REVERSE VSPS AND CROSSHOLE SEISMIC TOMOGRAPHY WHILE CORING
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ABSTRACT
At the Boise Hydrogeophysical Research Site, numerous 20 m deep wells were continuously cored with a split spoon sampler to detail geologic changes beneath the site. During the coring of one of these wells, we recorded the energy radiating from the drill stem using a combination of downhole hydrophones and surface geophones. The hydrophone strings were located in a pair of adjacent wells and the geophones were located along the surface between these wells and the well being cored. The experiment’s geometry provides a series of reverse VSPs and crosshole tomographic data sets that can help distinguish P-wave velocity changes in the subsurface. Energy from the core tip is not necessarily the first arrival. However, the near continuous recording of the source as it penetrates the ground enables us to locate the energy from the core tip. We also record energy when the source is in the vadose zone. Comparing the seismic while coring results with a similar experiment using a borehole sparker source confirms the reliability of recording seismic energy generated by the split spoon sampler. Core tip recording is an inexpensive seismic method that has great potential for borehole-to-surface and crosshole tomographic imaging at relatively large offsets in near-surface environments.

INTRODUCTION
Vertical seismic profiling (VSP) and crosshole seismic tomography can provide valuable information about near-surface seismic properties at and between wells (Milligan et al. 1997; Hyndman and Harris, 1996). A limitation of these methods is generating adequate energy without damaging the borehole casing. One way to get around this limitation is to record VSP and crosshole seismic data while drilling or coring (Rector and Marion, 1991). In this paper, we investigate the use of a split spoon corer as a downhole seismic source. We compare the results of reverse VSP (RVSP) and crosshole data acquired with a borehole sparker. The results show that the corer is an accurate and economical seismic source.

FIELD EXPERIMENT
We tested the use of a split spoon corer as a seismic source at the Boise Hydrogeophysical Research Site (BHRS). A description of this site can be found in Barrash and Knoll (in press), and several other papers presented at this conference (Barrash et al., 1999; Clement et al., 1999; Knoll and Clement, 1999; Liberty et al., 1999; Peretti et al., 1999; Peterson et al., 1999). There are presently 18 wells at the site, as shown in figure 1. The wells were “drilled” by continuous coring using a 2-foot long split spoon sampler. When the C2 well was cored, we used the split spoon sampler as a seismic source and recorded RVSP data and crosshole seismic tomography data. The split spoon sampler was pounded to a total depth of 17.4 m using a drill rig hammer. We recorded individual blows and did not vertically stack. We obtained an accurate and reliable trigger by attaching a geophone to the drill stem at the rig.

We recorded the split spoon sampler while coring well C2 with a downhole hydrophone string in well A1 and twenty-four 100 Hz geophones buried along the surface between the drill rig and well C5. The hydrophone string in well A1 consisted of 36 active hydrophones spaced 0.5 m apart. The first hydrophone was 19.8 m and the 36th hydrophone was 2.3 m below the measuring point in well A1. We placed a second hydrophone string (3 m spacing) in well C5 with the first hydrophone 18.6 m below the casing and the sixth hydrophone at 3.6 m depth. We
placed the surface geophones 0.5 m apart along a line from well C2 (being cored) through well A1 to well C5. To avoid interfering with the drilling operation, the first geophone was located at 5.3 m from the drill rig. The offset to the last geophone at well C5 was 17.3 m. The geophones were buried 0.2 m to reduce air-wave noise. The combination of the hydrophone strings and the surface geophones allows us to record the split spoon corer energy as RVSPs and as crosshole tomography experiments.

The offset RVSPs show strong, easily observed first arrivals when the source is below the water table (Fig. 2). Shots from a variety of depths are recorded with the geophone spread. By sorting the data by geophone, we obtain offset RVSPs for a range of distances away from the well. Offset RVSPs are useful for determining 2-D variations in velocity. Because these data record the same shots used in the tomography experiment, the offset RVSPs also can provide more traveltime information through the upper layers in tomographic inversions. Another benefit to offset RVSPs is that changes in the waveform recorded by different geophones can help delineate abrupt, lateral velocity changes. Offset RVSPs extend the velocity model away from the well and provide insight to the 2-D velocity distribution beneath the surface.

For the tomography data, we plotted the raw data from each hammer blow and picked the travel time of the arriving energy (Fig. 3). We combined the picks into one shot record for each 0.6 m depth interval down the well, computed the average and the standard deviation of the arrival time, and assigned the source point for each 0.6 m interval to the midpoint of that section. Thus, each summed trace records energy from 0.6 m of drilling. We had difficulty picking the arrival times for hydrophones 35 and 36 in well A1 because these phones were above the water table. We omitted these channels from the tomographic inversion. The final inversion involved 986 stacked traveltime measurements.

DATA PROCESSING AND INVERSION

When the hammer strikes the top of the drill stem, the energy propagates down the steel section to reach the split spoon corer. This energy travel time increases as the length of the steel section of the drill stem increases. Our drill mounted geophone triggers as the hammer strikes the drill stem, but the energy must travel to the bottom of the well before radiating from the split spoon corer. Consequently, we must account for the delay between the hammer strike at the top of the stem and the energy arriving at the corer at the bottom. To compensate for this delay, we applied static corrections to account for the length of the drill stem using a velocity for steel of 5900 m/s (Carmichael, 1989). This static correction is not linear with depth because steel sections are added to the drill stem in 1.5 m (5 foot) segments. However, we compensated for this timing delay by linearly interpolating the energy delay with source depth, realizing that we are introducing some error into our inversion.

On the deeper data sections, a consistent, low frequency, weak event arrives before the stronger energy from the bottom of the well. In figure 3c, this weak energy arrives earliest around 8 m depth. We think that the drill stem flexes at its middle and hits the side of the well. Although this event is the "first arrival", we picked the later, stronger event as the energy from the split spoon sampler.

We used an iterative, 2-D tomographic inversion routine to determine the velocity structure between the wells (Aldridge and Oldenburg, 1993). The forward routine calculates the first arriving travel time using a finite difference approximation to the eikonal equation. This method can accommodate curved travel paths. The program computes the raypaths, solves for the slowness using a LSQR routine (Paige and Saunders, 1982), and updates the model. The program iterates until the root-mean-square travel time residual is smaller than a specified value. The final velocity model is the reciprocal of the slowness model.
We used a grid spacing of 0.5 m, similar to the source and receiver spacing during data acquisition. We regularized the matrix equation to attain a solution using the first derivative finite-difference star. This first derivative approximation causes the solver to seek solutions that are locally smooth. We weighted the horizontal component by 75 and the vertical component by 15. Larger weights place more emphasis on the regularizing equations at the expense of the data equations. The regularization helps solve large, sparse matrix equations. The initial velocity for the non-linear inversion procedure was arbitrarily set to 2400 m/s. Tests showed that the inversion procedure is not very sensitive to the choice of the initial velocity model.

As the wells were drilled, the corer deviated from the vertical. Magnetic deviation logs were collected after drilling to determine the deviation. Deviated well locations were used in the tomographic inversion procedure. In wells A1 and C2, the maximum horizontal deviations are 0.16 and 1.08 m respectively. The tomographic inversion routine uses the horizontal distance and the depth to locate the source and the receiver for each arrival time. With the short source-receiver separations in our experiment, accounting for well deviation increases the accuracy of the velocity model.

**DISCUSSION**

Offset RVSPs can provide valuable information about the lateral variation of the velocity distribution. The slope of the first arrival picks is inconsistent with reasonable velocity estimates (Fig. 2). However, using picks from source depths below 12 m only, the velocity is about 1550 m/s using data from the offset RVSP at 5.3 m (Fig. 2a) and is about 2000 m/s using data from the offset RVSP at 13.3 m (Fig. 2b). For the recorded distances from the well and the depths, most of the energy does not propagate vertically and analysis of the offset RVSPs must account for ray bending and refractions. Thus, the calculated velocities represent apparent velocities and not the velocity of the subsurface. In future experiments, we would bury geophones closer to the source well to record vertically propagating energy.

The velocity tomogram for the split spoon experiment is shown in figure 4a. The velocity ranges from 580 m/s at the top of the model to 3515 m/s at twelve meters depth around well C2. In the upper two meters, the velocity is about 600 m/s. Between two to six meters, the velocity increases from 600 to 3200 m/s. Below six meters, the velocity varies between 2700 to 3500 m/s. A high velocity zone is in the center of the model between six to seven meters depth. Another high velocity zone of greater than 3000 m/s occurs at eleven to thirteen meters depth around well C2. At eleven meters depth, a relative velocity low is in the center of the model. A small high velocity zone is at seventeen meters depth between one to six meters laterally. Finally, a relative velocity anomaly is modeled at sixteen meters depth around well C2. In general, the final model shows an increase in velocity with depth and laterally from well A1 to well C2.

To assess the performance of the split spoon corer, we compared our tomographic inversion to a similar inversion using a downhole sparker source (Fig. 4b). For the sparker experiment, the hydrophones were located in well A1 and the sparker was located in well C2. The sparker was fired five times at each source point and the data later stacked. The source spacing was 0.5 m compared to 0.6 m for the split spoon corer. We picked and inverted the sparker data using the same procedure as we used for the split spoon data.

The inversion results for the sparker source are similar to the results from the split spoon corer. The sparker tomogram also shows a general increase in velocity with depth including a large gradient between three to six meters. However, the lateral change in velocities in the deeper part of the model is not as apparent. In the sparker tomogram, a high velocity zone is present in the center of the model at about five to six meters depth. This zone is approximately equivalent to the high velocity zone in the split spoon tomogram. The velocities in the sparker model range
from 1390 m/s to 3035 m/s, a much smaller range than exists in the split spoon model. However, most of the velocity difference is near the surface of the model where ray coverage is poor.

The near surface velocity of the split spoon corer is much slower and more realistic than the near surface velocities in the sparker tomogram. In the vadose zone at the BHRS, velocities are typically about 300 m/s. Seismic velocities are greater than 1500 m/s below the water table. The split spoon corer data included shot points in the vadose zone, whereas the sparker source only worked below the water table. The lack of shot points in the vadose zone may have resulted in the higher near surface velocity in the sparker tomogram.

To further compare the corer and sparker data, we computed the average horizontal velocity at each depth for the two tomograms (Fig. 4c). Below six meters, the average horizontal velocities agree to within 250 m/s except near 6.5 and 12.5 meters depth. Also, the trend of the average horizontal velocities is similar. The difference at 6.5 meters depth is probably due to the tomography algorithm’s difficulty with large velocity gradients. Also, the split spoon corer model has lower velocities in the near surface. This velocity difference and the large velocity gradient certainly affects the location of the velocity anomaly. At 12.5 m, the localized high velocity anomaly near well C2 of the split spoon corer model causes the velocity difference. Because this zone is localized at a source point, a bad shot gather may account for the anomaly. Although the details of the two models differ somewhat, the general features agree.

The number of rays traversing a model cell provides an indication of the resolution of that part of the velocity model. The raypath density is defined as the total raypath length per slowness cell divided by the grid interval (Aldridge and Oldenburg, 1993). Larger raypath density values indicate a more reliably determined velocity value compared to areas with smaller raypath densities. As figure 5a shows, the cells in the model’s center and in a U-shaped pattern near the top of the model have the most ray coverage. Although the ray density does not indicate the accuracy of the velocity value, higher density cells have more ray coverage than lesser density cells.

The travel time residuals also provide an indication of which model cells are well resolved. A travel time residual is the difference between the observed travel time and the calculated travel time. Figure 5b shows the travel time residuals for the sources and receivers. The mean travel time residual is -0.10 ms and the RMS value is 0.66 ms. The residuals range from -3.73 to 2.00 ms. The greatest magnitude residuals are located around three to four meters for both sources and receivers. The tomogram has a large velocity gradient between three to five meters. The misfit around three meters probably reflects the inversion algorithm’s difficulty modeling large velocity gradients. Horizontal or vertical stripes in the figure indicate poorly modeled travel times from a particular source or receiver. Plotting the travel time residuals provides an easy method to help determine the data quality and the reliability of results from tomography.

CONCLUSION

The split spoon corer is a valid source for offset RVSP and crosshole tomography analysis. Recording the corer is inexpensive if coring is part of the drilling program. Additionally, the corer is a high energy source compared to other downhole sources and is well coupled to the formation. An advantage of the corer is that coherent, observable energy is generated in the vadose zone above the water table. Differences between the split spoon corer and the sparker tomogram exist. Edge effects and poor ray coverage probably cause many of these differences. Although not designed as a downhole source, useful seismic data is obtained with the split spoon sampler through careful data acquisition and processing. We conclude that the split spoon corer is an inexpensive, reliable seismic source for offset RVSP and crosshole tomography experiments.
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REFERENCES


Figure 1. Generalized map of the BHRS showing the location of the wells and the seismic experiment. Drilling occurred at well C2 and the hydrophone strings were placed in wells A1 and C5. The black dots indicate the location of surface geophones and the two black diamonds show the locations of the RVSPs in Figure 2.
Figure 2. RVSPs from the split spoon corer at two different distances from well C2. The vertical axis indicates the depth of the split spoon corer. Depths are measured relative to the top of the well casing, about 0.63 m above the land surface. Gray dots are first arrival picks.
Figure 3. Shot gathers from the split spoon corer and the sparker source. Record sections of (a) the split spoon corer at 7.62 m depth, (b) the sparker at 7.5 m depth, (c) the split spoon corer at 14.94 m depth, and (d) the sparker at 15.0 m depth. These figures show the data quality of the different sources. Although the sparker source is higher frequency, the arrival of the energy is easily observed and picked with both sources.
Figure 4. Velocity tomograms of (a) the split spoon data and (b) the sparker data. The gray scale indicates the velocity in m/s and is the same for both plots. The solid white line at 0.63 m depth represents the land surface. The dashed line is the water table. We acquired the data on different days and the water level differed. The black circles are the hydrophone locations and the black stars are the source locations. (c) Average horizontal velocity versus depth of the velocity models from the split spoon (dashed line) and the sparker (dotted line) sources.
Figure 5. (a) Raypath density and (b) travel time residuals of the split spoon corer. The raypath density is a measure of the relative number of rays per cell. High values indicate that many rays pass through a cell and that velocity values are probably more reliable. The white lines mark the same features as in Figure 4. The gray scale shows the raypath density values. For the travel time residuals, the horizontal axis is the receiver depth and the vertical axis is the source depth. The gray scale shows the travel time residual in ms. Horizontal or vertical stripes in the plot may indicate locations of bad source or receiver data. Note the large residual around the 3 m source and 4 m receiver locations.