Imaging of thin beds using advanced borehole seismology

B. N. P. PAULSSON, J. W. FAIRBORN, and B. N. FULLER, Paulsson Geophysical Services, La Habra, California

The high cost of data acquisition and the limitations of energy sources have impeded the widespread use of borehole seismic techniques. While piezoelectric and air-gun sources continue to improve, these fluid-coupled sources have severe problems associated with generation of tube waves. Additionally, the piezoelectric sources have a narrow frequency bandwidth which peaks above 1 kHz, thus limiting their application to high-Q sediments. Consequently there is a need to complement the fluid-coupled sources with one which generates lower frequencies and which, by clamping to the borehole wall and thus achieving more efficient coupling of energy into the formation, will propagate energy to a greater range and minimize tube waves.

Industry and government addressed this need by forming a Cooperative Research And Development Agreement (CRADA) to design and build a powerful, commercial quality, downhole, three-component seismic vibrator. CRADA members are Sandia National Laboratories, representing the U.S. Department of Energy; Raytheon Aircraft; the Gas Research Institute; Pelton; Chevron; Exxon; Amoco; and Conoco.

A single-component axial vibrator was completed in 1997. The draw works, cable, and control equipment are mounted on a large trailer. For onshore application the equipment is used in a manner that is very similar to a standard wireline operation. For offshore applications the four modules that make up the draw works are taken off the trailer and operated on the deck of the platform.

Initial tests took place in February 1997. The tests were in the form of a single common-shot fan. Source depth was 500 ft. Receivers were at depths ranging from 1500 to 150 ft in 10-ft intervals. The receiver array was a five-level, clamped, three-component tool developed by Exxon Production Research. At the time of the first test, the receivers operated on a seven-conductor wireline. The system now operates on a fiber-optic wireline. The maximum number of receiver modules in the array is currently 10. The data-sampling interval is 0.25 ms.

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Operating principles. A direct analogy can be drawn between the borehole vibrator and surface vibroseis. Inside the borehole vibrator's sonde, a 250-lb reaction mass is suspended below a hydraulic piston that is set into axial motion by a hydraulic servo valve. The vibrator clamp is coupled to the motion of the piston and so reacts in an equal but opposite direction to transmit stress to the borehole wall and consequently seismic energy into the formation. Thus the clamp acts like the vibroseis base plate, and a radial clamping force provides the equivalent vibroseis hold-down weight. The wireline and the rest of the sonde are isolated from the clamp just as the vibroseis truck is decoupled from the base plate.

The most important criterion in the design of the vibrator was that the source provide a large amount of effective seismic energy without harming the cement-casing interface. The only source that can achieve this is one that transmits a controlled signal over a long time, thus keeping the stress low while transmitting considerable energy. This design, properly implemented, can also achieve the broadest frequency range of any seismic source. The reaction mass, clamp surface area, and mass acceleration were designed to provide an optimum compromise between output force and shear stress on the borehole wall (which should be less than 120 psi, the API-recommended maximum shear stress for maintaining the cement bond).

Reaction mass accelerations peak at about 30 gs, so the 250-lb reaction mass causes a maximum output force of approximately 7500 lbs. This force is fairly constant from about 90 Hz to 200 Hz and slowly tapers off at either end of the seismic spectrum. The force is down to about 2000 lbs at frequencies of 20 and 600 Hz. The force generated by a large surface vibrator is on the order of 60 000 lbs, or eight times greater than the downhole vibrator. However, the borehole vibrator does not lose any energy to surface waves and does not need to contend with the weathering layer, so the usable energy from the borehole vibrator is approximately the same as that of a surface vibrator.

The hydraulic pump in the downhole vibrator is driven by a 12 kW electric motor in the tool (that is powered from the surface). The high current carried by the wireline to the motor generates a large electric noise field. In order to minimize interference of control signals to the vibrator, temperature, pressure and accelerometer data from the tool are transmitted to and from the surface on fiber-optic lines.

Test site data example. Chevron's borehole test site consists of two boreholes separated by 400 ft with depths of 2000 ft. The sediments in both the San Pedro and Fernando Formations at the site are poorly consolidated sands and silts with an average velocity across the fan of about 6500 ft/s and a Q in the mid-20s. The formation has similar properties to unconsolidated Gulf Coast sediments.

The test consisted of a crosswell survey with the source at 500 ft. The data were recorded as a common shot fan with receivers at 10-ft intervals between 150 and 1500 ft. Each record is the correlated output of one 4-s, 10-800 Hz linear sweep. Figure 1 shows the data recorded on the vertical geophone component of the common source fan after a 50-700 Hz bandpass filter. There are a number of interesting features in these data:

1) The numerous events peeling away from the direct *P*-wave with opposite moveout are reflections in which the reflector depth is at the point of intersection with the direct arrival. The major reflections are at 160 and 930 ft, which probably represent the upper and lower boundaries of the San Pedro Formation. Note the apparent vertical wavelength of these reflections is only about 20 ft, suggesting that bed resolution for crosswell reflections could be less than 5 ft at this site.
2) The amplitude of the direct *P*-wave decreases as receiver depth approaches source depth. This is to be expected, given the radiation pattern of an axial borehole vibrator, which has a null in the plane perpendicular to the wellbore and a maximum in the direction axial to the wellbore. The radiation pattern is well suited for reverse VSPs, particularly in deep wells where the upcoming seismic energy would reach the surface at low angles of incidence.
3) The direct shear wave is very strong at small vertical source-receiver offsets, but as shown on the smaller scale plot on Figure 2, it weakens considerably with increasing receiver depth. Again this could be attributed to the vertically polarized, shear-wave radiation pattern, which has a maximum in the plane perpendicular to the wellbore and a minimum in the parallel direction. At small vertical offsets the direct shear wave is complicated by high-amplitude reverberations, which may represent trapped modes within a low-velocity zone. Note the top of the moveout pattern is somewhat flattened, possi-

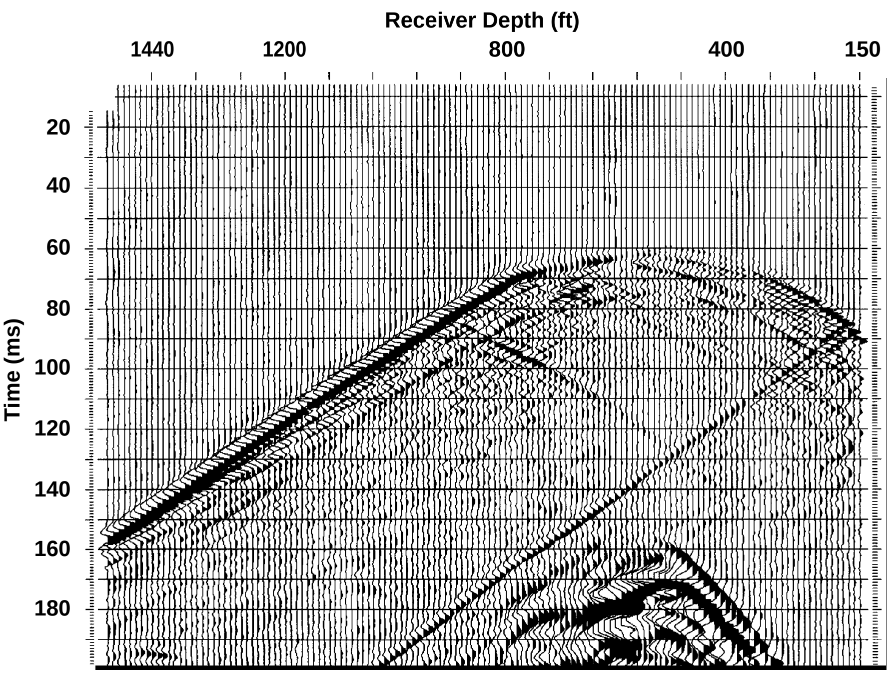

Figure 1. Common source fan. The source was positioned at a depth of 500 ft. The five-level receiver array was positioned from 150 to 1500 ft in 10-ft increments.

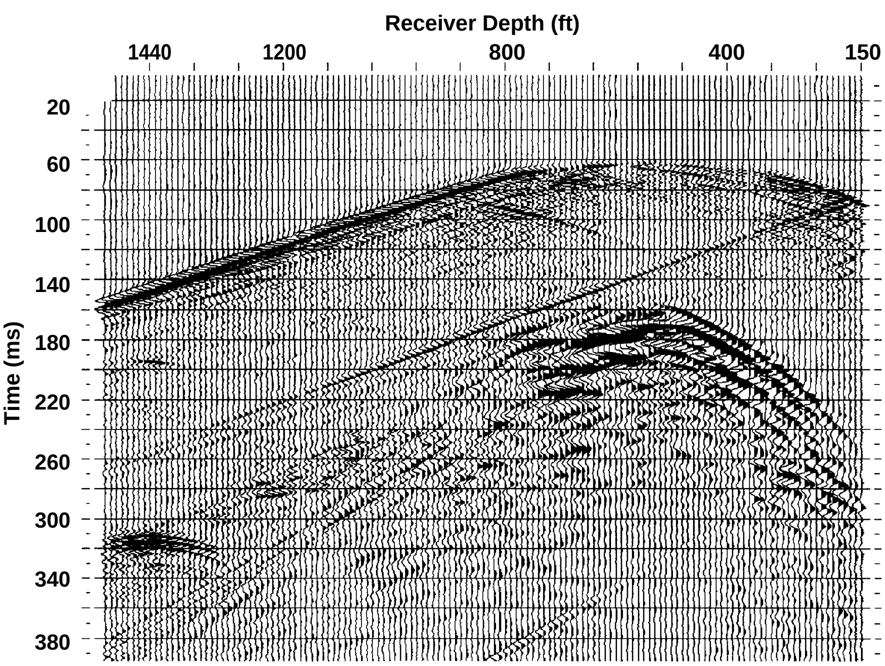

Figure 2. Common source fan showing direct *P*-wave and *S*-wave arrivals.

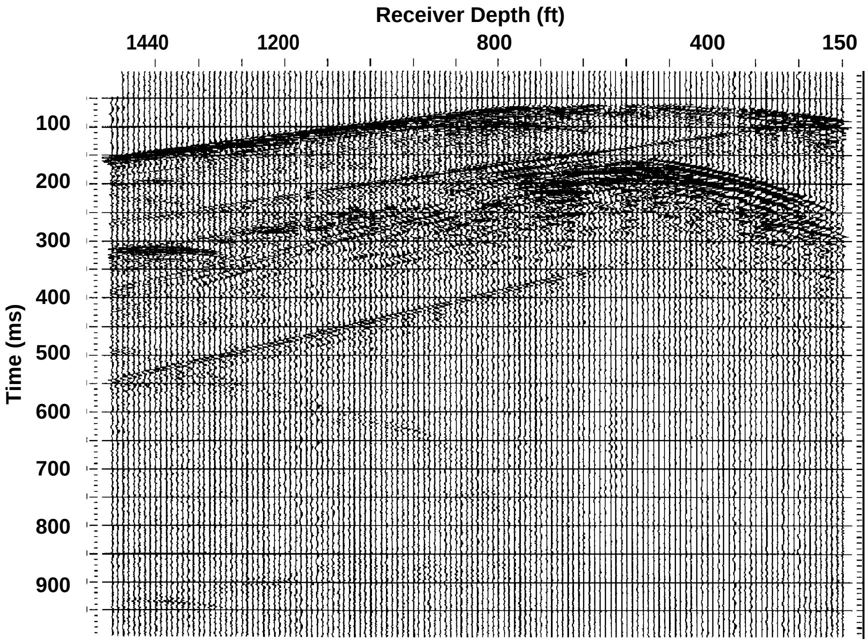

Figure 3. Common source fan showing deep reflection intersecting left edge of plot at about 500 ms.

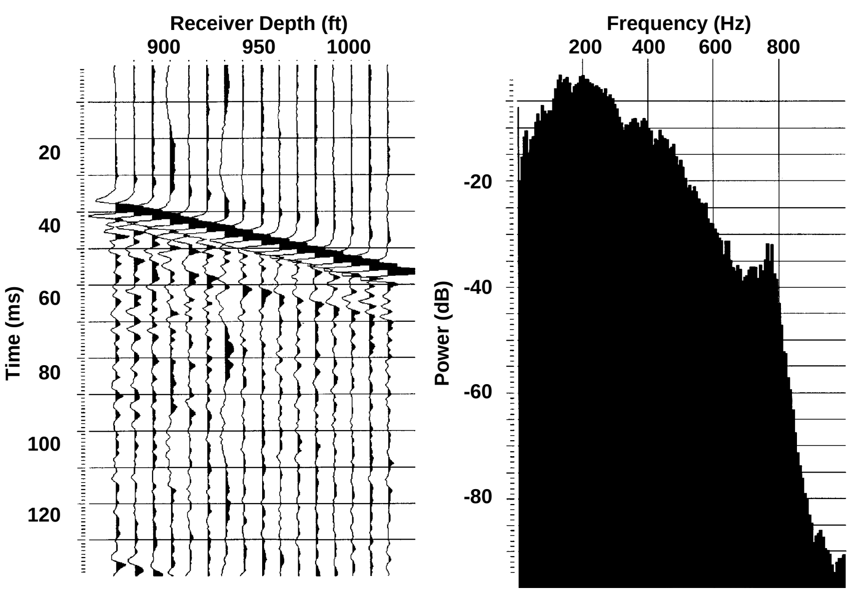

Figure 4. Power spectra of direct *P*-wave arrival averaged over traces shown on left.

bly caused by a time delay in this zone.

4) Figure 3 shows an even smaller scale plot of the same data to enhance the upgoing reflection that intersects the left edge of the plot at about 500 ms. Extrapolating back to the direct arrival suggests the reflector depth is about 2400 ft, representing a total travel path of just less than 4000 ft. This can serve as an indication of expected data quality for surveys in Gulf Coast type sediments.

5) The power spectrum of the direct *P*-wave, averaged between the receiver depths of 870 and 1020 ft and without the bandpass filter, is shown on Figure 4. The 15-dB cutoff is at about 10 and 500 Hz, giving a bandwidth of about 5.5 octaves at that level. We believe that no other nondestructive downhole seismic source can achieve this bandwidth.

6) Finally on Figure 4, note the clear, zero-phase appearance of the direct arrival, indicating that the seismic energy going into the formation remained in phase with the pilot sweep.

Generally speaking the borehole vibrator data exhibit high energy over a broad range of frequencies, including frequencies low enough to ensure propagation over long distances in moderately well-consolidated sediments.

In Figure 5 the crosswell seismic data are shown beside the geologic cross-section generated from well logs. Wavefield separation, amplitude scaling, and VSP-CDP transform were applied to the shot record in Figure 5 to generate the image that is inserted between the well logs in Figure 6. The interpreted image in Figure 6 shows that crosswell seismic data can image beds and faults with resolution of a few feet. For example, the strong event at a depth of 890 ft on the right side of the image is a reflection from a sand bed that is less than 10 ft thick. In Figure 7 the VSP-CDP transform has been extended to a depth of 3000 ft, 1500 ft below the deepest receiver. While the image section is narrow below the wells, this figure demonstrates a technique for high-resolution seismic imaging between and below wells.

This image is generated from a single common source fan. This is equivalent to creating a surface seismic section from a single shot. The image would be dramatically improved with more borehole seismic data. In a typical borehole seismic survey 100 or more source points are recorded, each with 50-100 receiver stations.

Oil-and-gas field data examples. The downhole vibrator system was deployed in three oil-and-gas field surveys in 1997. The first was a crosswell survey in east Texas for a consortium of oil companies headed by Union Pacific Resources. The second was for the Salt Imaging Consortium headed by Texaco. The third was performed for a large independent operator in east Texas.

The first commercial survey for the downhole seismic vibrator was a crosswell seismic survey in conjunction with a massive hydrofracture experiment. We encountered significant operational problems with the controller for the downhole electric motor driving the hydraulic pump. Only a few successful sweeps were recorded, one of which is shown in the lower portion of Figure 8. The data are from a single 10-s, 10-360

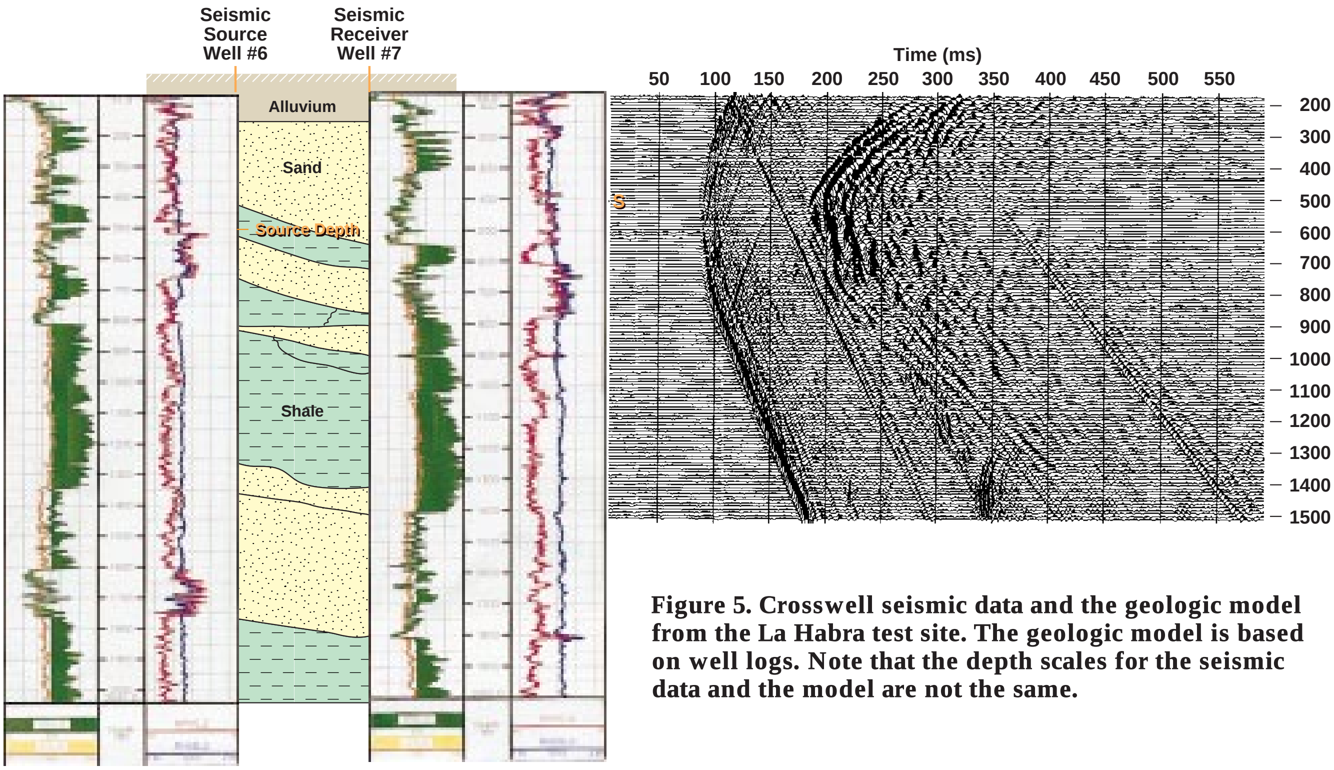

Figure 5. Crosswell seismic data and the geologic model from the La Habra test site. The geologic model is based on well logs. Note that the depth scales for the seismic data and the model are not the same.

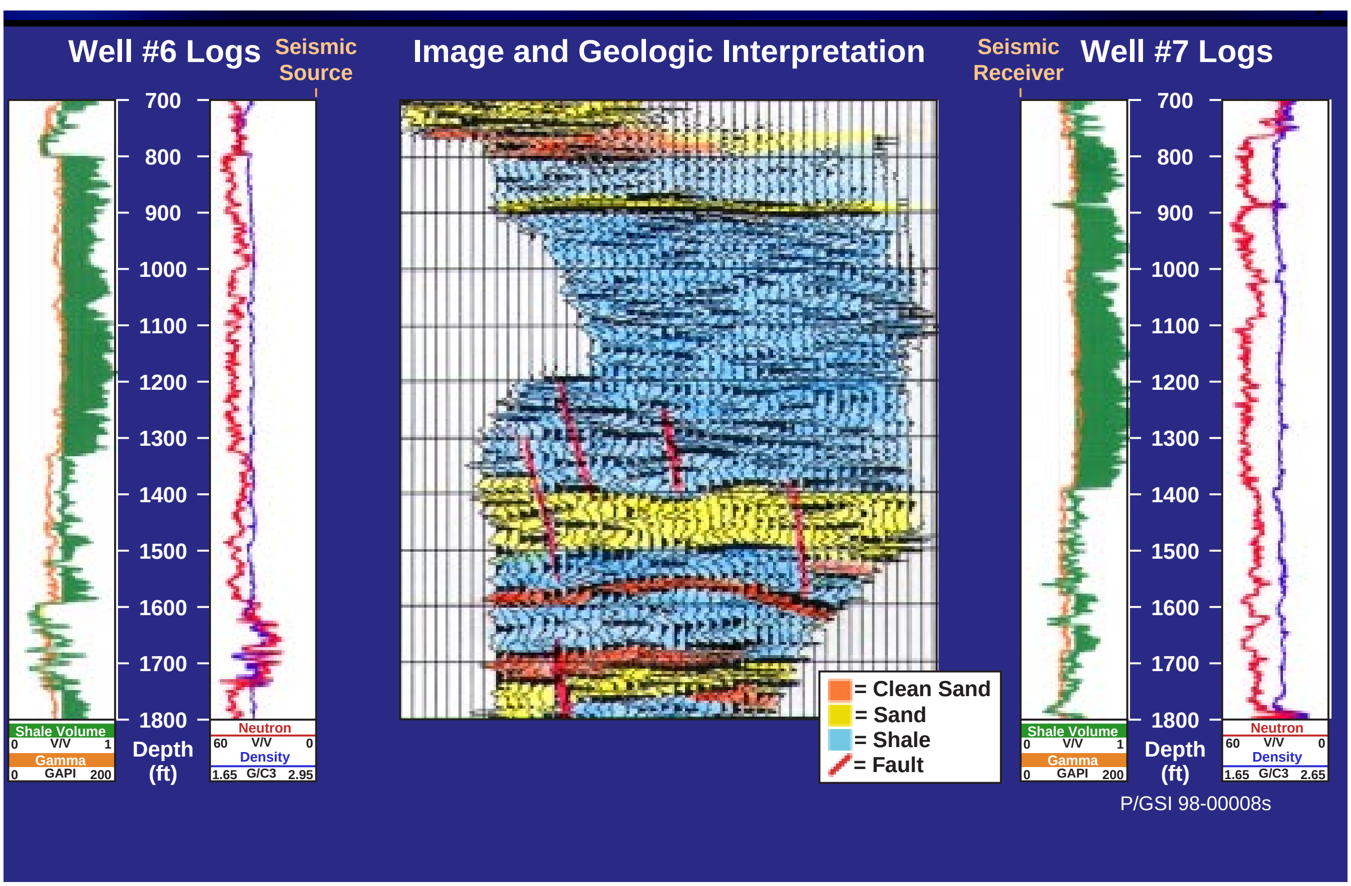

Figure 6. Interpreted crosswell seismic image with well logs on either side. The reflection image shows beds and fault displacements with resolution of a few feet.

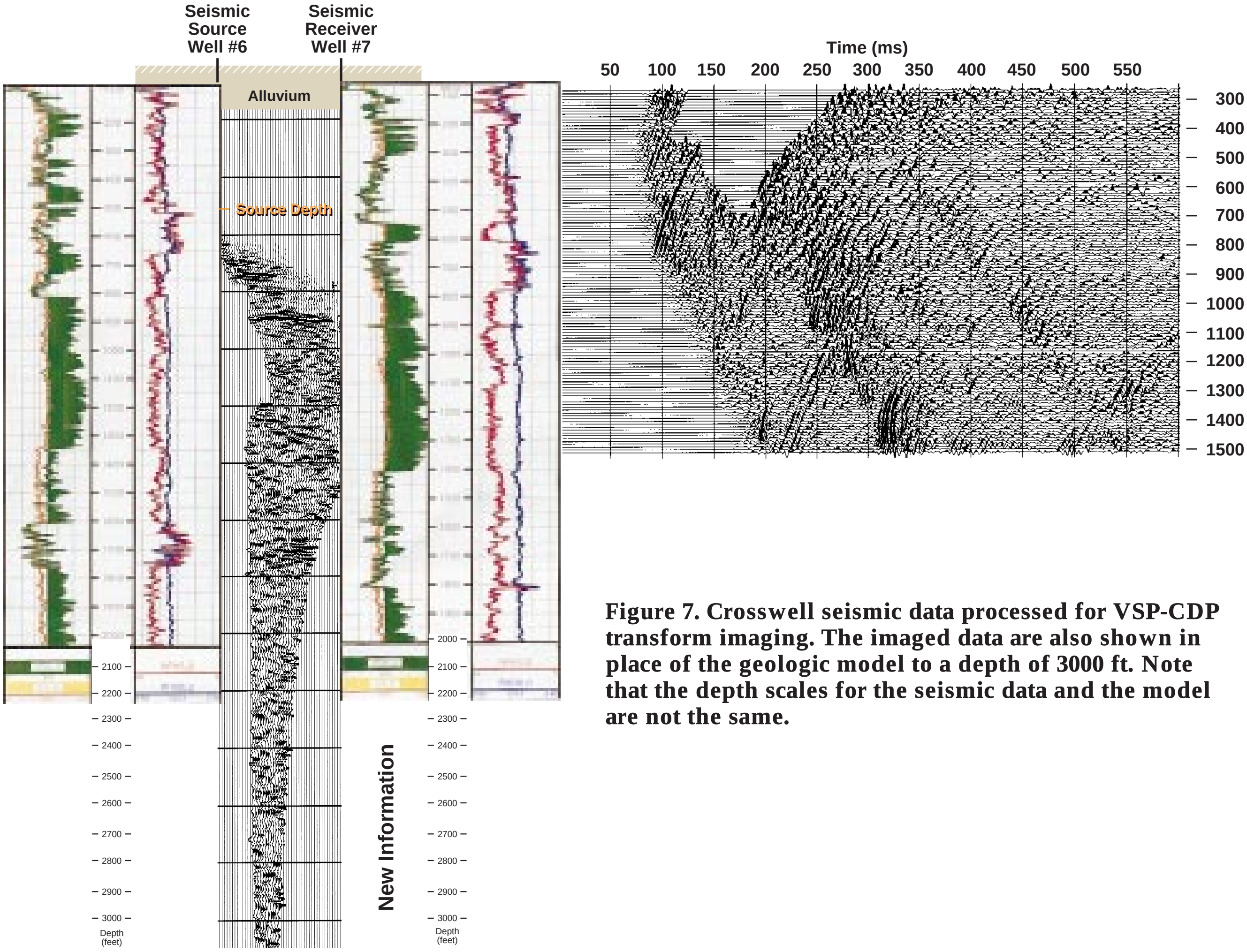

Figure 7. Crosswell seismic data processed for VSP-CDP transform imaging. The imaged data are also shown in place of the geologic model to a depth of 3000 ft. Note that the depth scales for the seismic data and the model are not the same.

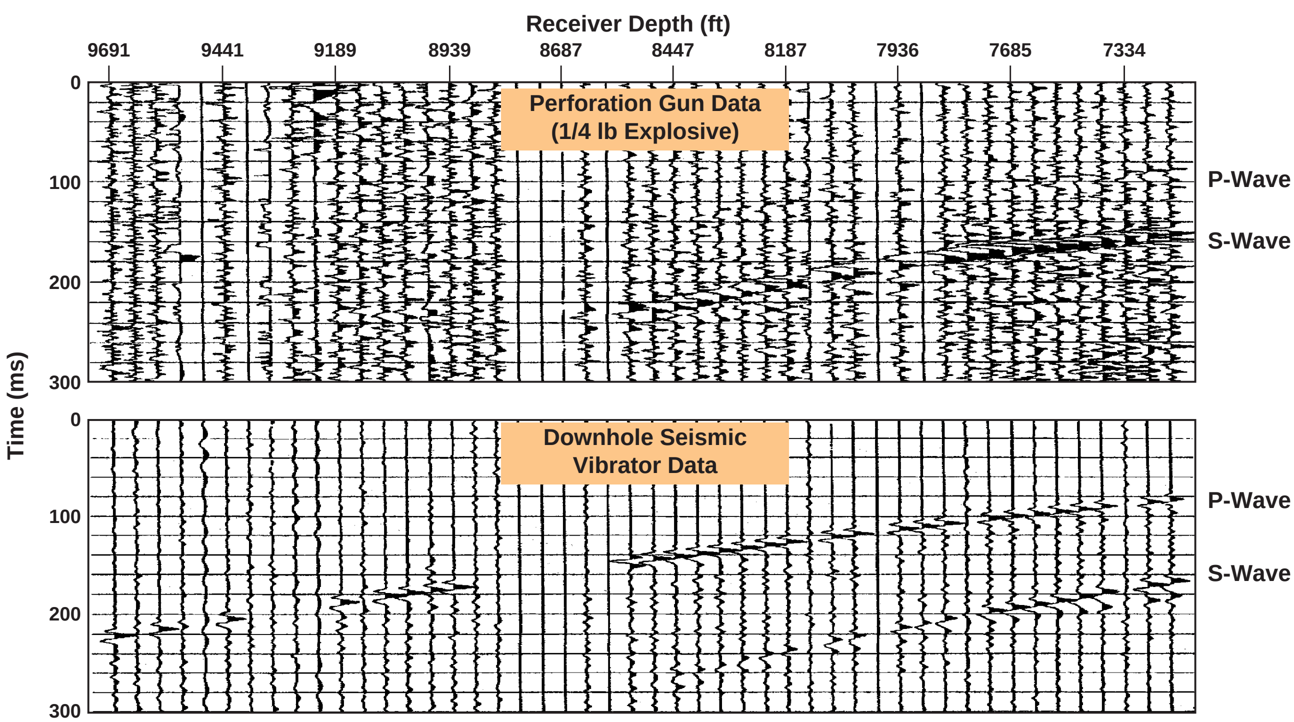

Figure 8. Comparison between data from a small explosive inside a perforation gun and data from the downhole vibrator. The survey was performed in east Texas. The data were recorded on a 48-level, cemented three-component receiver array.

Hz sweep. The upper portion of this figure shows data generated by a small explosive inside a perforation. The receivers, the cemented geophone array, and the recording system for both data sets were identical. The data from the downhole vibrator are clearly superior.

Figure 9 shows a few selected waveforms and their average spectrum from the vibrator data in Figure 9. Note the waveforms have an excellent zero-phase appearance. Well-defined waveforms are critical to precise time-picking as well as precise determination of the attenuation parameters of the formation. Compact waveforms also make it possible to separate reflections from closely spaced reflectors.

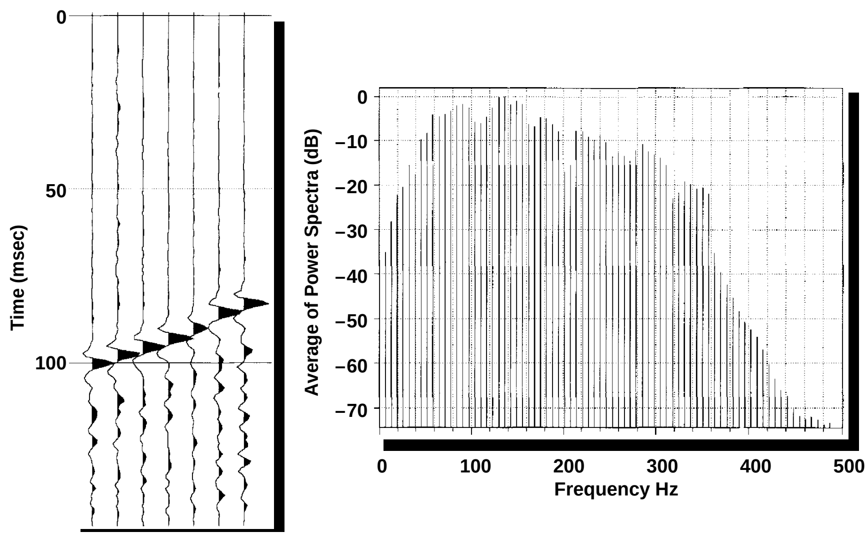

Figure 9. Amplitude spectrum of data from the downhole vibrator. The distance between the source and receivers for the data exceeds 2000 ft.

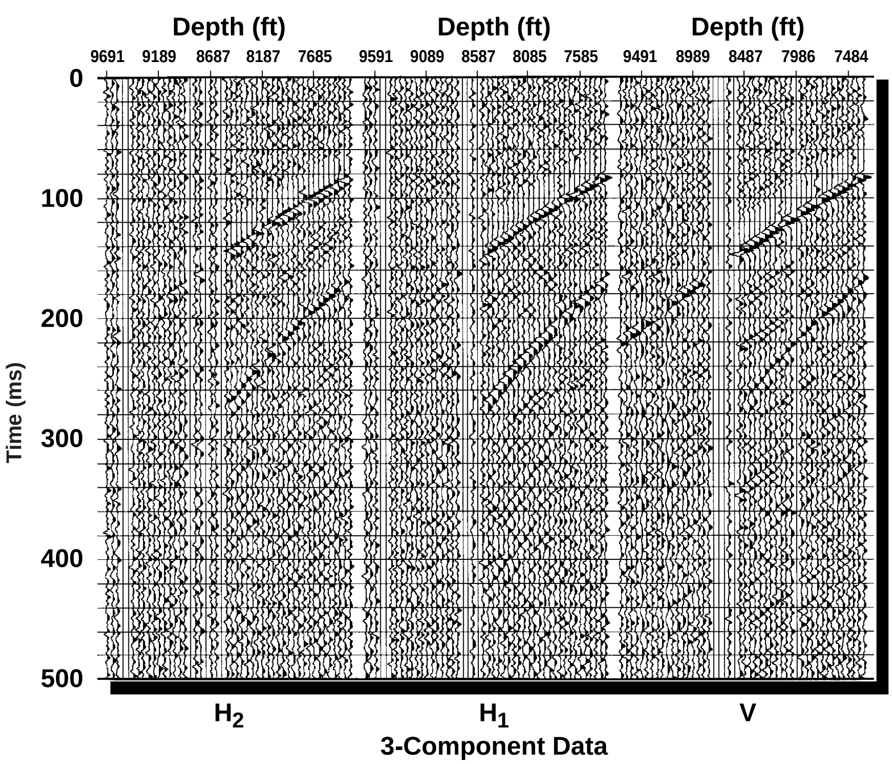

Figure 10. Borehole seismic data recorded using the downhole vibrator and the cemented, three-component 48-level geophone array. All three components are shown. The shear-wave reflections from below the receiver array are especially apparent on the H_1 component. The data are aliased since the spatial sampling of the array (50 ft) is approximately the same as the shortest wavelength (40-50 ft).

Figure 10 shows all three geophone components recorded by the 48-level cemented geophone array. It is interesting to note that the different components apparently record very different information. The vertical component records a large number of downgoing reflections from layers above the source (placed at 6000 ft). The H_1 component (center) recorded one very clear upgoing *P*-to-*S* reflection (between 120 and 200 ms, coming from about 8300 ft) between the *P*- and *S*-wave direct arrivals. The H_1 component also recorded high-quality upgoing *S*-wave reflections arriving between 200 and 500 ms. Many of these later reflections apparently have their origins well below the TD of the receiver wells. These data show the power of long arrays in recording seismic data in boreholes.

Figure 11 shows 1 s of the data recorded by the vertical components on the 48-level array. A number of reflected events can be seen with a total traveltime of 1 s. The *P*-wave velocity of the formation at this site is 16 000 ft/s, indicating that the seismic energy has a travel path of 16 000 ft.

The second survey performed by the downhole vibrator was at the Bayou Choctaw salt dome in Louisiana. The survey's objective was to record reflections from the nearby salt dome using a simulated single-well survey. The source was placed in one well and the receivers in a second, making this effectively a crosswell survey. The vibrator successfully performed 300-plus sweeps over six days. A large number of *P*- and *S*-wave reflections were recorded in the soft sediments. Some reflections had traveltimes exceeding 1.5 s, translating to a raypath length exceeding 12 000 ft. Unusually strong events, interpreted as salt-flank reflections, were also recorded.

The third commercial survey was a reverse VSP survey in east Texas. When the source was placed at 5000 ft, reflections from a depth of 8000 ft out to a lateral offset of more than 8000 ft were observed. The travel path for this seismic energy is approximately 14 000 ft. This opens up the possibility of performing 3-D reverse VSP surveys in at least medium deep wells.

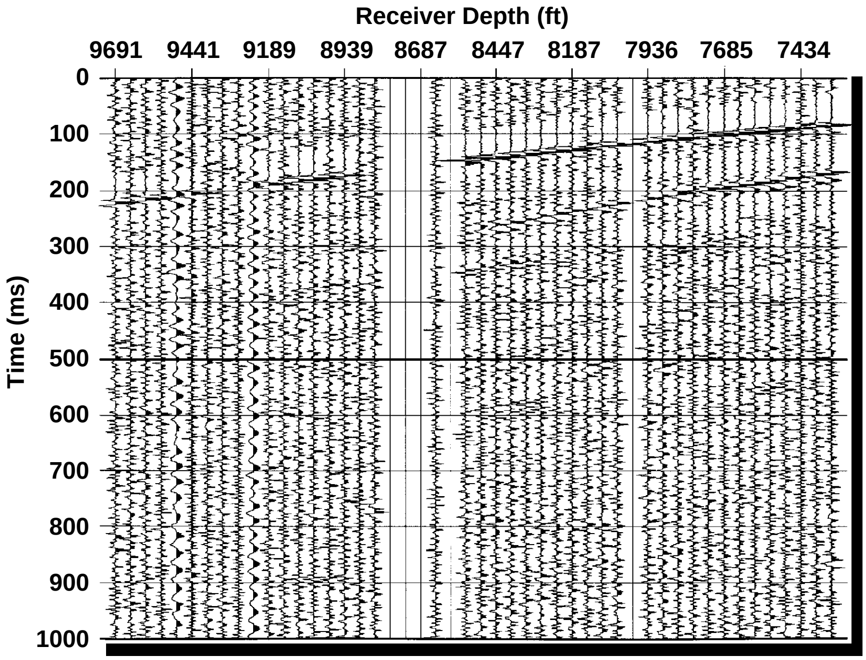

Figure 11. 1 s of the vertical component of the crosswell data. The longest direct travel path from the source (positioned at 6000 ft) to the deepest receiver (9691 ft) is 3900 ft. This arrival is seen at 220 ms on the far left of the record. Reflections from geologic interfaces at depths several thousand feet below the receiver array can also be seen. Some of these reflections can be seen at a traveltime of 1 s, indicating a total travel path in excess of 16 000 ft.

Summary and conclusions. A high-energy, but nondestructive, broadband, clamped borehole vibrator was successfully used for a number of surveys in oil-and-gas fields in 1997. The surveys produced data of excellent quality. The successful tests indicate that the source has the potential to make borehole seismology more widely used for reservoir delineation and characterization due to its higher resolution reflection images and tomography velocities across widely spaced wells.

The new tool's effective force output will allow it to be used in areas with large well spacing and in reservoirs with highly attenuating sediments (e.g., the Gulf Coast). It also has a very broad seismic bandwidth, which provides both long range and high resolution. Since the source is clamped, the tool can also be used in gas-filled wells — a unique feature of this tool. Clamping also helps to minimize tube waves during single-well surveys.

Complementing the downhole vibrator is a three-component receiver system. The receivers are equipped with a fiber-optic data-transmission system with an effective transmission rate of 25 Mbit/s. This is 100 times faster than industry-standard data-transmission technology operating on seven-conductor wirelines. The fiber-optic technology eliminates much of the electric noise commonly recorded using standard electric transmission systems. The advanced borehole seismic system is the first in the oil-and-gas industry in which the source and the receivers operate on fiber-optic wirelines. LE

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Corresponding author: Bjørn Paulsson
1-562-694-7161