

GC Exploring Beneath High-Velocity Surfaces*

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General Statement

In general, the quality of conventional P-wave seismic data is poor when data are acquired across areas where high-velocity rocks (primarily carbonates and basalts) form the exposed, first-layer of the Earth. Some basins that have high-velocity rocks exposed at the surface have deeper layers with good oil/gas potential. Examples would include:

- Large areas of Argentina, Paraguay and Brazil (basalt outcrops).
- The Val Verde Basin and other areas of West Texas (carbonate outcrops).

Numerous other carbonate-covered and basalt-covered exploration areas could be listed. Explorationists working in these high-velocity outcrop areas are frustrated by their inability to acquire seismic data that have signal-to-noise character sufficient to see and map deeper hydrocarbon plays.

Here we examine some principles of seismic imaging in areas where the seismic propagation velocity in the shallowest Earth layer is greater than the velocity in the layers immediately below the surface layer. We consider the question “Does the downgoing compressional (P) wave successfully penetrate a high-velocity surface layer and illuminate deeper targets?” and then the cause of poor data quality before one option for resolving the imaging dilemma.

Example of Surface Problem

A generalized picture of the geology that needed to be imaged in one basalt-covered area is shown as [\(Figure 1\)](#). The Earth surface here was covered by a thick basalt layer characterized by a fast seismic velocity, a rough surface and numerous large internal voids. Normal siliciclastic and carbonate rock layers existed below this exposed basalt. The seismic propagation velocities in these deeper shale, sandstone, and carbonate rocks were less than the propagation velocity in the basalt.

Oil production had been established across this particular area by random drilling, without the aid of seismic data because conventional P-wave seismic data were too noisy to define drilling targets. Inasmuch as random drilling is not an efficient or cost-effective option for developing a prospect, the operator decided to acquire offset-source VSP data in several wells to attempt to image across interwell spaces and to develop a better exploration model.

VSP data acquired in one well are displayed as [\(Figure 2\)](#) after considerable data processing has been done to isolate downgoing and upgoing P and S (shear) wave modes. The seismic source was a vertical vibrator offset about one kilometer from the well – the same source used in several failed attempts to acquire usable surface-based P-wave data across the area. These VSP data show several important facts, namely:

- A robust downgoing P wave (center panel), as well as a strong downgoing SV wave (left and right panels), travels through the deep, slower-velocity layers. All doubts are removed about the possibility that the downgoing source wavelet does not penetrate the surface basalt layer and illuminate deeper geology. A good-quality illuminating wavelet reaches all target depths.
- Good-quality upgoing P-wave (left panel) and converted-shear (SV) reflections (center panel) are generated at several deep interfaces, including interfaces associated with critical reservoir intervals.

At this point we know that the deep geology has been illuminated and that reflection events from our primary targets head back toward the Earth's surface. Yet these reflections cannot be recognized by surface-positioned receivers.

Why not? We appear to have isolated the imaging problem to something that occurs in the local vicinity of the surface receivers.

Cause of Surface Problem

Because good-quality reflections head upward toward the earth's surface, why do we not capture these reflections with earth-surface receivers? The culprit that prevents the capture of good-quality reflection events often seems to be severe, unorganized ground-roll noise. The earth model in [\(Figure 3\)](#) will be used to illustrate the wave physics. There are two kinds of surface waves that travel horizontally away from a source station and spread across the earth-air interface:

- One surface wave is the Rayleigh mode, created by any surface-based source that produces a vertical displacement. Almost all onshore seismic sources (vertical vibrators, explosives in shotholes, weight droppers, etc.) create a vertical displacement and thus produce a Rayleigh wave. The common term used for a Rayleigh wave is “ground roll.” The particle motion associated with a Rayleigh wave is a vertical, retrograde, elliptical motion as shown in [\(Figure 3\)](#).
- The second surface wave that can propagate along the earth-air interface is a Love wave, which can be generated only by an SH shear source that creates pure horizontal displacement, and the wave propagates horizontally as a pure SH shear mode that produces no vertical displacement [\(Figure 3\)](#). Of these two surface waves, the Rayleigh mode is the “bad” noise mode when the surface layer has a fast seismic propagation velocity. The Love wave is the “good” noise mode. You just have to love the Love wave when you operate in an area having high-velocity outcrops.

Why is the Rayleigh ground roll so troublesome across outcropping basalts and carbonates? For most poor-data areas, the answer is that the exposed high-velocity layer usually has a rough surface and numerous large internal voids [\(Figure 1\)](#), and these randomly positioned irregularities cause the ground roll to backscatter from many azimuth directions and at many different time delays to create a continuous overprinting of high-amplitude, unorganized noise on top of the deep reflection events that arrive at each surface receiver.

Because this noise is unorganized (i.e., it does not arrive from a fixed direction, and its components have variable time origins), it is difficult – and usually impossible – to remove from the data. Upcoming reflections from deep targets do indeed arrive at the surface receivers as we suspected, but these reflections are overwhelmed by the reverberating, unending ground-roll noise.

Solution

How then can geology beneath a high-velocity outcrop be imaged? The answer is a beautiful bit of wave physics explained in one or two textbooks and which is summarized by the following equation that defines the frequency components of a propagating Love wave:

$$\omega_n = \frac{n \pi V_{S1}}{H} \left[1 - \left(\frac{V_{S1}}{V_{S2}} \right)^2 \right]^{\frac{1}{2}}$$

In this equation, ω is the frequency (Hz) of the Love wave, H is the thickness of the high-velocity surface layer, V_{S1} is the S-wave velocity in the surface-exposed layer and V_{S2} is the S-wave velocity in the interval beneath the surface layer. When V_{S1} is greater than V_{S2} , as it is when the surface layer is basalt or carbonate, the quantity inside the square-root bracket is negative; this results in an imaginary frequency. Because no Love wave can have an imaginary frequency, the physical consequence is that no Love wave propagates in this type of velocity layering, and there can be no surface noise mode. If we therefore use SH shear technology to image beneath high-velocity outcrops, we have no surface-wave noise, and we should be able to capture SH reflections from deep targets.

Concluding Example

One test of this principle – work done years ago by researchers at Arco – is shown in [\(Figure 4\)](#) to illustrate the physics. The P-wave data are not too bad in the right half of the image space, where there is a slow-velocity earth surface, but the data are unusable on the left, where the profile moves onto the fast-velocity surface. In contrast, SH data acquired along the profile produce a valuable image beneath both the low-velocity surface and the high-velocity surface and imply that below the fast-velocity surface there is a faulted trap that could be a good drilling target.

Excessive Rayleigh ground roll destroyed the P-wave reflections along the high-velocity surface. The absence of a Love surface mode on the high-velocity surface allowed SH reflections to be seen. SH seismic technology should be considered if you have a bothersome high-velocity surface that hinders the use of P-wave data across a prospect area.

References

Fix, J.E., J.D. Robertson, and W.C. Pritchett, 1986, Shear-wave reflections in three West Texas basins with high-velocity surface rocks: *Geophysical Developments*, v. 1, p. 180-196.

Pritchett, W.C., 1990, *Acquiring Better Seismic Data*, Chapman and Hall Ltd, London, 427 pages.

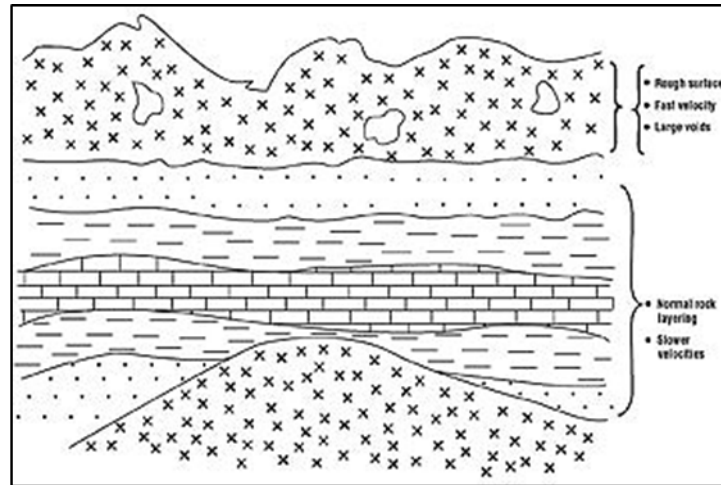


Figure 1. Generalized geological model of the geology associated with one basalt-covered surface where deep oil reservoirs cannot be seen with surface-based seismic sources and receivers.

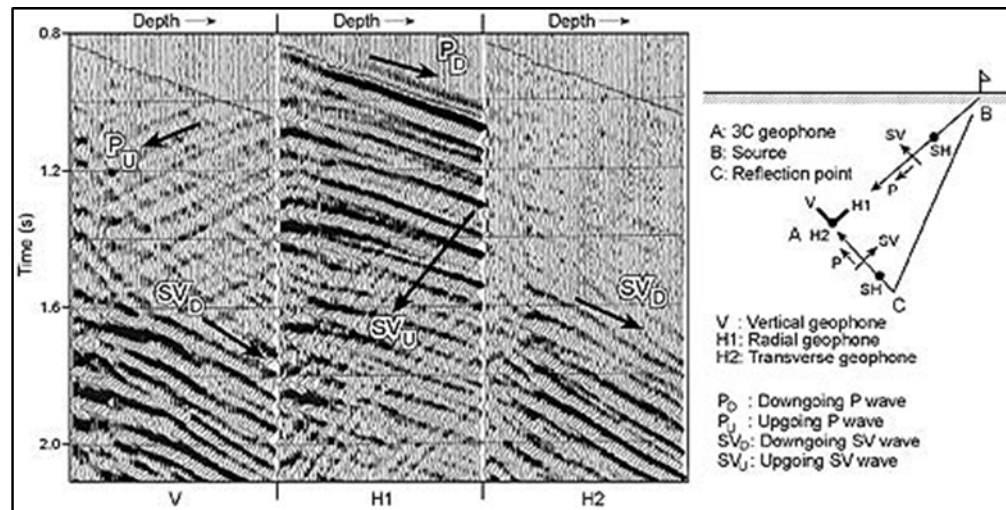


Figure 2. VSP data acquired in a well that was drilled through the basalt layer and into the interval where the hydrocarbon play was focused. All data are recorded below the surface basalt layer. These data confirm that the downgoing wavefield illuminates deep targets, and that robust upgoing reflections are created. The diagram on the right shows the orientations of the particle-displacement vectors (short arrows) associated with downgoing and upgoing raypaths. The large arrows atop the data panels identify downgoing and upgoing P and S events.

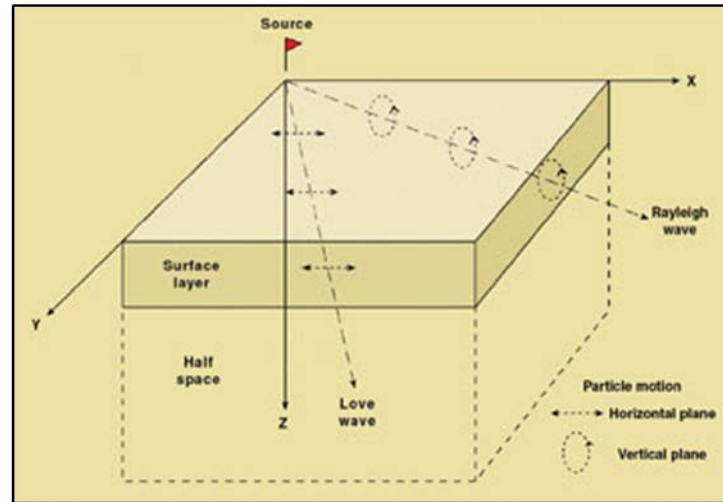


Figure 3. Earth model illustrating the two types of surface-wave noise modes (a Rayleigh wave and a Love wave) that can propagate along the Earth-air interface.

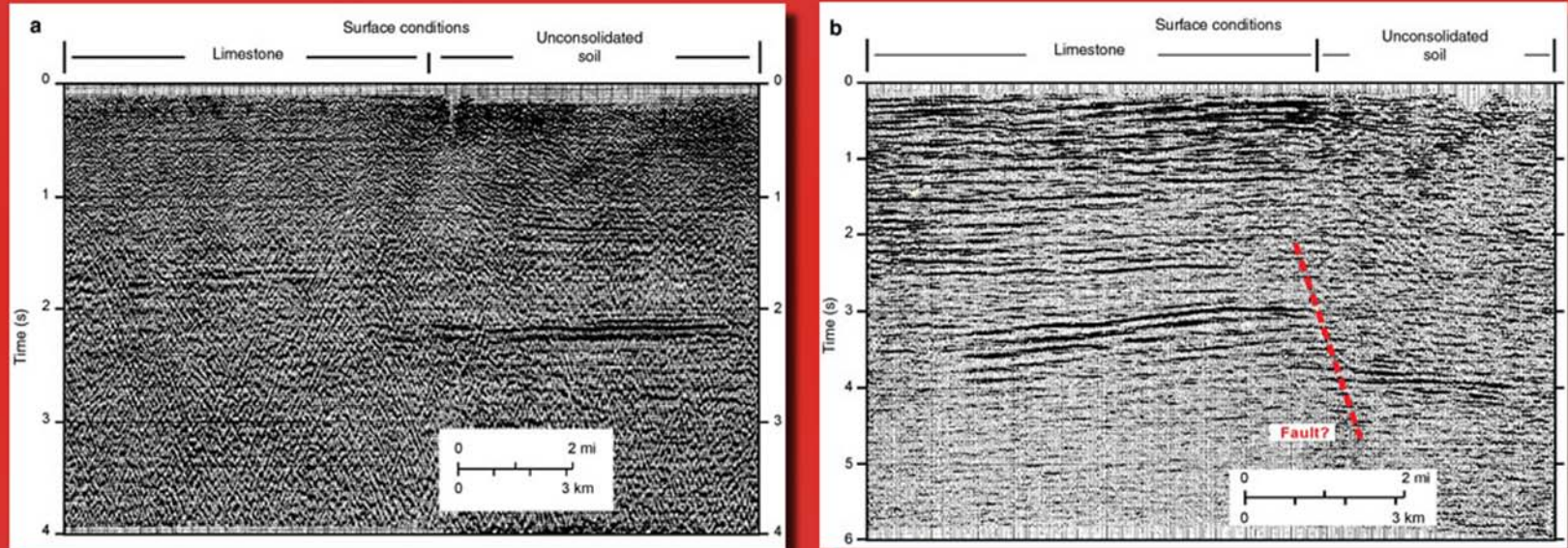


Figure 4. Comparison of P-wave data (a) and SH data (b) acquired along a profile that traverses a low-velocity Earth surface on the right and a high-velocity surface on the left. The SH data image beneath the exposed carbonate; the P-wave data do not. (From Fix et al., 1986).