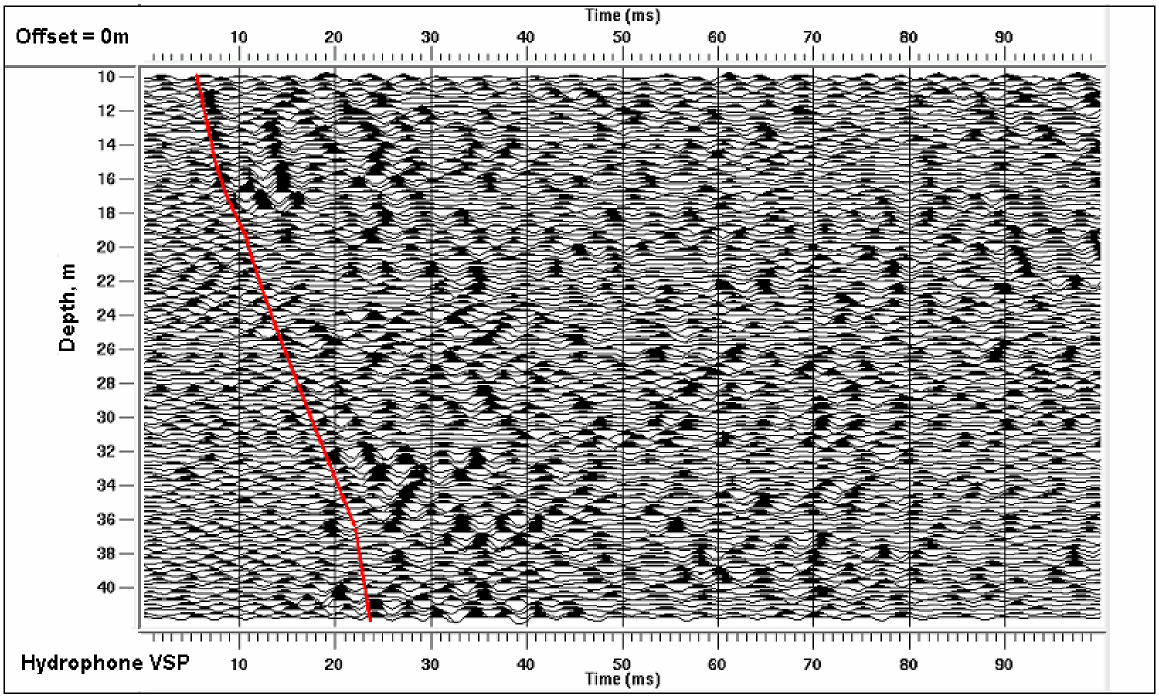

FIG. 5. Hydrophone VSP with source offset of 0 m. Apparent velocities are about 1600 m/s to 1750 m/s; however, the time picks are not reliable.

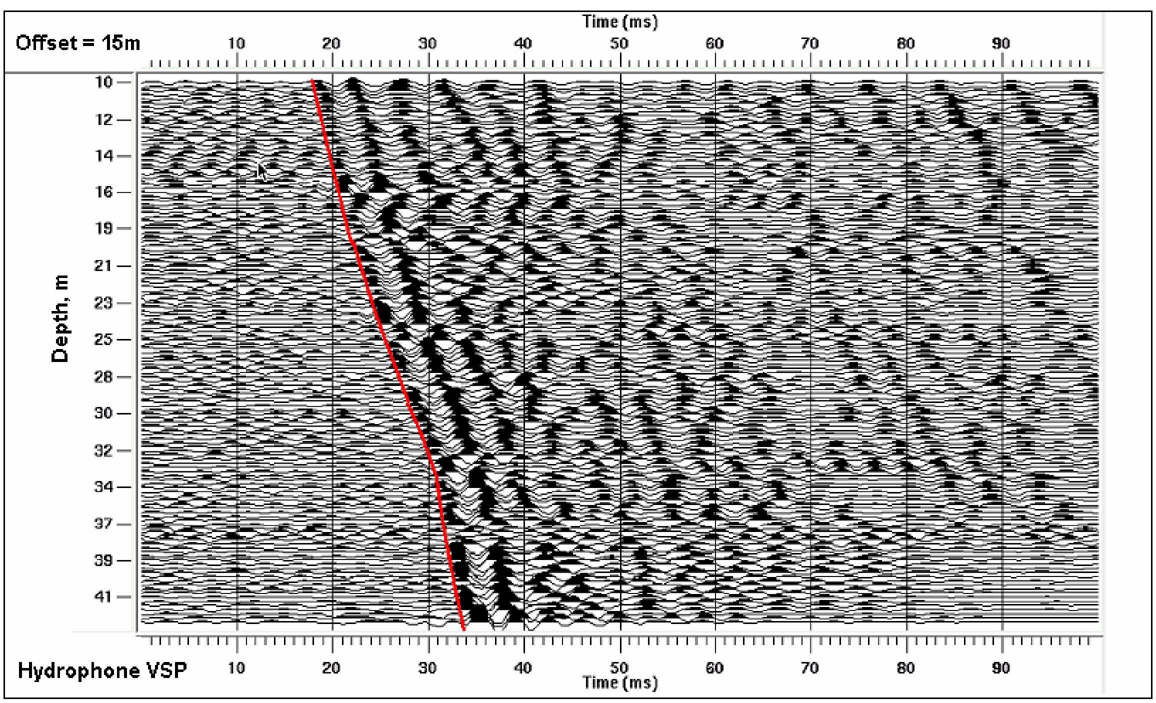

FIG. 6. Hydrophone VSP with source offset of 15m. Calculated apparent velocities are in the range 1050 m/s to 1310 m/s.

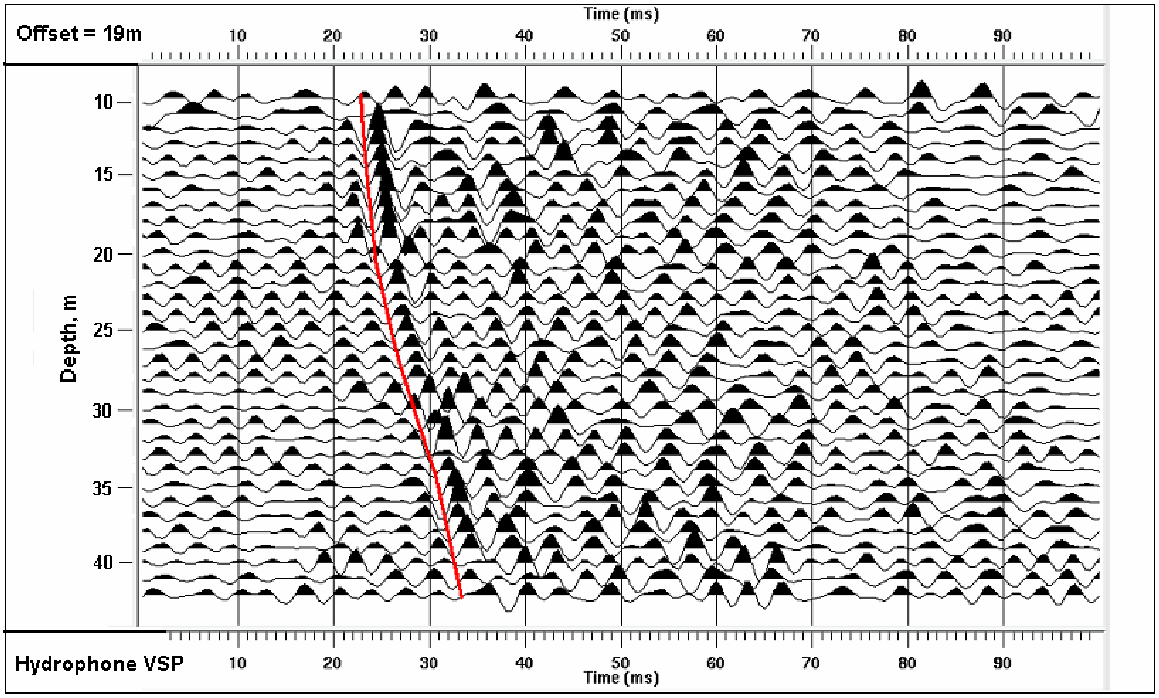

FIG. 7. Hydrophone VSP with source offset of 19 m. Calculated velocities are about 1000 m/s to 1300 m/s, depending on how the arrival times are picked.

The dominant frequencies appearing on the hydrophone VSPs are 200 Hz to 300 Hz. These observed frequencies unexpectedly high for propagation through unconsolidated sand and gravel. The hydrophones contain an integral high-pass filter with a low-cut frequency of about 200 Hz.

Velocity values for P waves have been calculated based on estimated first arrival times and the geometric configuration of the particular VSP. These values range from about 1000 m/s to 1700 m/s. The high velocities attained from the zero offset VSP are not reliable because of the difficulty of picking arrival times for the weak signals.

Downhole geophone VSPs

Figures 8, 9, and 10 are the vertical, inline, and transverse component VSPs recorded using the BHG-2 geophone at a source offset of 9 m. When 3-C geophones are properly aligned, the inline sensor responds to horizontal particle motion pointing towards the seismic source, while the transverse sensor responds to horizontal particle motion perpendicular to that sensed by the inline sensor. However, for our particular downhole geophone, no azimuthal control is possible, so that the terms inline and transverse in these data merely indicate two orthogonal horizontal directions.

The data have been bandpass-filtered with an Ormsby filter defined by the corners 60-80-200-300 Hz. We see dominant frequencies of 80 Hz to 150 Hz. The vertical component appears to have the best coherent first arrivals, while the transverse component is the least coherent. Gathers for other offsets are of similar quality.

Compared to hydrophone VSPs, the 3-C geophone VSPs have lower frequencies, have a lower signal-to-noise ratio, and show less trace-to-trace consistency. We suspect that the quality of the geophone VSPs have been adversely affected by several factors.

1. The clamping mechanism of the geophone tool, which operates with fairly long aluminum lever arms, possesses resonances that cause mechanical crosstalk between the three measured components of particle velocity.

2. Poor clamping may have occurred: At several depths, the downhole tools lodged as they were lowered downed the wells, indicating irregularities in the inner diameters of the wells. This was most noticeable at the joint between the upper casing section and the lower well screen section.

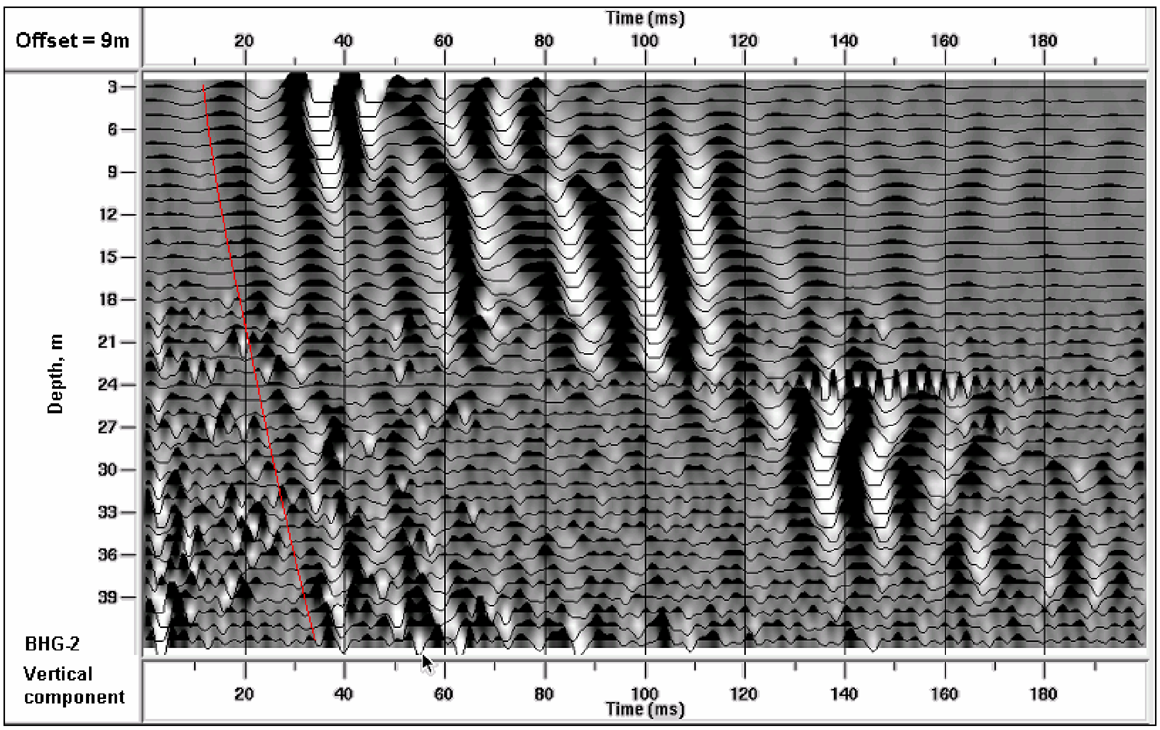

FIG. 8. Geophone-recorded VSP (vertical component) with source offset of 9 m.

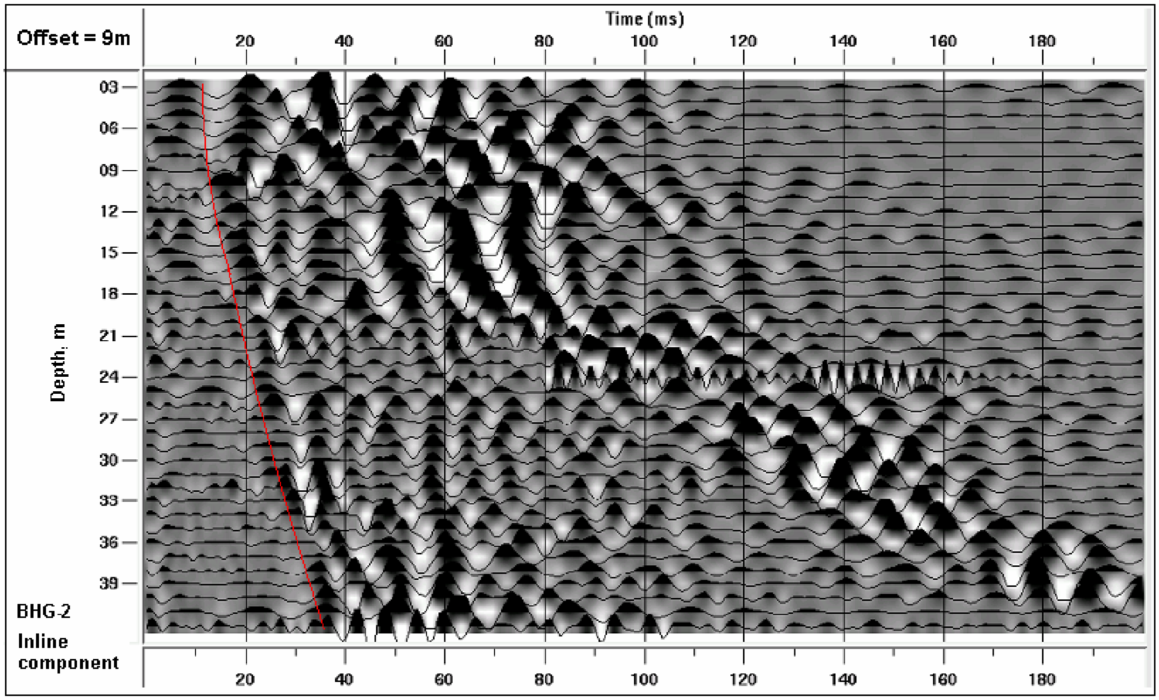

FIG. 9. Geophone-recorded VSP (inline component) with source offset of 9m.

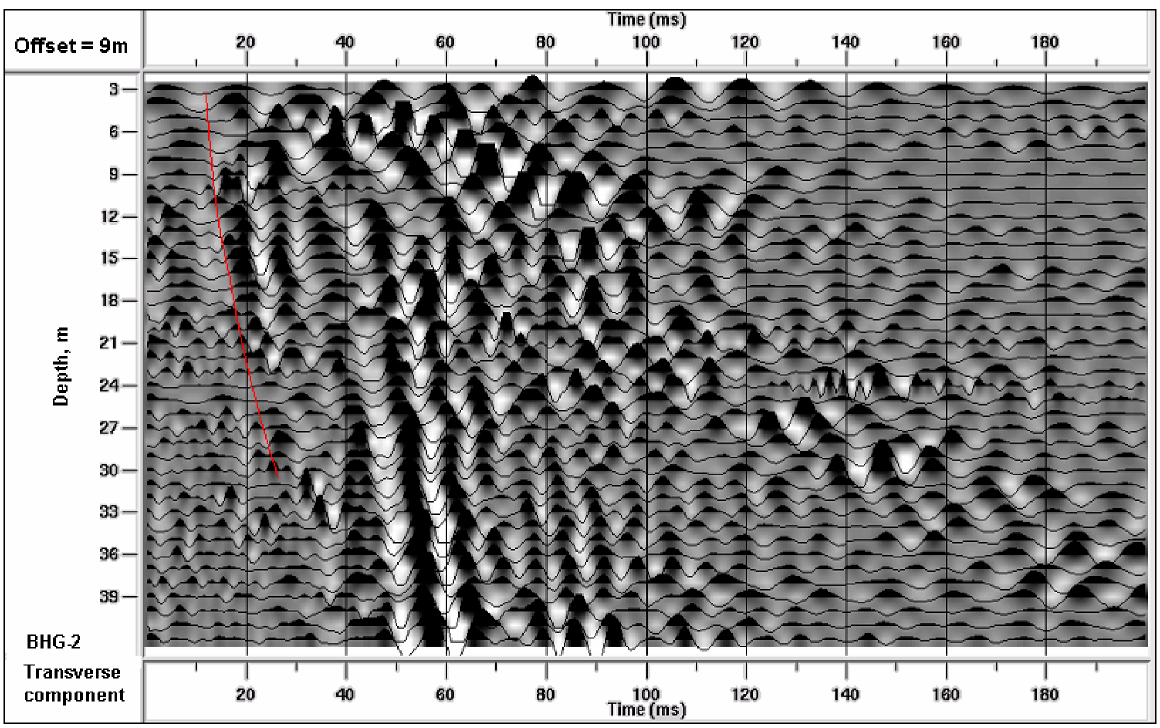

FIG. 10. Geophone-recorded VSP (transverse component) with source offset of 9 m.

3. The casing and well screen are not grouted. Although the upper cased section of the well was sealed by forcing a bentonite mixture down the outside of the casing, it is unclear if lower portions of the casing are fully bonded. The coupling between the clamped geophone with the unconsolidated overburden materials is therefore suspect. We predict poor coupling where permeable zones of coarse gravel occur, as is the case in the screened (unsealed) sections of the wells.

Walk-away profiles

Figures 11 and 12 are receiver gathers recorded with the downhole 3-C geophone at depths of 15 m and 40 m, respectively. Traces are from hammer source points with offsets from -31 m to +31 m with 2 m spacing. The 15 m-depth gather shows a strong event between 40 ms and 90 ms. This same event occurs on the flanks of the 40 m-depth gather at 130 ms to 140 ms. We interpret this event to be the direct S-wave arrival. Using the straight-raypath distances and time picks, we calculate velocities of 350 m/s to 400 m/s – a reasonable range for S-waves in unconsolidated sand and gravel.

The same receiver gathers are shown with expanded time scale for early times on Figures 13 and 14. The 15 m gather (Figure13) shows a coherent first arrival between 13 ms and 25ms. On the 40 m gather (Figure 14), the first arrivals are delayed, appearing between 35 ms and 45 ms. We interpret these arrivals to be the direct P-wave. Using the straight-raypath distances and first-arrival times, we calculate apparent P-wave velocities between 1100 m/s and 1300 m/s – not unreasonable values for unconsolidated overburden.

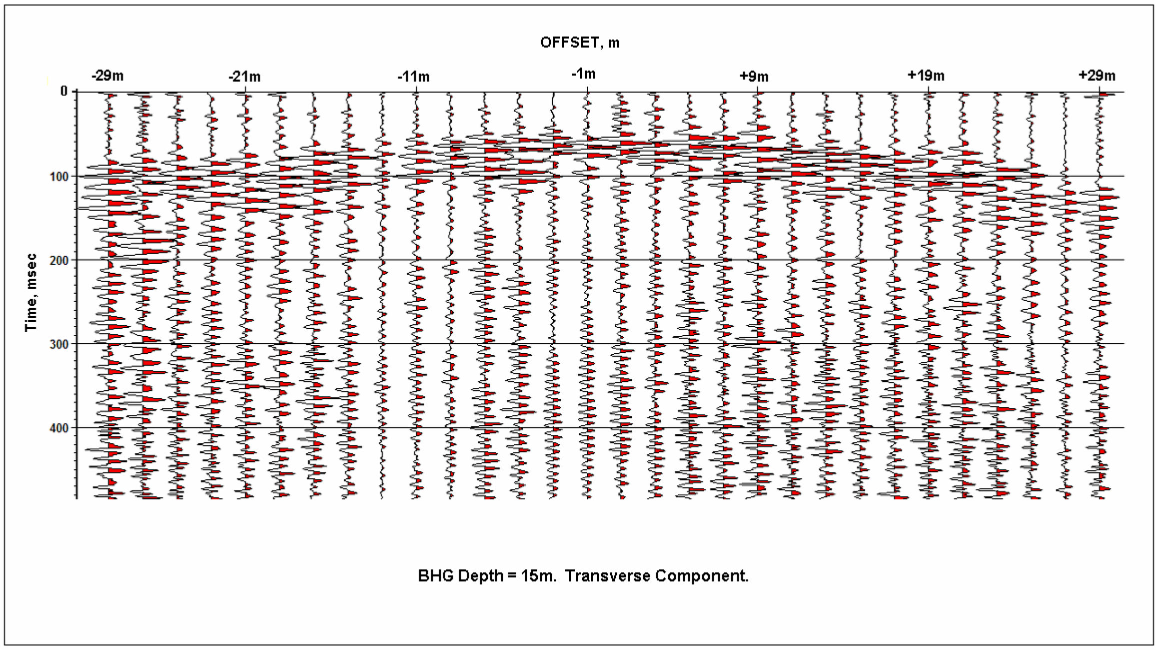

FIG. 11. Walk-away gather (transverse component) with geophone depth of 15 m. Traces are plotted with AGC emphasizing the S-wave arrival.

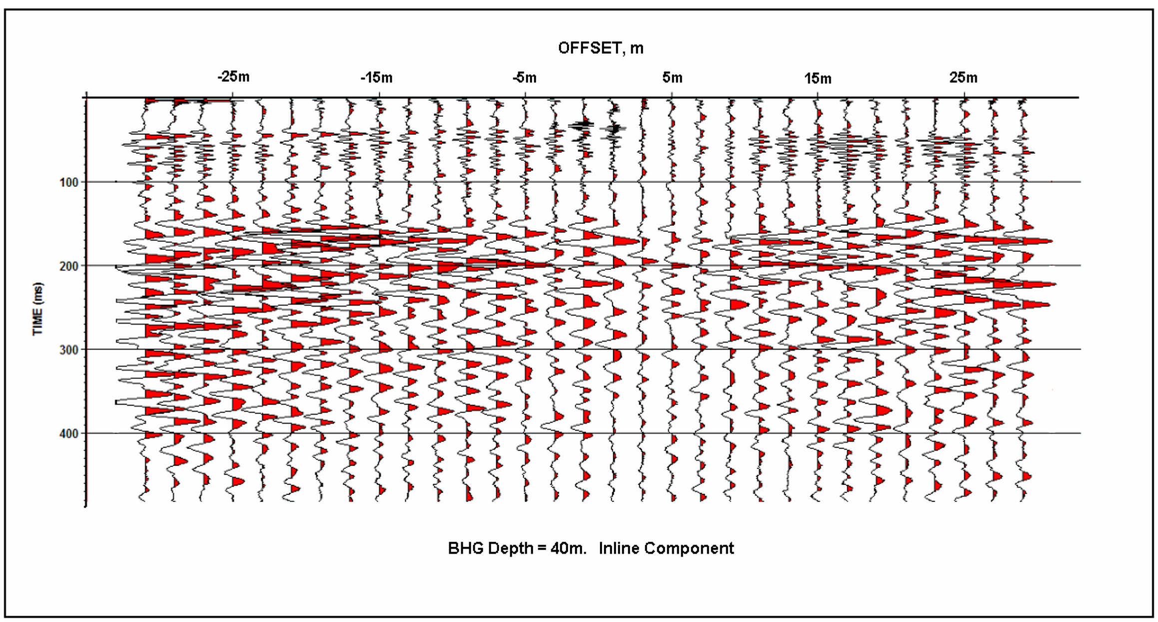

FIG. 12. Walk-away profile (inline component) with geophone depth of 40m. Traces are plotted with AGC emphasizing the S-wave arrival.

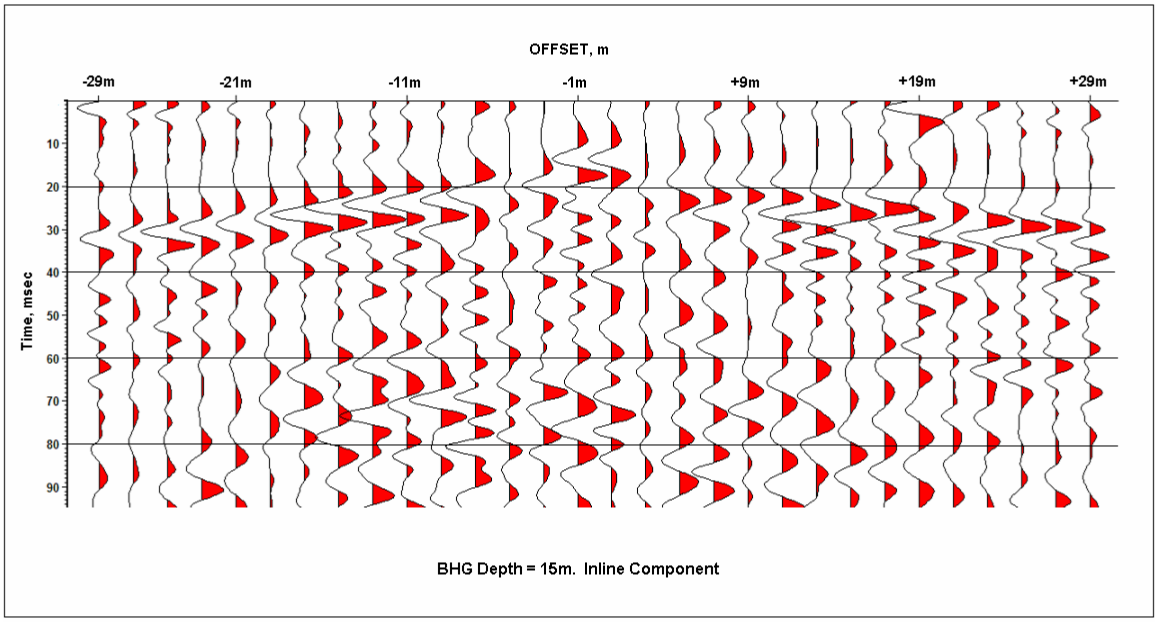

FIG. 13. Walk-away profile (inline component) with geophone depth of 15m. Traces are plotted with AGC emphasizing the early P-wave arrival.

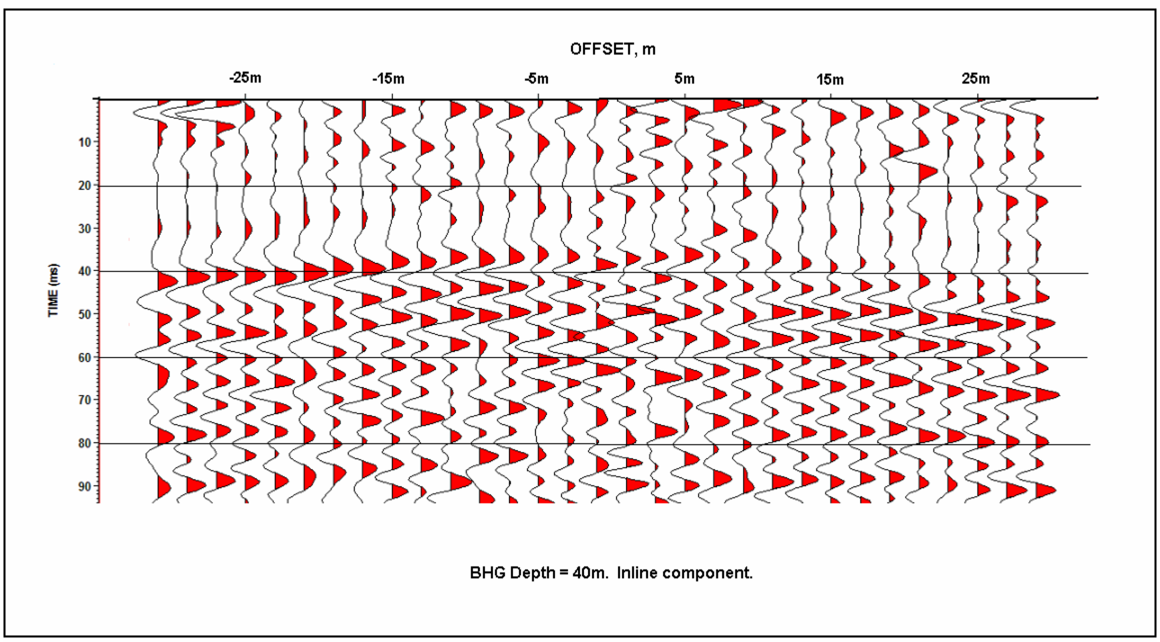

FIG. 14. Walk-away profile (inline component) with geophone depth of 40 m. Traces are plotted with AGC emphasizing the early P-wave arrival.

DETERMINATION OF A VELOCITY- DEPTH PROFILE

Gross estimates of seismic velocities based on arrival times and straight-line source–detector distances were given above. More accurate P-velocity values can be derived from VSP first arrival times by tracing rays through a layered earth model, and matching the arrival times while honoring Snell's Law on the boundaries between velocity layers.

We followed this procedure for the VSP with 15 m offset shown on Figure 6. In our model, we set the seismic boundaries near the Lodge Well at depths close to those shown on Figure 4. We performed repeated ray-tracing through the model while adjusting the velocities in the layers until the calculated arrival times matched the observed arrival times within the estimated picking error, which is about 1 ms. The final model is shown on the left side of Figure 15 with a suite of traced rays. Also shown, on the right side, are the observed times from Figure 6 and the times calculated using the model. The agreement between modeled and observed times is satisfactory, considering that error in the picked times is at least 1 ms.

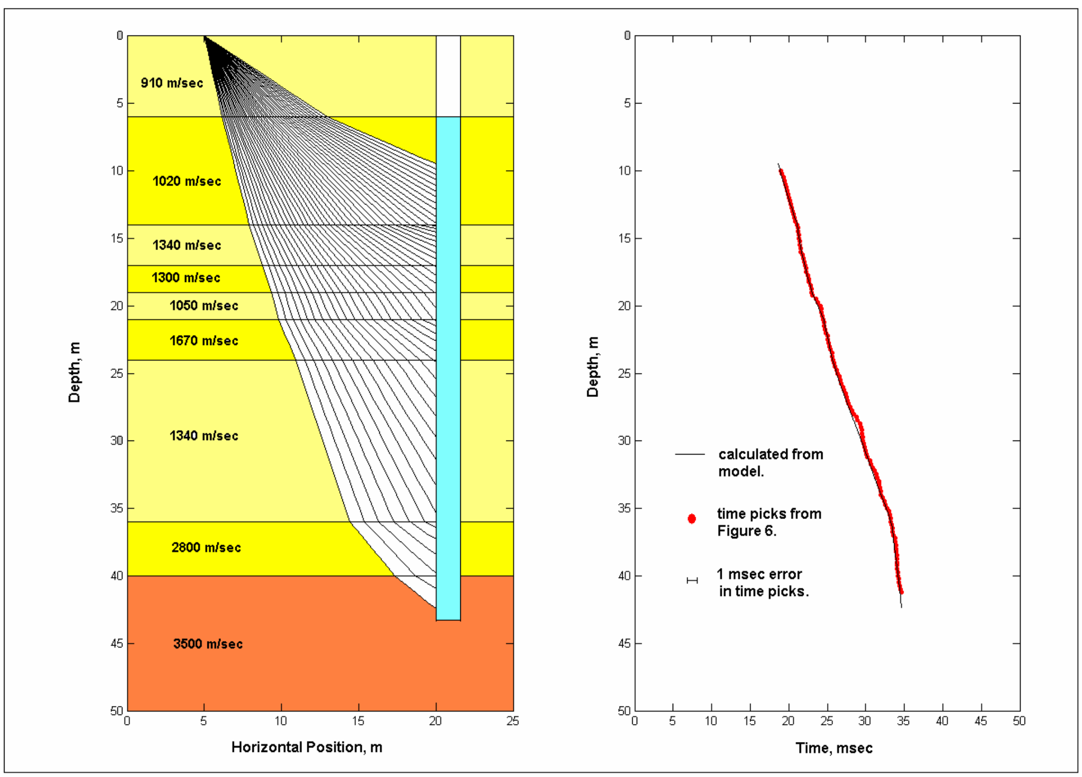

FIG. 15. Ray-tracing and fitting of first arrival times picked from the 15m offset VSP of Figure 6 using a layered velocity model. Left: The model with a sample of refracted rays. Right: Comparison of the observed times with the calculated times from the ray tracer.

CONCLUSIONS

As a field school exercise, students from the University of Calgary Department of Geology and Geophysics carried out a shallow VSP experiment at the Castle Mountain Ski Resort. Using a sledge hammer source and a downhole 3-C geophone and a hydrophone array, a VSP dataset around two shallow water wells on resort property was recorded with a Geometrics R60 seismograph. Despite the difficult seismic conditions encountered at the site (e.g., poor coupling between uncemented well casing and formation; high-loss unconsolidated sand and gravel in the overburden), the data acquired around the Lodge Well is of good quality.

For the data recorded with the 3-C downhole geophone, coherent arrivals may occur on plots of one component but not occur on other components. This behavior is not surprising, because the way an incident seismic wave affects each component of a triaxial geophone depends on the geophone orientation with respect to the propagation direction of the wave. We had no ability to control the orientation of the geophone once it was lowered into a well. Though mathematical rotation of the horizontal axes could correct this problem, the poor data quality hampered our ability to perform rotation analysis.

Seismograms obtained with hydrophone sensors compared favorably with those obtained with a downhole clamping geophone. Both P and S waves were clearly observed on gathers using the geophone. Using picked arrival times and assuming a straight-line raypath, we estimate apparent velocities to be 1100m/s to 2000m/s for P-waves and 350m/s to 400m/s for S-waves. More accurate velocities were found for the P-wave by fitting the first arrival times from a VSP with 15 m source offset with times calculated during tracing of refracted rays through a layered-earth model.

ACKNOWLEDGMENTS

We thank the management of the Castle Mountain Ski resort for providing the property plan map and the driller’s logs for the water wells. We also acknowledge their generosity for giving access to their property and permission to use the Lodge and Duplex Wells for these field school experiments. We express our gratitude to JODEX Applied Geoscience Limited for the loan of the hydrophone array and other essential field equipment.

REFERENCES

Hardage, R.A., 1985, Vertical seismic profiling, part A-principles: 2nd Ed., Geophysical Press.