VSP – The Link Between Geology and Geophysics*

By

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General Statement

Geophysicists interpret surface seismic reflection data presented in time, and geologists construct models, drill wells, and acquire well logs in depth. An accurate velocity model of the subsurface is required to link the two types of data (time and depth).

Vertical seismic profile (VSP) data is generated by a surface source and recorded by geophones located at many depth levels spanning the entire borehole. The VSP and surface seismic data invariably match in character due to the common source and receiver type used in both surveys. This may not always be the case for the sonic-log-derived synthetic seismogram, which is often used to tie well logs to surface seismic data.

In this article we review the acquisition, basic data objectives, and interpretation of VSP data.

VSP Data Acquisition

The operation of the VSP survey is as follows:

- The sonde containing the geophone package of three orthogonal X, Y, and Z geophones (Figure 1) is lowered to a prescribed depth location.
- A locking arm on the sonde pushes the geophone assembly against the borehole wall.
- The surface source energy source is fired.

Acoustic energy from the source is recorded at the geophone sonde. The locking arm is then retracted and the sonde is moved to the next depth location.

Figure 2 illustrates VSP source and receiver geometries. The near- or zero-offset VSP geometry occurs when the source lies vertically above the geophones (source S_1 and receiver A in Figure 2A). A far-offset VSP occurs when there is substantial offset distance between the vertical projection of the sonde to the surface and the source (source S_2 and geophone A in Figure 2A). In deviated boreholes, source S_3 in Figure 2B can be zero-offset for location A, but far-offset for location B. In general, the zero-offset VSPs will seismically image the geology at the borehole, and the far-offset VSPs will image laterally from the borehole in the direction toward the surface source.

Figure 1. The VSP tool shown above consists of 12 individual sondes linked by an electronic cable and terminated with a logging cable head. The distance between each sonde can be 10, 15 or 20 m. Each sonde contains three orthogonal geophones (two horizontal and one vertical) and a single hydrophone. A hydraulically powered locking arm (shown retracted) ensures that the geophone package is secured against the borehole wall. (Photograph furnished by CGG.)

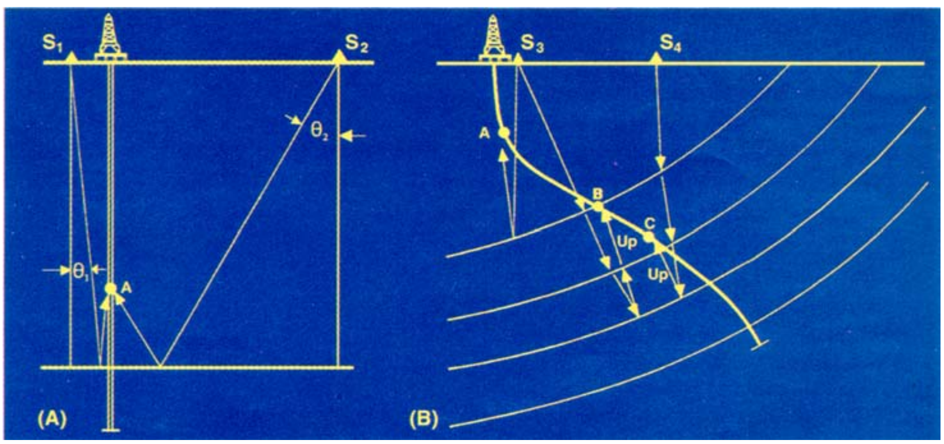

Figure 2. Example geometries of surface source and sondes (containing the geophone package). A survey should be planned with the travelpath of the seismic energy in mind. A far-offset VSP field setup such as a source at S_2 and receiver at A would image the interface at the borehole if the position A was at the interface and up to half the offset distance along the interface if the geophone position A was at the surface.

Zero- or Near-Offset VSP

In Figure 2, the raypaths of the acoustic energy shown are reflections up from interfaces located below the sonde. Surface seismic surveys also record energy arriving from below the geophones. Unlike surface seismic surveys, VSP data also contain acoustic energy traveling downward toward the geophones in the sonde.

"Upgoing" VSP events are defined as VSP events that decrease in traveltime as the sonde is lowered down the borehole -- and cease to exist once the sonde is below the interface from where the reflection took place. “Downgoing" events are defined as events whose traveltime increases as the recording depth increases.

An example of zero-offset VSP data is shown in Figure 3A. Note that the downgoing events are much higher amplitude than the upgoing events, which dip in the opposite direction. The first arriving event (first break curve) is the primary P-wave downgoing event. A downgoing event arriving later in time than the primary must be a multiple. The VSP downgoing wavefield contains all of the multiple events that contaminate our surface seismic data. Since the downgoing and upgoing events are linked at the interfaces, we can use the downgoing events to eliminate multiples from our upgoing VSP data.

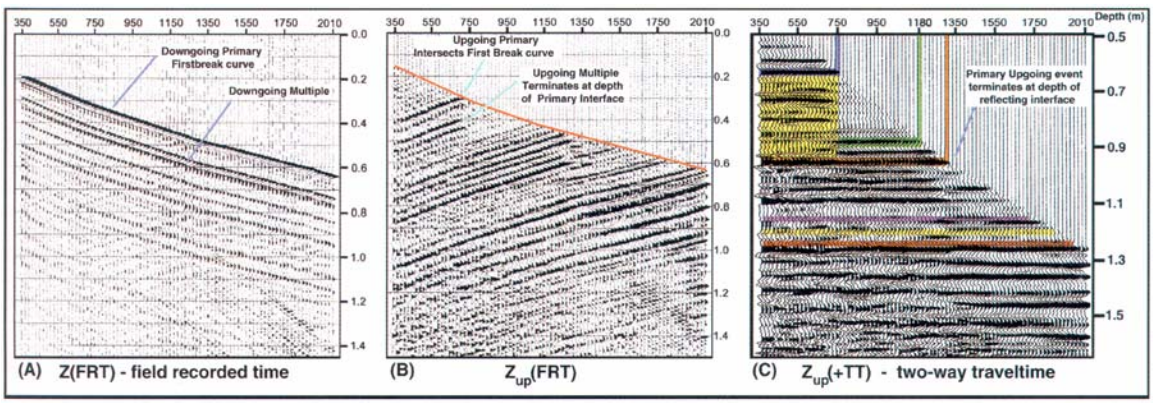

Figure 3. The full wavefield (both up- and downgoing events) zero-offset VSP data in (A) shows high amplitude downgoing events. The upgoing events in (B) can only be seen easily after wavefield separation (downgoing waves are isolated and subtracted out of the data). In (C), the upgoing events are aligned in two-way traveltime (+TT) and can be tied to the surface seismic stacked section. The upgoing event colored orange intersects the first break curve at the trace representing the depth of the interface which caused the reflection.

The difference in traveltime between zero-offset VSP upgoing events (shown in Figure 3B) and the two-way traveltime of a surface seismic event is the traveltime along a raypath connecting the sonde location to a surface geophone. This is equivalent to the traveltime of the primary downgoing event (Figure 4). Bulk shifting each zero-offset VSP trace by its first break time aligns the upgoing events into pseudo two-way traveltime (Figure 3C).

One can determine the depth of the geological interface that created the upgoing event by:

- Interpreting the upgoing event on the shallow depth traces out to the trace where the event intercepts the first break (time of first recorded data).
- Following the trace up to the top of the plot to read off its depth value.

(Look at Figure 3 and do this for the orange colored upgoing event in panel C. This is the interpretive link between the geophysical seismic event and its associated geological interface.)

Multiple identification can be easily done using VSP data. An upgoing multiple is an upgoing VSP event whose raypath undergoes more than one reflection bounce during its travel to the sonde. Find the primary upgoing event in Figure 3C (colored blue) that terminates at the first break time of the 750-meter depth trace. A multiple upgoing event whose last upgoing reflection occurred at the 750-meter interface arrives later in time but also terminates at the 750-meter trace.

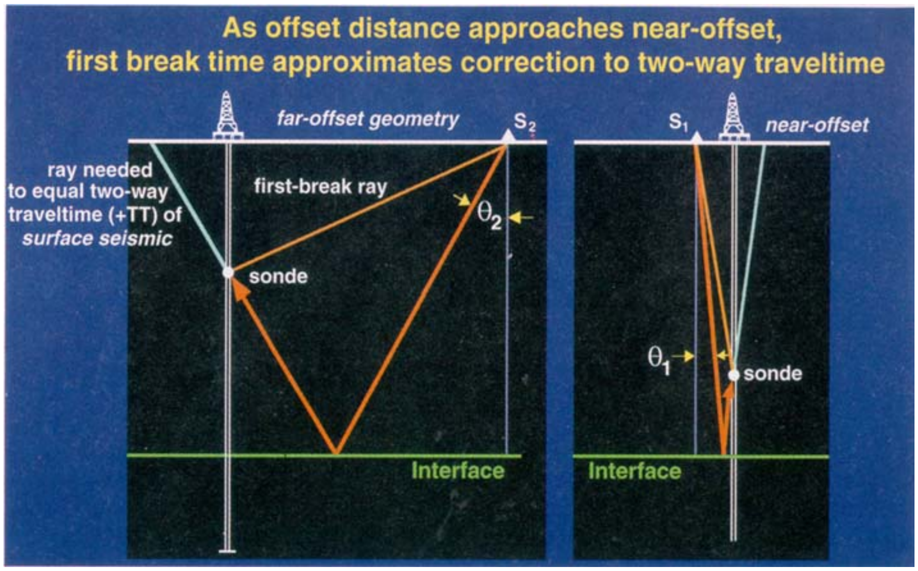

Figure 4. On a zero- or near-offset VSP, the upgoing reflected event travels down to the reflecting interface and up to the sonde containing the geophones. If the raypath had continued to the surface along the additional blue line, the event would be in two-way traveltime. The traveltime along the blue path is the first break time for zero-offset geometry. By adding this time to the trace recorded at the sonde, the VSP data is placed into pseudo two-way traveltime.

Why? -- When the sonde is lowered below 750 meters, rays traveling upwards from the 750-meter interface never reach the sonde. The multiples of our upgoing primary event (blue) in Figure 3C are highlighted in yellow. This allows one to interpret multiples, which may be contaminating later arriving primary upgoing events. Can you see one? The green-colored upgoing primary generated at 1,180 meters can be seen to extend from the first break curve to the multiple contaminated data highlighted in yellow and change in character.

Multiple elimination can be achieved by using the downgoing events. In Figure 3A, the multiple downgoing events parallel the first break curve. We design an operator that will collapse all of the downgoing events arriving after the primary downgoing event (first break curve). This operator can be applied to the data in Figure 3C. The deconvolved upgoing events can be seen in Figure 5B. The deconvolved data can be compared to the surface seismic data to evaluate the residual multiple contamination left in the processed surface seismic data.

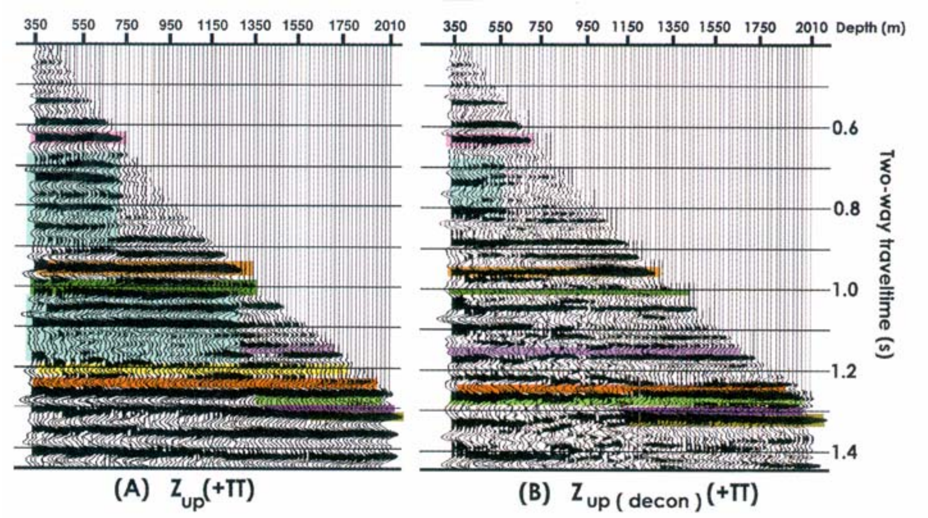

Figure 5. The deconvolved upgoing events in (B) show that the VSP deconvolution has been fairly successful when applied to the data in (A). The purple event at about 1.16 s is now continuous across all traces. Some residual multiple contamination remains on the shallow depth traces.

Far-Offset VSP Data

When the surface source is not located vertically above the downhole receivers, the up- and downgoing traveling seismic energy arrive at the sonde at angles other than vertical. At any given sonde location, the up- and downgoing events are distributed onto all three geophones (two horizontal, X and Y and vertical Z).

In the processing of the far-offset data, our aim is to separate the downgoing events from the data and then isolate the upgoing events on a single data panel for interpretation. In Figure 2, the far-offset raypaths show that interfaces will be imaged from the borehole out to half the source receiver offset. The final upgoing event panel will be processed to take on the appearance of a seismic line. Look at the X, Y and Z data in Figure 6. The primary downgoing event is distributed onto all three panels. As the sonde is lowered to different depth levels during the VSP survey, the sonde rotates. This rotation effect can be seen in the inconsistent first break wavelets on the X and Y panels.

We want to isolate the upgoing events. To do this, we process the X, Y, and Z data using polarization filters (mathematically redistributing the up- and downgoing events into the plane defined by the wellbore and source). Wavefield separation is performed to isolate the upgoing events. A final round of polarization processing is performed to isolate the upgoing events onto a single data panel. Using the X, Y, and Z data contained in Figure 6 as input, the final isolated upgoing events are presented in Figure 7A.

In Figure 2A, we saw that the far-offset VSP geometry resulted in reflections along the interface laterally away from the borehole. In fact, the coverage extends from right at the intersection of the interface with the borehole (sonde at depth of interface) out to half the source/well offset (sonde at borehole surface). As the data is recorded at various downhole locations starting from the surface down to the depth of the interface, the geology along the interface is continuously imaged.

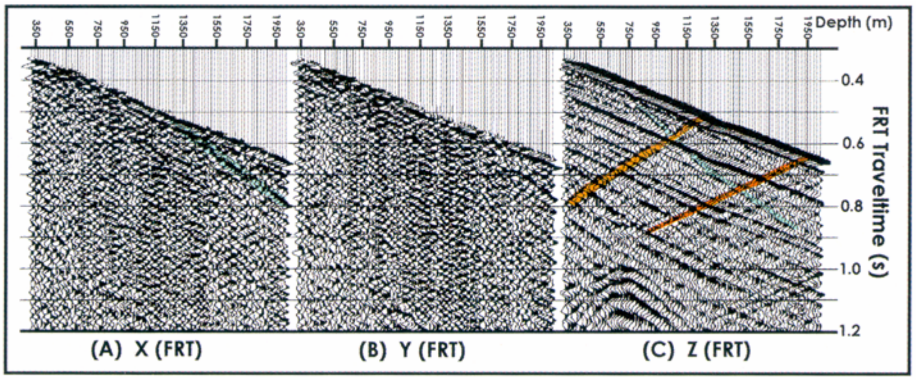

Figure 6. The first break event is found on both the X and Y data. The wavelet is sometimes more consistent on one compared to the other. This is due to the tool rotating in the borehole between tool relocations. The first break event in (A) is the primary downgoing P- or compressional wave. A mode-converted SV or shear event is highlighted in blue in panels (A) and (C). This event dips in a different direction than the downgoing P event because of its slower velocity. In panel (C), the P-wave up- and downgoing events are easily recognized. Note that near the bottom of the data panel there is a hyperbolic-shaped event which could be a refracted shear at the 750 m interface.

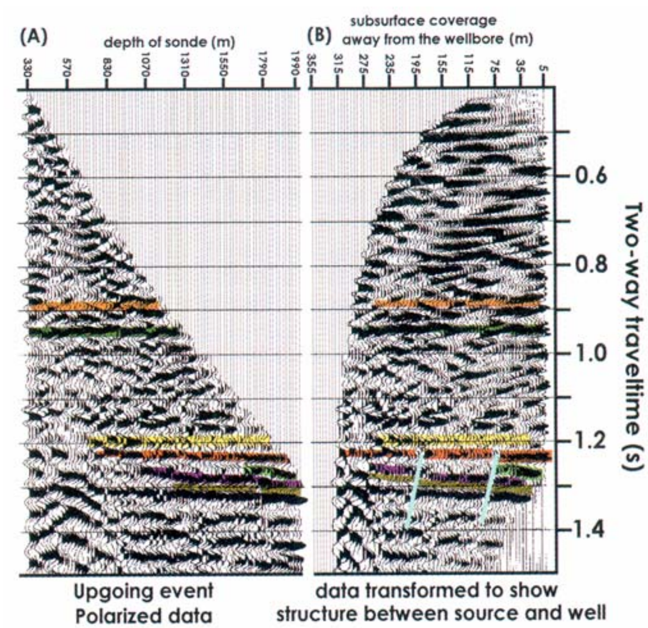

Figure 7. The data in (A) resulted from applying several data polarization steps to the X, Y, and Z data shown in Figure 6. The isolated upgoing event data is plotted in depth of sonde location (trace) versus two-way traveltime. In order to visualize the geology extending from the well laterally towards the source direction, the VSPCDP transformed data is computed and shown in (B). The data show two faults, and the green event truncates against the first fault located approximately 75 meters from the well location.

To transform the data in Figure 7A into a pseudo-seismic section, we use a model of the velocity around the borehole. With this model, we stretch or transform every depth trace into the offset from the well/traveltime domain. This procedure, called the VSPCDP mapping, is shown in Figure 8 for the deepest and shallowest depth traces. We apply this process to all the traces and then re-bin the data to look like seismic traces.

The output of this process is shown in Figure 7B. The horizontal axis is now distance from the well in meters. In Figure 7B, two faults can be interpreted. The distance from the well location where the faulting occurs can be determined using the horizontal axis. The fault nearest the well can be interpreted to be 75-80 meters away, and the farthest fault is 205 meters from the well. A seismic event -- highlighted in green -- can be seen to truncate against the fault nearest the borehole. The borehole itself is located along the right edge of the plot in Figure 7B.

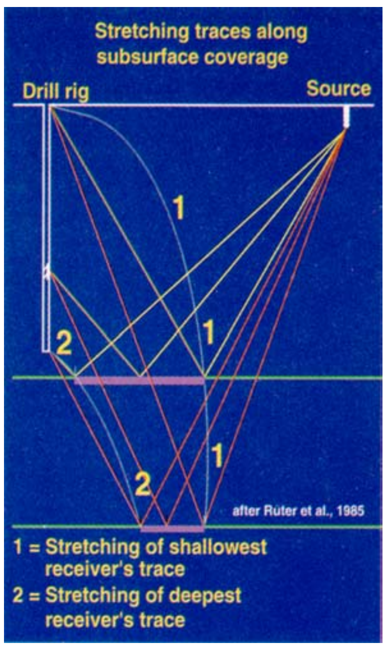

Figure 8. The VSPCDP transform converts the depth/traveltime data in Figure 7(A) to the lateral offset away from the well/traveltime data in Figure 7(B). This enables one to interpret subsurface geology between the well and the source.

Conclusions

The zero-offset VSP gives us a link between surface seismic and reflector depths at the borehole location. Interpretation is easy and the geological logs can be tied confidently to the VSP and then directly to the surface seismic. The VSP data illuminate multiples clearly.

If one has access to VSP data in an area where he/she wants to drill an exploration well, a quick check for the existence of multiples on the VSP data should be done. This could prevent drilling a dry hole if the interpretation was based on surface seismic multiples. The far-offset VSP gives information of the subsurface away from the well. The lateral imaging can be used to locate missed targets such carbonate reef edges or missed sand channels.