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Vertical Seismic Profiling at Borehole B-1015 Lawrence Livermore National Laboratory

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VERTICAL SEISMIC PROFILING AT BOREHOLE B-1015, LAWRENCE LIVERMORE NATIONAL LABORATORY

Motivation, Data Acquisition, Data Analysis, and Formation Velocities

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Motivation and Survey Goals

The initial goal of the three-dimensional (3-D) vertical seismic profiling (VSP) at Lawrence Livermore National Laboratory (LLNL) was to characterize seismic wave velocities and frequencies below the vadose zone in order to design the acquisition geometry for a high-resolution 3-D seismic reflection survey. VSPs are also used routinely to link surface seismic data with well logs. However, a test of the two-dimensional (2-D) seismic line recorded at the LLNL Livermore Site in the spring of 1994 (Fig. 1) indicated that obtaining high-quality reflection images below the vadose zone, but shallower than about 160 ft, would require an expensive, very finely sampled survey (<1-m receiver spacing). This paper presents the difficulties encountered during initial data acquisition and processing, and attempts to alleviate the difficulties in the field and laboratory.

Extensive image processing of the LLNL 2-D test line indicated that the most reliable reflection was from the top of the water table; however, reflections could be roughly correlated to well W-452 centered on the 2-D line (Fig. 2). The low quality of the reflections appears to be due to the comparatively deep vadose zone at LLNL (45 to 115 ft) comprised of unconsolidated, highly heterogeneous alluvial deposits. The thick vadose zone attenuates the reflection signals, particularly at the higher frequencies (above 100 Hz). In addition, the vadose zone at LLNL creates a seismogram in which surface-propagating noise overlaps with the reflection signals for reflections above 160 ft. In contrast, when the vadose zone is not thick, high frequencies can propagate and noise will not severely overlap with reflections.

Based on the results from the 2-D seismic line and the encouraging results from a VSP run concurrent with the 2-D seismic experiment, we modified the objectives of the research and expanded the scope of the VSP imaging at LLNL. We conducted two 3-D multioffset VSP experiments at LLNL in the summer and fall of 1994. These VSP experiments were designed to characterize the seismic propagation characteristics at two different locations on the LLNL Livermore Site. The first experiment involved a well with a relatively shallow water table (about 30 ft), whereas the second experiment involved a well with a relatively deep water table (about 80 ft). Other goals of the VSP experiments were to:

- Characterize the velocity structure in the vicinity of the boreholes.

- Determine if any advantages were apparent between measurements in cased versus uncased boreholes.
- Attempt to image reflections away from the boreholes.

The analyses of the VSPs recorded at borehole B-1015 with the shallow water table are given in the following sections.

B-1015 3-D VSP Acquisition and Analysis

B-1015 was a relatively deep borehole drilled to a total depth of 437 ft. We conducted the VSP prior to casing the well. We collected VSP data in two configurations: zero offset and 3-D offset. For each configuration, we used a 24-element hydrophone string to record the VSP data (hydrophone spacing was 0.5 m, resulting in a total array length of 11.5 m) and an 8 gauge Betsy Seisgun source deployed in a 2- to 3- in.- diameter, 3-ft deep, water-filled shothole. The shallowest hydrophone level was about 35 ft below the ground surface, roughly at the water table. We used an EG&G 24-channel, 24-bit Strataview recording system to record the data with a 0.2- millisecond sampling interval and a 40 Hz analog and digital low-cut filter.

Data Acquisition and Seismogram Analysis

Figure 3 shows a cross section of the acquisition geometry for the VSP survey. To obtain velocity information, we recorded eight levels of zero offset data with the hydrophone array beginning at a depth of about 35 ft and extending to about 325 ft. Field data analysis displays were very limited with the Strataview, and the field data appeared satisfactory.

After bringing the data back to the U.C. Berkeley laboratory, we produced a composite display of the zero offset VSP acquisition. This display indicated that the first arrival energy consisted of a complex mix of tube waves and direct P-waves. As a result, we were not able to produce as finely sampled interval velocity log as we wished. Figure 4 shows the interval velocity logs that were produced from the data recorded.

The interval velocities do not appear to correlate well with a smoothed version of the drilling geologist's lithology log; therefore, we believe that in this area there is not a clear correlation between P-wave velocity and lithology. The principal factors that control velocity in shallow clastic environments are clay content and porosity. We observed that clays generally have lower velocities than sands with similar porosities, but these observations were not universal. When the velocity data were incorporated with other information, such as gamma and resistivity logs to correlate lithology with seismic properties, we observed a much better fit.

As mentioned previously, the strong tube waves prevented use of small intervals to estimate velocity. Attempts to use smaller intervals resulted in unrealistic velocities and a poor correlation to the lithology log. As discussed in the next section, the first arrival can be identified when data from a small source offset is utilized. However, later-arriving tube waves remained a problem for all the data from this well, until we were able to cancel much of the interference during processing.

3-D Offset VSP: Data Acquisition and Seismogram Analysis

Figure 5 shows a map view of the 3-D offset VSP data acquired at borehole B-1015. We recorded three hydrophone string levels beginning at the top of the water table (~35 ft) and extending down to about 140 ft. Including some overlap, we recorded 65 receiver levels and 50 source positions, resulting in over 2,500 traces recorded in a little less than a day. A comparable surface seismic survey conducted over the same surface area would probably have taken more than 2 days to record, without the velocity advantages of VSP. The goal of the offset VSP survey was primarily to determine whether continuous reflections existed at this site and whether they could be reliably extracted and imaged.

Unlike the zero offset VSPs, the tube waves were less dominant, and the direct P arrival was reliably picked with the radial offset VSPs. We hoped to find high frequencies in the data because the higher frequencies (1) would provide higher resolution (to image a hypothetical 3-ft thick gravel in the saturated zone) and (2) should theoretically have less tube wave noise. We found that the maximum frequency in the data was about 250 Hz below what would be needed to image a 3-ft thick gravel. In addition, we found that the high frequencies contained very high amplitude electrical noise. We also found that the preamplifiers on the hydrophones were recording trigger noise from the shot as well as ambient electrical noise. Based on these results, we developed an optical isolator for the shot trigger, and we experimented with different grounding and baffling techniques for the hydrophones.

We performed multichannel wavefield separation to attenuate the tube waves and the electrical noise and enhance upgoing reflections. Figure 6 shows the results of the wavefield separation processing compared to a synthetic seismogram generated from the gamma log. We found that the reflections recorded appear to correlate well with the synthetic seismogram generated from a gamma-ray log run after the completion of drilling. Several strong correlatable reflections can be seen above 100 ft. These reflections are consistent with a decrease in the gamma log reading. We should note that the wavefield separated data appear to be lightly corrupted by residual tube wave interference and trigger noise. However, we were able to identify reflections and reliably map reflections away from the wellbore. We were disappointed with the poor quality of the data below 100 ft, but additional processing in progress appears more promising. Fortunately, the sands and gravels imaged above 100 ft were our target intervals.

There are not any particularly strong correlations between any of the geophysical logs run in the well with the VSPs, although the sonic log appears to be particularly unreliable. In low-velocity sediments, the sonic log records a velocity that can be quite inaccurate. This is due to the fact that the fluid arrival can precede the arrival refracted along the borehole wall. When the fluid velocity is greater than the formation velocity, a refracted arrival cannot be measured, and dipole logs that 'infer' the shear velocity from the Stoneley wave velocity are needed. In these situations, the VSP can be used in place of the sonic log. For the B-1015 well, the VSP interval velocities have up to 25% error due to the strong tube wave interference. If the tube wave could be attenuated, we believe that the VSP could accurately yield P-wave velocities.

Conclusions

Due to difficulties in obtaining reflection signals through the low-velocity and highly attenuating vadose zone, we modified the scope of the project to investigate whether 3-D VSP could provide reflection images of the subsurface at LLNL. In principle, VSP has several advantages over surface seismic techniques for shallow imaging:

- VSP can image acoustic contrasts as shallow as 15 to 30 ft, whereas surface seismic has difficulty resolving acoustic contrasts above 90 ft.

- VSP provides a direct correlation to geophysical and lithologic well logs.

- VSP is unaffected by near-surface statics.

- VSP resolution is roughly a factor of 4 times better than surface seismic profiling in shallow environments.

We found that the principal impediment to obtaining high-quality VSP reflections at LLNL was the presence of very strong tube waves that travel up and down the receiver borehole. These tube waves are produced from multiple points in the borehole. The tube waves are generated as the direct P-wave hits every hydrophone and as the direct P-wave arrives at borehole diameter changes.

Since the first experiment in August 1994, we have spent a great deal of time developing techniques to attenuate the tube waves. We have developed a baffling system and signal processing techniques that attenuate the tube waves by over 10 Db. We have found that using frequencies below 120 Hz for VSP imaging takes a tremendous amount of wavefield separation and signal processing. In areas of strong attenuation, such as the LLNL Livermore Site, these frequencies are dominant and there is little energy above 120 Hz. If Rayleigh scattering is the principal attenuation mechanism in the vadose zone, we would expect that (1) the attenuation would be low, and (2) above a cutoff frequency we would need an extremely large source of energy to get very high frequencies through the vadose zone.

When we recorded a VSP in bay fill at our Richmond, California, test site where the water table is present at about 9 ft, we observed frequencies up to 1400 Hz, traveling for distances of up to 160 ft. We now believe that it is essential to have a relatively shallow water table (15 to 35 ft maximum) for any shallow high-resolution seismic technique to work, be it surface or VSP. Because the presence (or absence) of high frequencies appears to be the limiting factor in obtaining high-quality VSP data, we are currently characterizing different sites at LLNL with shallower water tables. Results of subsequent work will be published as the data becomes available.

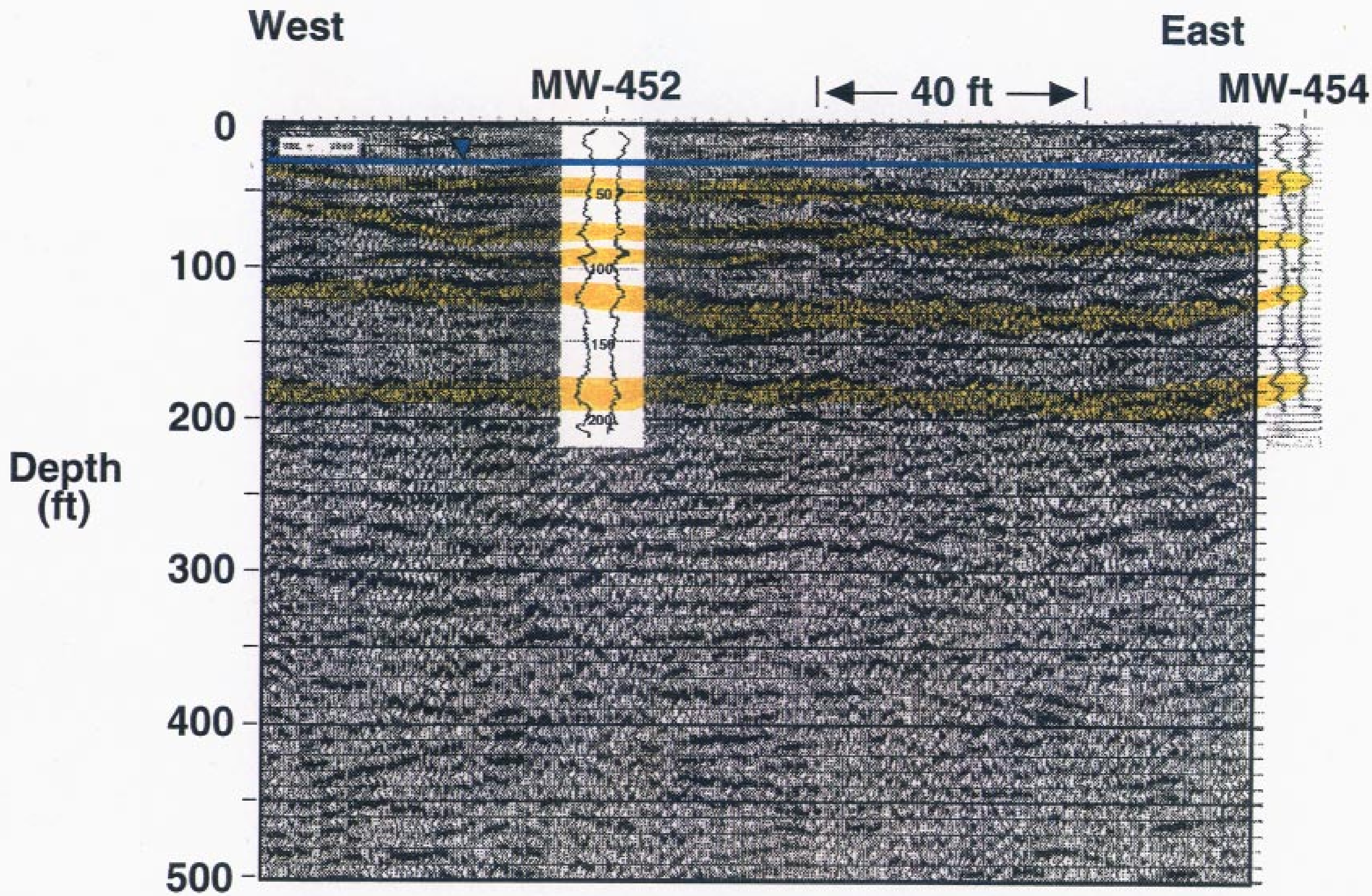

Figure 1. Brute stack of 2-D reflection line.

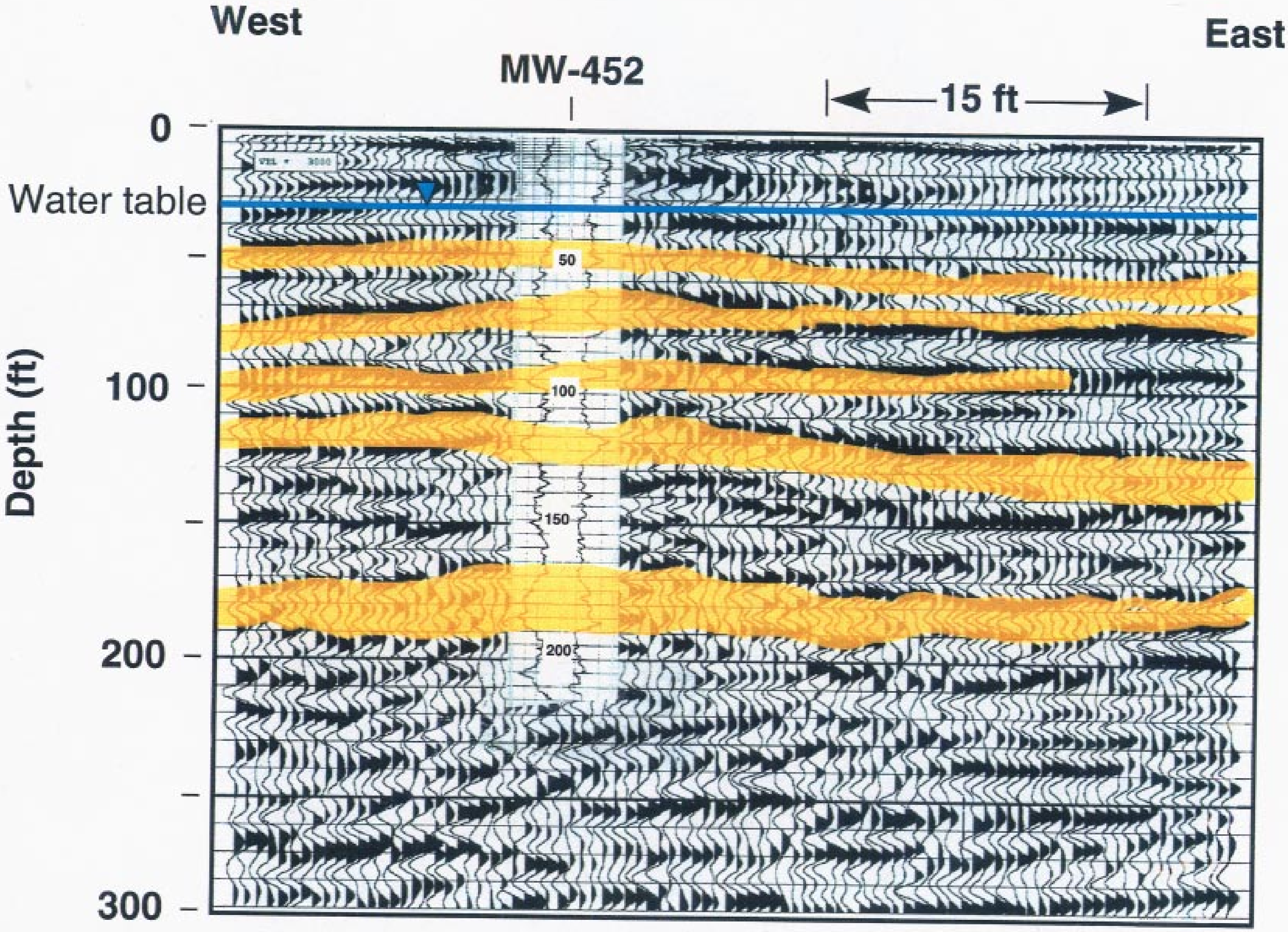

Figure 2. 2-D reflection line after extensive processing.

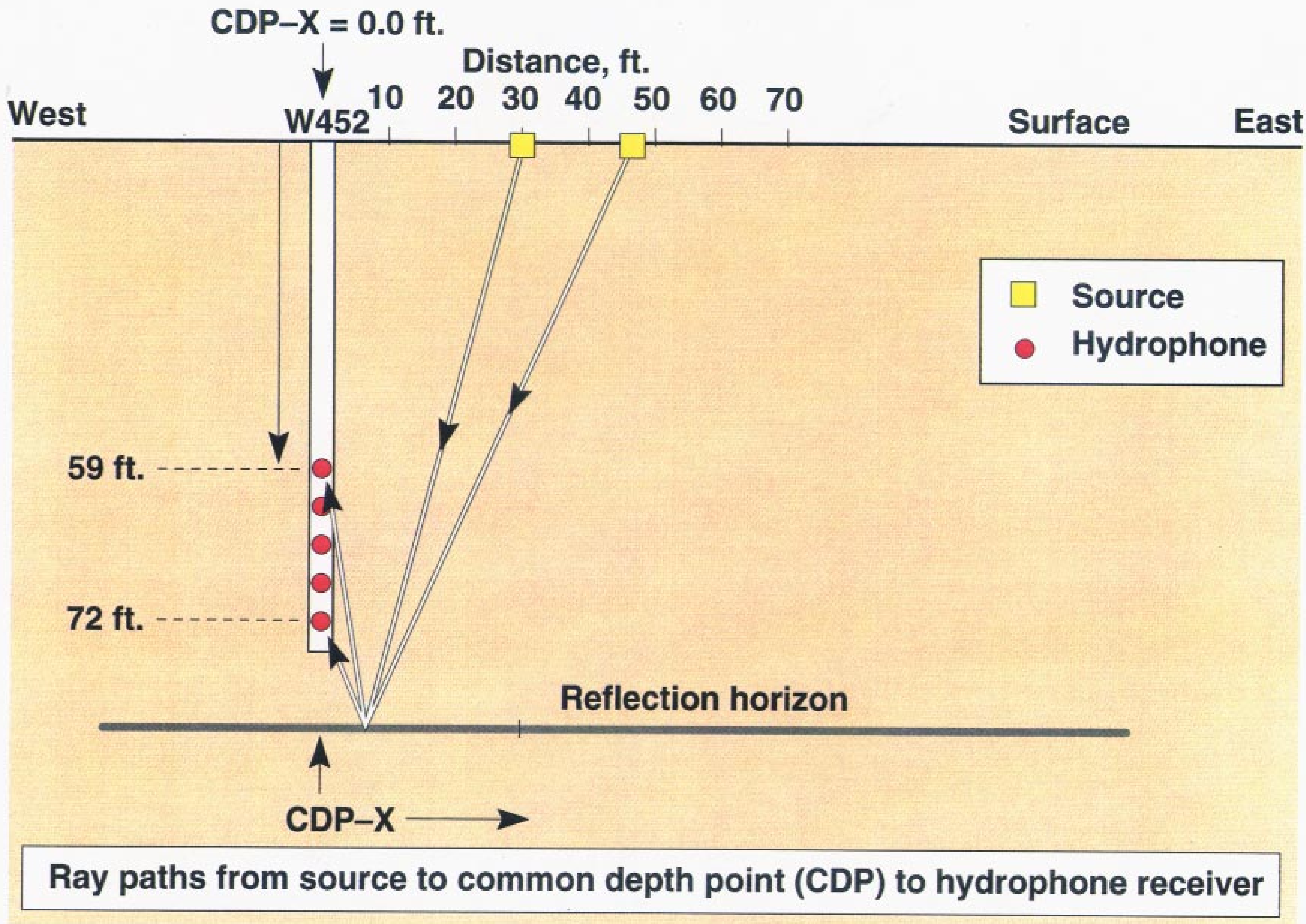

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Figure 3. VSP acquisition geometry.

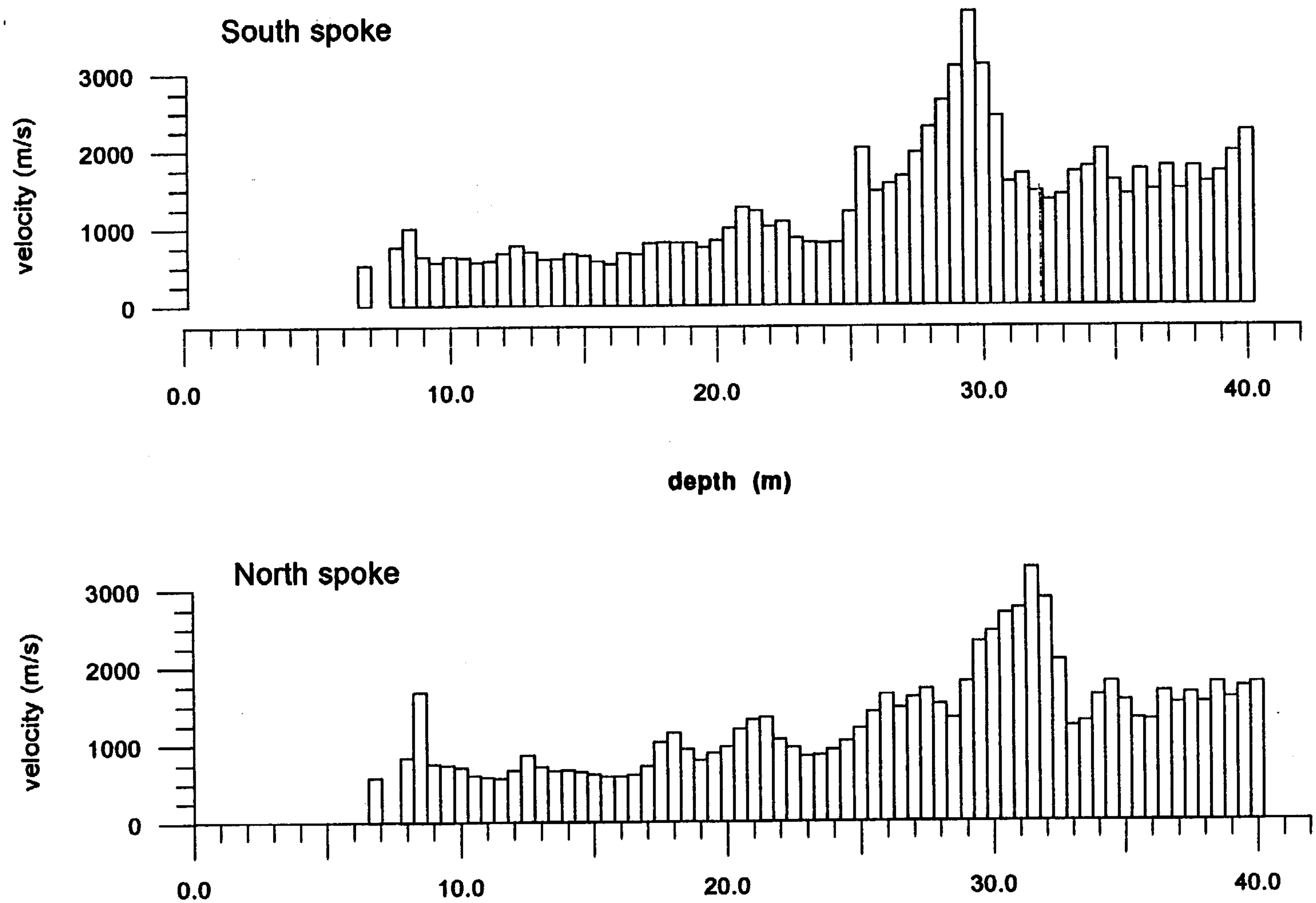

Figure 4. Well B-1015 interval velocities.

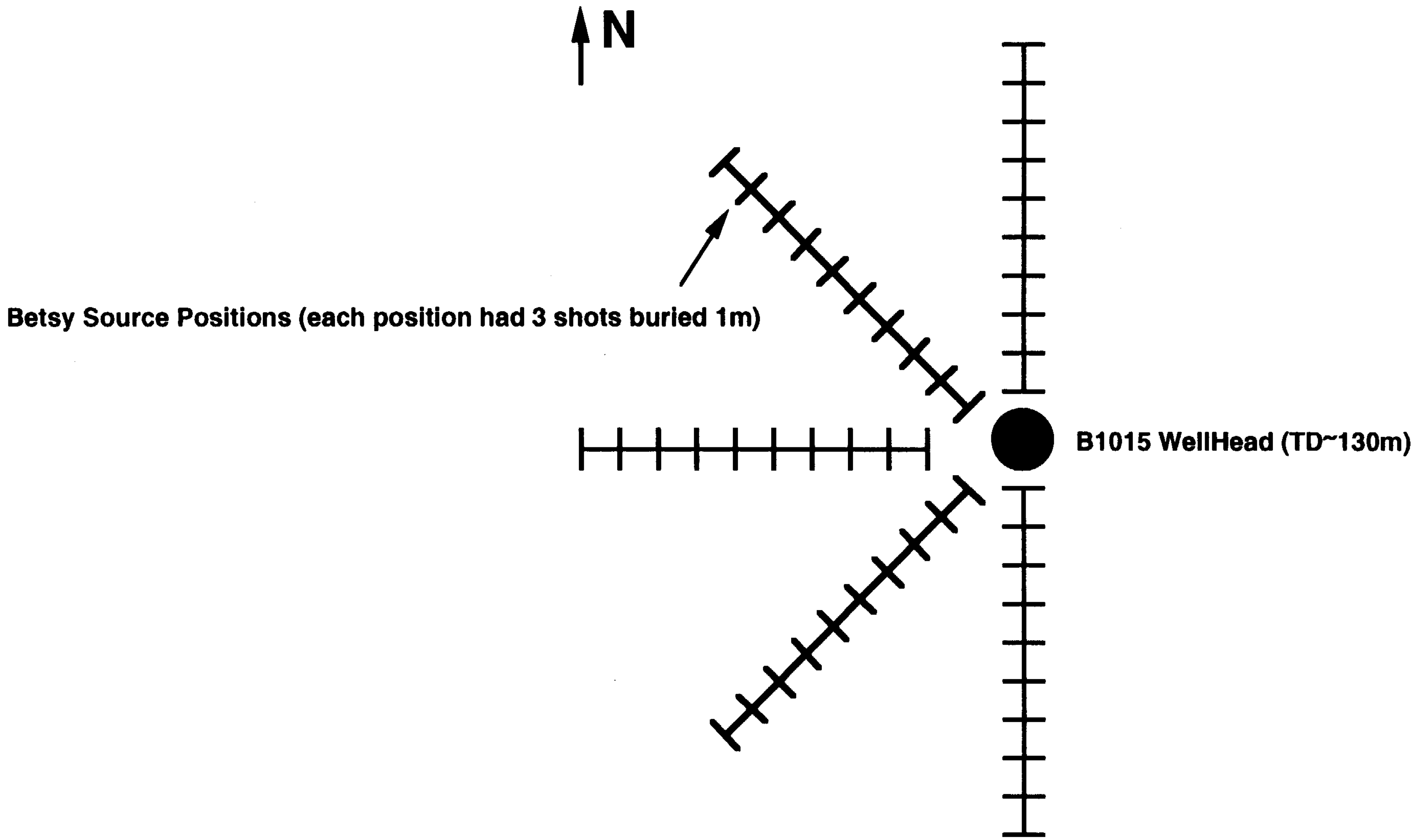

Figure 5. Map view of offset VSP acquisition geometry.

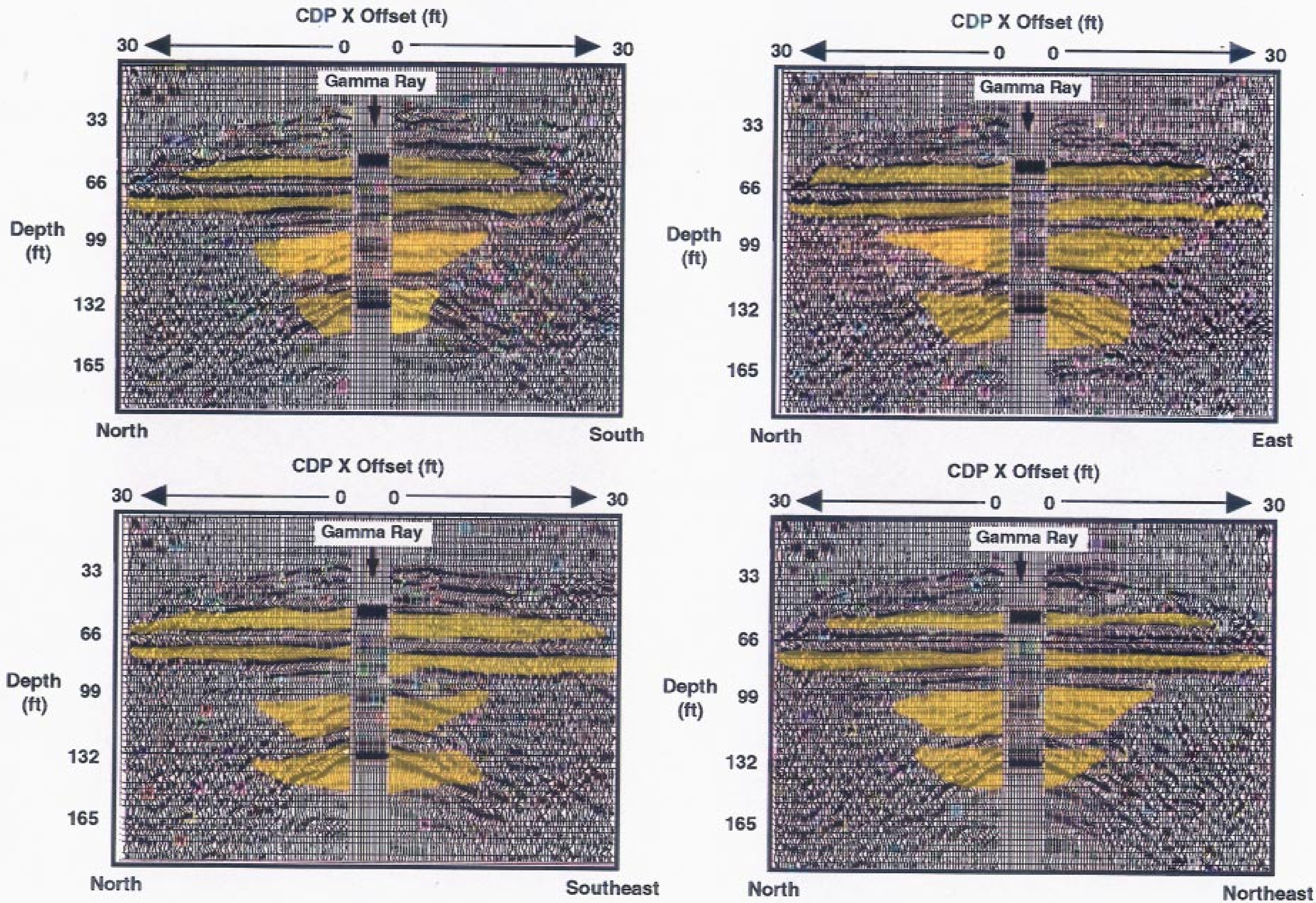

Figure 6. Radial VSPs.

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