A New Low-Cost Way to Include S-Wave Data in Prospect Evaluation

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Land-based P-wave sources include vertical vibrators, vertical impacts, and buried explosives. Recent tests and imaging efforts at the Bureau of Economic Geology at the University of Texas at Austin have established that two types of illuminating wave fields, an illuminating P wavefield and an illuminating SV wavefield, are produced by all of these sources. These downgoing illuminating P and SV wavefields are produced immediately at a source station and are referred to as a *direct-P* or a *direct-SV* wavefield to distinguish them from *converted-P* or *converted-SV* wavefields that are produced at interfaces remote from a source station.

Two new concepts now have to be included in the physics of seismic reflection seismology with P sources. The first concept is that all traditional P sources produce both a robust direct-P and a robust direct-SV illuminating wavefield (Figure 1a). This fundamental wave physics has been ignored for decades, and so far reflection wavefields produced by only the direct-P mode generated by "P sources" have been used in reflection seismology. The second concept is that the direct-P and direct-SV wavefields produced by "P sources" cause vertical geophones to always record two independent and interlaced reflection wavefields (a P-P wavefield and a SV-P wavefield). Similarly, horizontal geophones also record two independent and interlaced wavefields (a SV-SV wavefield and a P-SV wavefield), as illustrated in Figure 1b.

First, let us attempt to understand why the valuable SV illuminating wavefield produced by P sources has been ignored. Theoretical calculations of the direct-P and direct-SV radiation patterns that a point P-source creates in isotropic, homogeneous media were published by Miller and Pursey (1954) and are exhibited in Figure 2a. Examination of Figure 2a shows that a surface-based P source (a vertical-displacement source) does indeed create much more SV energy than P energy. However, these calculations also indicate that no SV energy propagates away from a P-source station inside the critical take off-angle range that extends from +30 degrees to -30 degrees from vertical, which is required for imaging deep targets. Instead, essentially all of the emitted SV energy refracts, travels horizontally, and cannot be used for deep imaging. Based on this modeling result, geophysicists began to assume in the 1950s that the robust SV energy produced by a P source was not effective for imaging deep geologic targets, and unfortunately, that view of SV illumination by P sources still dominates the thinking of reflection seismologists today.

The author has worked with VSP data since the 1970's and has observed many VSP data examples where a robust downgoing SV wavefield created by a zero-offset P source (usually a vertical vibrator) was recorded by a vertical array of geophones stationed directly beneath a P-source station. Thus

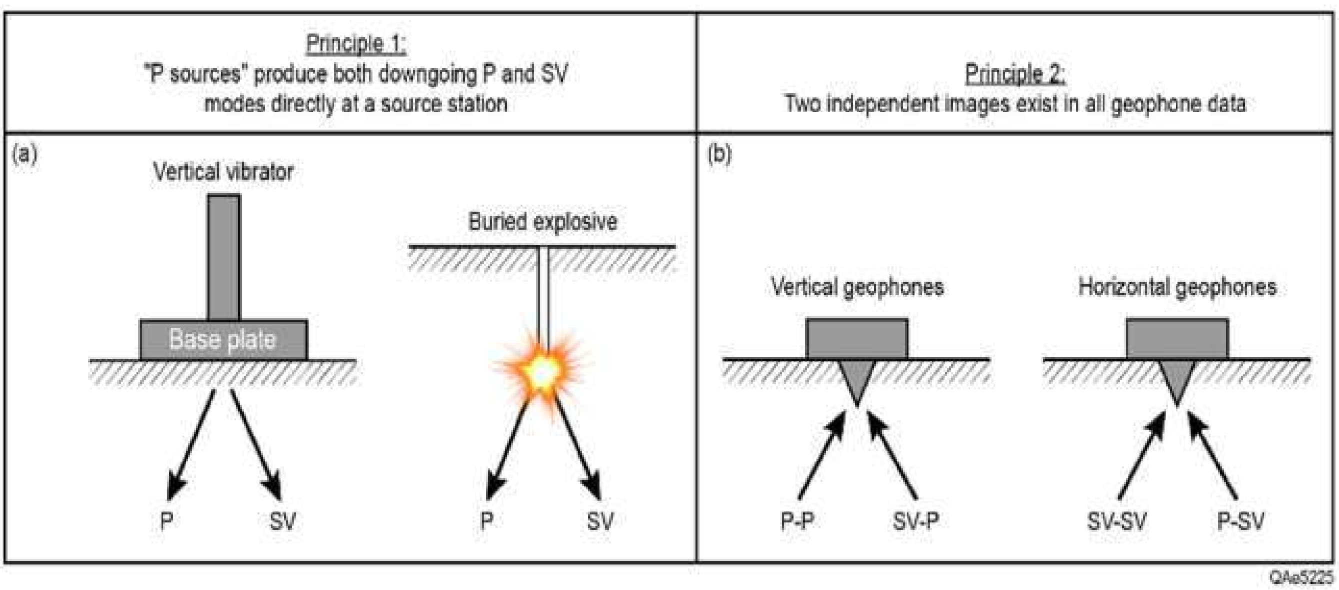

Fig. 1: (a) Key concept #1 common P-wave sources produce both a direct-P illuminating wavefield and a direct-SV illuminating wavefield. (b) Key concept #2 as a result of this dual, direct-wavefield illumination, vertical geophones record two independent reflection wavefields, and so do horizontal geophones.

a VSP field test was done in which direct-P and direct-SV radiation patterns created by all generic classes of P sources and S sources were measured using a walkaway source geometry recorded by an extensive vertical array of 3C geophones. An example field measurement of the direct-P and direct-SV radiation patterns produced by a vertical vibrator is shown in Figure 2b. Note that this P source causes SV energy (red and blue dots) with amplitudes greater than P energy (red dots) to travel at vertical and near-vertical takeoff angles. A great deal of radiated SV energy still travels at takeoff angles exceeding 30-degrees from vertical, but the important point is that the amount of SV energy that now travels at takeoff angles less than 30-degrees from vertical is sufficient for deep-target imaging. Similar near-vertical direct-SV radiation behavior was observed for all other types of P sources (vertical impacts and buried explosives) in this field test.

Thus we have a quandary. Which radiation physics result is correct the radiation pattern predicted for an isotropic, homogeneous earth (Figure 2a), or the real data measurements (Figure 2b)? To assist in reaching a decision on this matter, a finite-difference method of calculating direct-P and direct-SV radiation patterns was done. The advantage of a model space built from finite-difference cells is that small, near-source irregularities can be included in seismic-wavefield propagation space. These near-source irregularities account for minor changes in stiffness coefficients of the earth immediately around a P-source station. Such small irregularities represent differences in stiffness coefficients that could be caused, for instance, by the root system of a bush extending perhaps a meter into the soil and creating a stiffer medium on one side of a source station, but only shallow grass roots, and thus a less-stiff medium, being present on the other side of the source station, or by lateral changes in the mineral mixtures of layered soils occurring at short distances of 2 or 3 meters from a source station, or by other similar, natural, irregularities in near-source earth conditions. This finite difference modeling showed that when common, small-scale, near-surface irregularities are positioned near a source station, SV radiation increases in near-vertical takeoff angles (Figure 2c) just as direct-SV illumination is observed to do at a real-earth source station (Figure 2b). This finite-difference modeling indicates that it is time to replace the over-simplified, isotropic, homogeneous earth model used in 1954 modeling with more realistic earth models that better represent a real-earth, near-source environment and that better describe realistic irregularities that are common in a seismic propagation medium.

Expanded imaging options provided by P sources were first discussed in geophysical literature in 2014 (Hardage and Wagner, 2014a, 2014b; Hardage, et al., 2014). Before these papers were published, there was no example in the literature of a SV-P image or a SV-SV image produced by a P source. Important S-wave images and rock/fluid attributes are now available for geologic interpretation across geologic targets when P-source data are considered from the points of view that: (1) two down going wavefields (a direct-P wavefield and a direct-SV wavefield) are produced simultaneously by P sources that traverse a target area, and (2) two overlapping reflections (one produced by the direct-P wavefield and one produced by the direct-SV wavefield) are present in vertical-geophone data.

A west-Texas example will illustrate why a focus on creating SV-P images from vertical-geophone data is justified. An opportunity arose whereby, SV-P imaging of the Ellenburger carbonate could be investigated across an area on the western shelf of the Midland Basin in west Texas using legacy P-source data. The seismic source was an inline array of three vertical vibrators. The data used in this study were recorded 12 years earlier than initiating this SV-P imaging

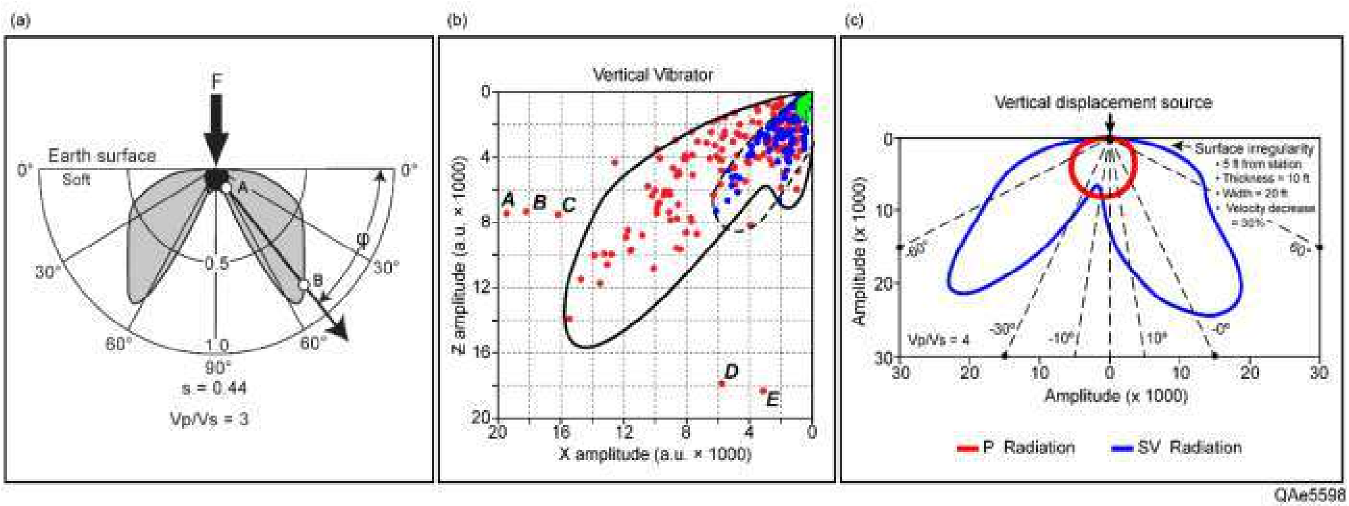

Fig. 2: (a) Calculated P and SV radiation patterns (Miller and Pursey, 1954) generated by a surface-based, single-point, P-source in an isotropic, homogeneous medium in which Vp/Vs = 3. SV illumination vanishes at takeoff angles extending from vertical to 30-degrees from vertical. (b) Real-data measurements of P and SV radiation patterns generated by a single, vertical vibrator, and recorded by properly rotated 3C geophone in a walkaway VSP. Note that the amplitude of SV radiation (red points for radial geophones and blue points for transverse geophones) at near-vertical takeoff angles does not vanish as in panel (a) and exceeds the amplitude of P radiation (green points). (c) P and SV radiation patterns produced by the single-point source in panel (a) when Vp/Vs = 4, and Vp and Vs are reduced by 30-percent in a surface-exposed layer, 10-ft thick and 20-ft wide, that is laterally offset 5 feet from the source station. Now, SV energy travels in near-vertical takeoff directions as do real data in panel (b).

effort. The data were recorded with 3C geophones, which allowed P-SV images to be created from horizontal-geophone data and compared with SV-P images extracted from vertical-geophone data. At this west Texas study location, the depth of the Ellenburger was approximately 16,000-ft (4900-m). Side-by-side displays of P-P, SV-P, and P-SV images of the Ellenburger created in this investigation are displayed in Figure 3. A unique feature of the Ellenburger carbonate is that it contains a variety of karst features. Examination of the seismic profiles in Figure 3 show that an important outcome of this investigation was that the SV-P image at this study location shows evidence of karst fracturing, faulting, and minor formation collapse that cannot be easily seen in either the P-P or the P-SV images. The high sensitivity of S-mode images to the presence of fractures and subtle faults are key factors that demonstrate the value of SV-P imaging across prospects where such features can be important in reservoir characterization.

An additional point is that SV-P and P-SV images should be identical, but in this west-Texas case, and in other SV-P image investigations the author has done, P-SV images do not reveal geological detail as well as SV-P images do, and P-SV images often have poorer signal-to-noise character than SV-P images. For the present, one can only conclude that any superiority of SV-P images over P-SV images is caused by seismic crews not taking proper diligence to deploy 3C geophones, with the result that horizontal geophones (needed for P-SV imaging) are not coupled to the earth as well as are vertical geophones (which are used for SV-P imaging).

A second example of the reliability of SV-P imaging with P sources is the outcome of an imaging study across a CO2 storage reservoir in Wellington Field, Sumner County,

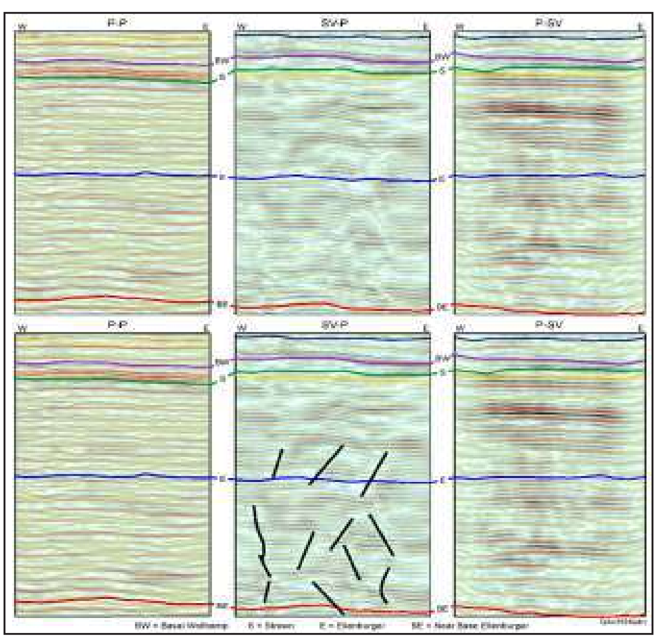

Fig. 3: (Top) Comparison of depth-equivalent P-P, SV-P, and P-SV images of the Ellenburger interval in west Texas. (Bottom) Evidence of karst-collapse shown by solid lines on the SV-P profile is difficult to find in the companion P-P and P-SV profiles.

Kansas. The Kansas Geological Survey acquired 2D profiles of 9C data across this site, which allowed a comparison between SV-P images made with a horizontal vibrator, considered to be the gold-standard source for producing illuminating SV wavefields, and SV-P images made from illuminating SV wavefields produced by a vertical vibrator. Comparison of images are shown in Figure 4. The SV-P image made with a horizontal vibrator is shown as the right half of the profile image, and the SV-P image made with a vertical vibrator is shown as the left half of the profile image. The two images tie at the center calibration well, and there is evidence that the vertical-vibrator version has better resolution because vertical-vibrator sweeps extend over a wider frequency range than do horizontal-vibrator sweeps. In this case, the SV-P image made with the P source is just as valid, and perhaps superior to, the SV-P image made with the gold-standard S-wave seismic source, a horizontal vibrator.

Several scientists who have assisted in testing the concepts of practicing S-wave reflection seismology with P-wave sources conclude that SV-P data extracted from vertical-geophone responses are an excellent choice for providing lower-cost S-wave information to the global seismic community. The attraction of the SV-P mode provided by P sources is based on the following facts:

1. Vertical-displacement land sources (vertical vibrators, shot-hole explosives, and vertical impacts) produce direct-SV modes as well as direct-P modes. Thus the seismic sources needed to generate SV-P data are common P-wave sources that are widely spread around the globe.
2. Because the up going ray path of an SV-P mode is a P wave, SV-P data are recorded by vertical geophones. In contrast, P-SV data must be recorded by horizontal geophones, which requires that 3C geophones be deployed. In some instances, there can be cost savings in the data-acquisition phase of a seismic program when data are acquired with vertical geophones rather than with 3C geophones. Also, many field-oriented geophysicists observe that vertical-geophone data are often superior to horizontal-geophone data because vertical geophones usually couple to the earth better than do horizontal geophones.

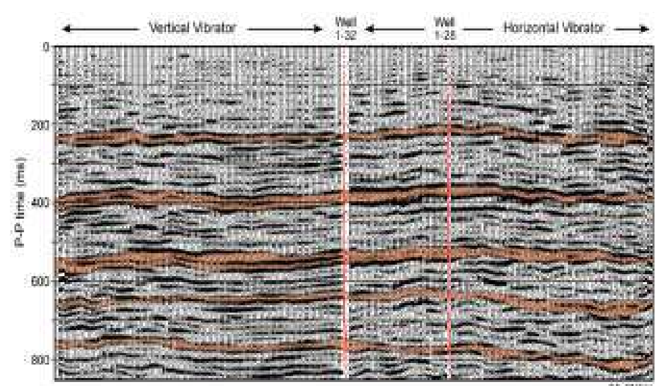

Fig. 4: Comparison of SV-P images made by a "gold standard" SV source (a horizontal vibrator) and by a vertical vibrator. The two images match satisfactorily at a mid-profile calibration well. Horizontal-vibrator data are shown on the right side of the well and vertical-vibrator data on the left side. Adapted from Gupta (2017).

3. Because SV-P modes reside in data generated by common P-wave sources and recorded by single-component vertical geophones, there is a huge amount of untapped SV-P data in legacy P-wave seismic data (both surface-based data and VSP data) preserved in seismic-data libraries in many countries. Thus for many prospect areas, interpreters may be able to produce valuable S-wave images from legacy P-wave data and will not even have to acquire new seismic data. All SV-P images shown in this article were produced from legacy data acquired several years before SV-P imaging was attempted.

The combination of these facts leads to the conclusion that a focus on SV-P data may be the lowest cost and most widely available way to provide S-wave information to the global seismic community.

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