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A COMPARISON OF SEISMIC SOURCES FOR VSP'S IN A CASED WELL

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ABSTRACT

The production and use of vertical seismic profiles (VSPs) can be influenced by factors related to the well environment, the sources, and the amount of other data available for interpretation. This paper uses several data sets acquired at an old cased well to illustrate and summarize some of these factors. In particular, some implications of using vibrators and air guns are noted. The effect of the source distance from the wellhead is illustrated with three data sets acquired with a vibrator.

A well such as this one is typical of many old wells that have minimal or missing log data, making stratigraphic correlation of the VSP events difficult. In this summary, the use of old open-hole and newer cased-hole well logs for correlation is illustrated. The successful operation of vertical seismic profiling in older wells is important because of their numbers and availability, and the advantage of not having expensive drilling rigs on site.

DATA ACQUISITION

All seismic data used here were acquired with Schlumberger's standard logging system, the Cyber Service* unit (CSU*), which is adapted for seismic work by adding two equipment modules and one computer program. Seismic signals are amplified in the tool, digitized and further amplified in the CSU instrumentation, recorded in digital form on nine-track tape, and recorded on film and paper for on-site inspection. Each record can also be viewed on a screen as it is acquired, thus providing quality control during acquisition. For impulsive sources (such as dynamite or air guns), data are recorded at 1.0-ms intervals for 3.0 s after an operator-determined delay time. For vibrator sources, data are acquired for up to 18.0 s at 2.0-ms intervals. Sign-bit correlation is performed by the CSU program for on-site inspection of vibrator data. The uncorrelated sweeps are recorded on tape for full correlation at the computing centre.

The downhole tool is shown in Figure 1. It is clamped in the borehole with a hydraulically controlled arm equipped with teeth. After it is clamped at a position in the well, the wireline is slackened to decouple the tool from surface noise. Four 10-Hz vertical-motion seismometers are mounted in series in the base of the tool. In normal operation, the tool is lowered to the bottom of the well and acquisition begins. After a sufficient number of shots have been obtained at a level, the tool is pulled up to the next level without closing the arm. Spring tension keeps the arm open, generally speeding up the operation.

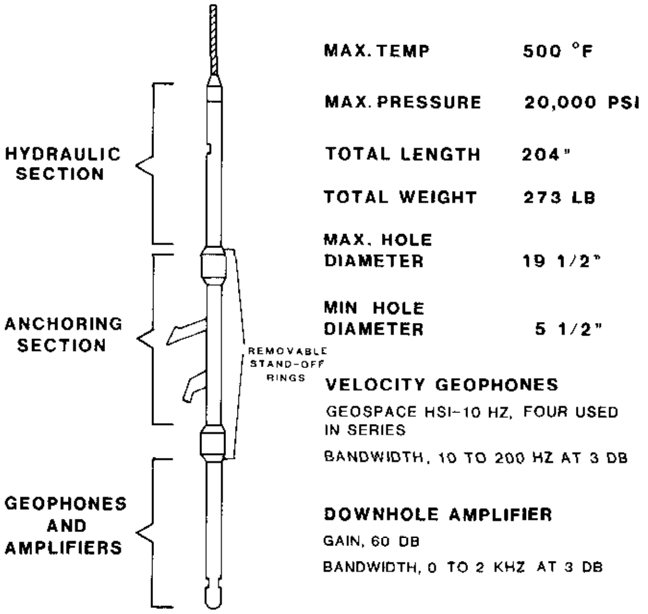

Fig. 1. Well seismic tool.

THE WELL ENVIRONMENT

Seismic acquisition in cased wells has been described previously (Ording and Redding, 1953; Levin and Lynn, 1958; Van Sandt and Levin, 1963; Mack, 1966; Hardage, 1981). These studies used a variety of surface sources

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and, with varying qualifications, the authors concluded that acceptable seismic signals could be acquired in cased wells.

All the seismic data used here were acquired from a well drilled and cased 27 years ago (Fig. 2). The casing diameter is 7.0 in and the well is filled almost to the surface with water. There is a single set of casing in the interval over which data were acquired (4,000 to 8,000 ft). The well's total depth is 8,400 ft. Geologically, the well is located in shales and sands with some thin carbonated sandstones or limestones.

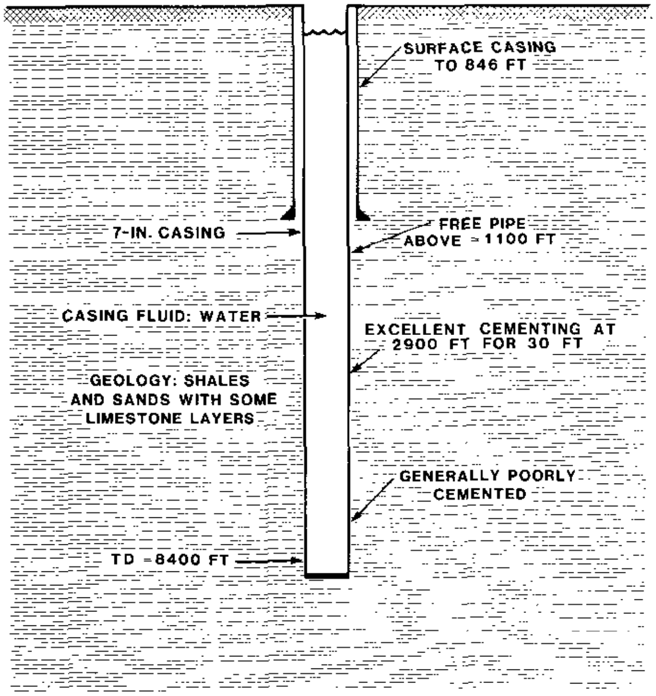

Fig. 2. Details of test well.

The signal recorded by the Well Seismic tool can be significantly influenced by the quality of coupling of the tool to the formation. In this case, the tool will be clamped in the casing, and it is reasonable to anticipate that this portion of the seismometer's link to the formation should be consistent and good. The coupling of the casing to the formation is affected by the quality of cementing, which can be studied with a Cement Bond log (CBL). This log is derived from the measurement of a 20-kHz acoustic pulse emitted and received by transducers in the sonic tool. A diagram of the process and records from three portions of the well are shown in Figure 3. In uncemented casing, the acoustic signal is transmitted primarily through the casing, producing a strong, early, first arrival. The casing collar produces the broken pattern in the middle of the record. The upper 1,100 ft of the well have this quality of cementation. In well-cemented casing (the middle record of Fig. 3), the sonic tool's signal travels through the casing into the formation, and a large portion of the signal's energy arrives late in the record as a formation arrival. Only about 30 ft of this well have this quality of cementation. In poorly cemented casing, the acoustic signal is partitioned between the two media, as shown in the lower record. It was with this quality of cementation that all the data used here were acquired. However, although much of the cement bond for the casing appears to be uniformly poor or absent, it is probable that there has been slumping and settling of sediments against the casing during the long life of the well. This has facilitated the coupling of the casing and the tool to the earth.

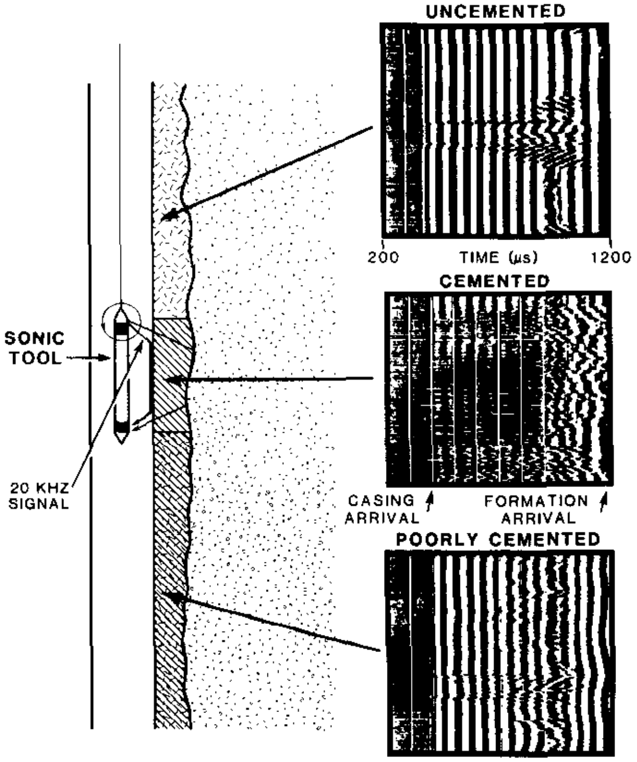

Fig. 3. Acquisition of Cement Bond log (CBL) and selected records from test well.

The velocity structure of the wellsite is shown in Figure 4. The continuous velocity sonic log was acquired through casing 27 years after the well was drilled. The technique used to acquire the through-casing compressional wave log is described by Chang and Everhart (1982). Compressional velocities range from 8,000 to 10,000 ft/s in the sands and shales and are as much as 14,000 ft/s in the harder sandstones and limestones.

Figure 5 shows the arrangement of sources around the well. The air gun was a Bolt 200-cu-in gun with a wave-shaping kit and was operated at 2,000 psi. It was suspended in a pit 5 ft in diameter and 10 ft deep, which had been lined with steel culvert and sealed at the bottom with drilling mud. The vibrator was a Litton Model 309.

The Well Seismic tool was positioned at 100-ft intervals beginning at 8,000 ft. The tool was left in the same position at each level for acquisition from both sources. Typically, three or four shots were acquired with the air gun and about the same number of sweeps with the vibrator at each level.

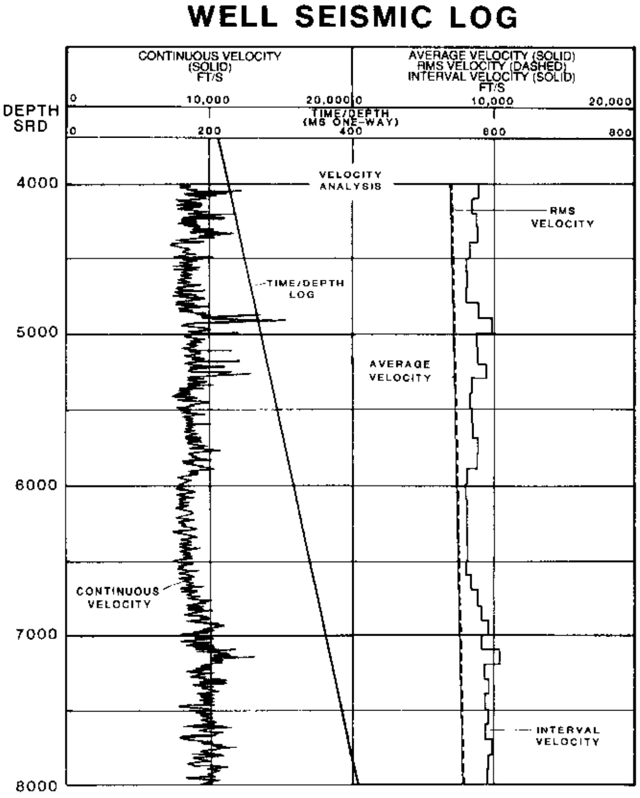

Fig. 4. Test well velocity summary.

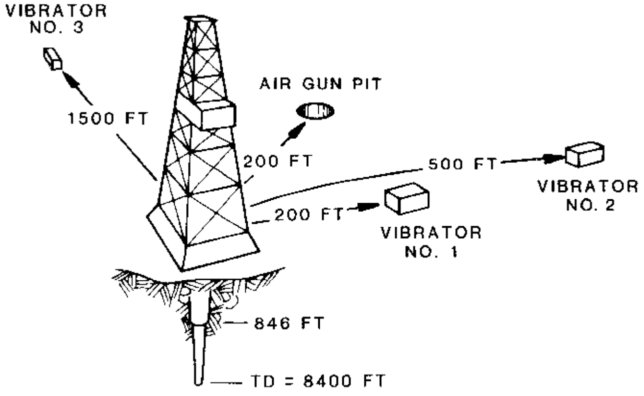

Fig. 5. Seismic source arrangement at test well.

PROCESSING THE VSP

The general VSP processing procedure is illustrated in Figure 6. There are three main stages: a preprocessing stage in which editing, filtering and time-varying gains are applied to the stacked section; a velocity-filtering stage in which the upgoing (reflected) events are separated from the downgoing (direct) signals on the basis of their opposite slopes on the section; and a deconvolution stage in which operators for wavelet and predictive deconvolution are computed from the downgoing trace and applied to that trace and the corresponding upgoing trace. Typically, there is some subsequent arrangement of the data to match a surface seismic section or other data sets.

The raw stacked section for the air-gun source at 200-ft offset is shown in Figure 7a. These traces are composed of three or four shots and illustrate noise typical of the borehole environment, arising from wireline motion, electrical sources and, possibly, tool motion. The most prominent "noise" event on the section is the tube or mud wave, which has a velocity of approximately 5,000 ft/s. It appears to be composed of an early, high-frequency event, possibly arising from a direct compressional wave encountering the wellhead, and a later low-frequency event, probably arising from the arrival of surface wave motion at the wellhead. Both events maintain their frequency characteristics throughout the well's depth. The low-frequency tube wave is reflected back up the well, as is the high-frequency tube wave, but with a much diminished amplitude. Figure 7b shows the same data set after editing and the application of an 8- to 40-Hz bandpass filter, which removed the high-frequency event. The low-frequency tube wave, with a frequency of about 20 Hz, remains.

The application of the velocity filter (described by Seeman and Horovicz, 1981) produces two data sets: a downgoing wave set and an upgoing wave set (Figs. 8a, b). These sets are the results for the air gun after the application of predictive and wavelet deconvolution. The reflection events are now in two-way time, and they can be tied back to depth and lithology by reference to the logs. Black events correspond to increases in acoustic impedance. Using the open-hole resistivity log, initially one of the only logs available, the high-amplitude reflection just caught at the top of the VSP

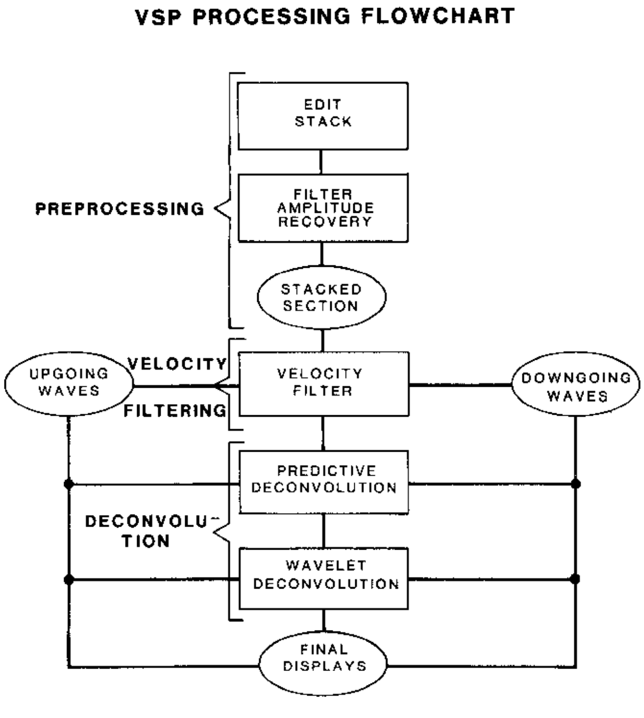

Fig. 6. Processing procedure for calculation of vertical seismic profile (VSP).

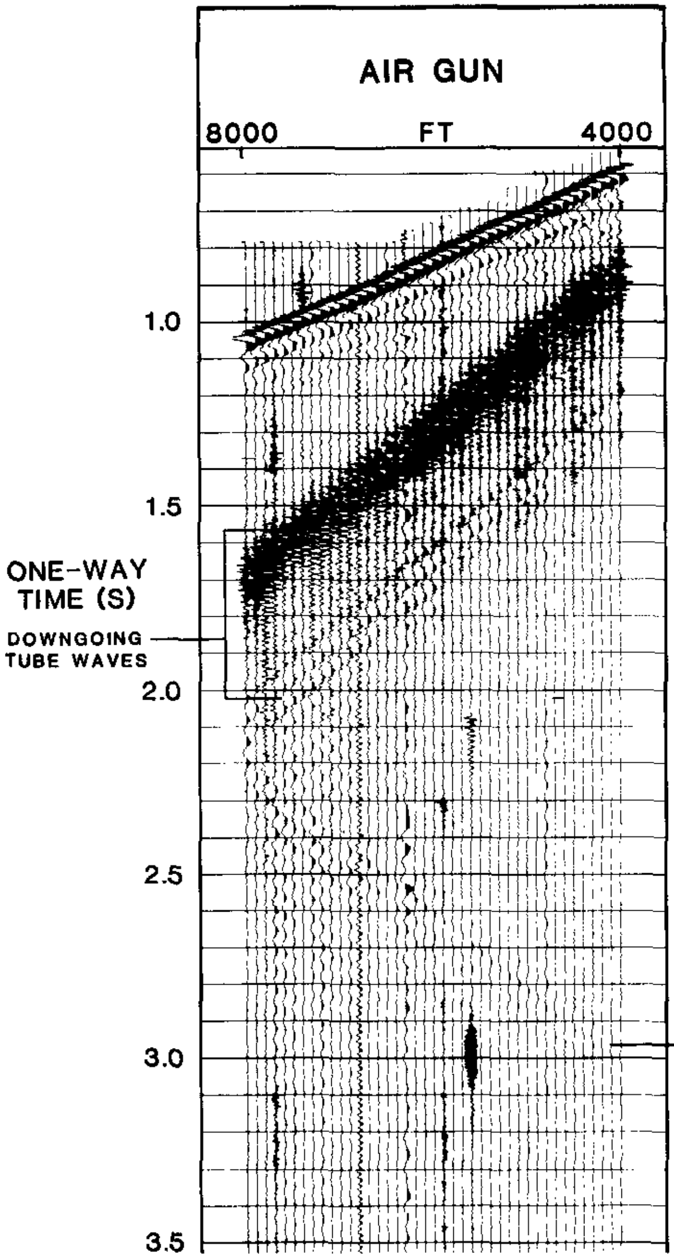

Fig. 7a. Raw air-gun stacks (200-ft offset).

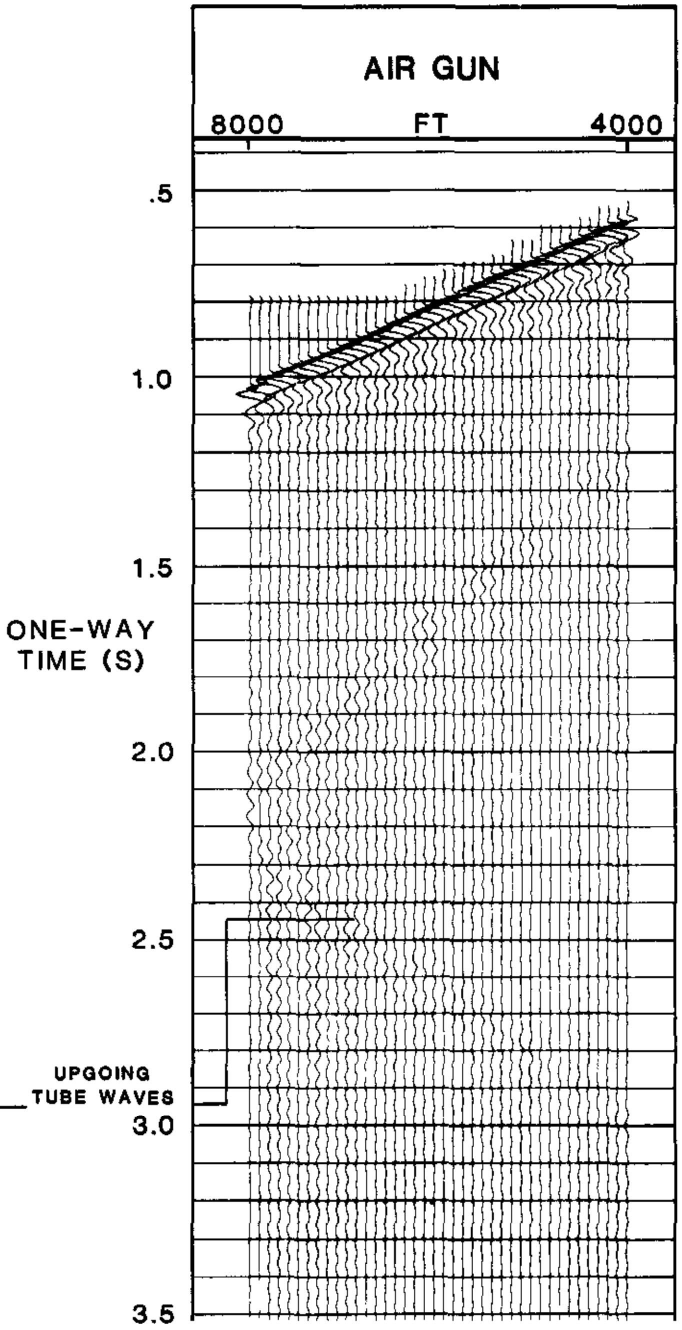

Fig. 7b. Air-gun stacks after editing and filtering (8- to 40-Hz bandpass).

can be related to an approximately 30-ft-thick indurated sandstone or limestone at 4,900 ft. The lower-amplitude, broader reflection at about 1.86 s corresponds to a thicker formation of lower resistivity at 7,100 ft. These high-resistivity formations correspond to the high-velocity formations observed in the through-casing sonic log shown in Figure 4. Reflection events later than about 1.95 s occur below total depth (TD). Also visible on the section are the downgoing tube wave, somewhat reduced by the velocity filtering, and its upgoing component, undiminished by the filtering. Clearly, such events on VSPs could obscure reflections of interest below TD and are therefore normally removed by processing techniques such as F-K filtering. They are retained in these data sets to illustrate the effects of source types and positions.

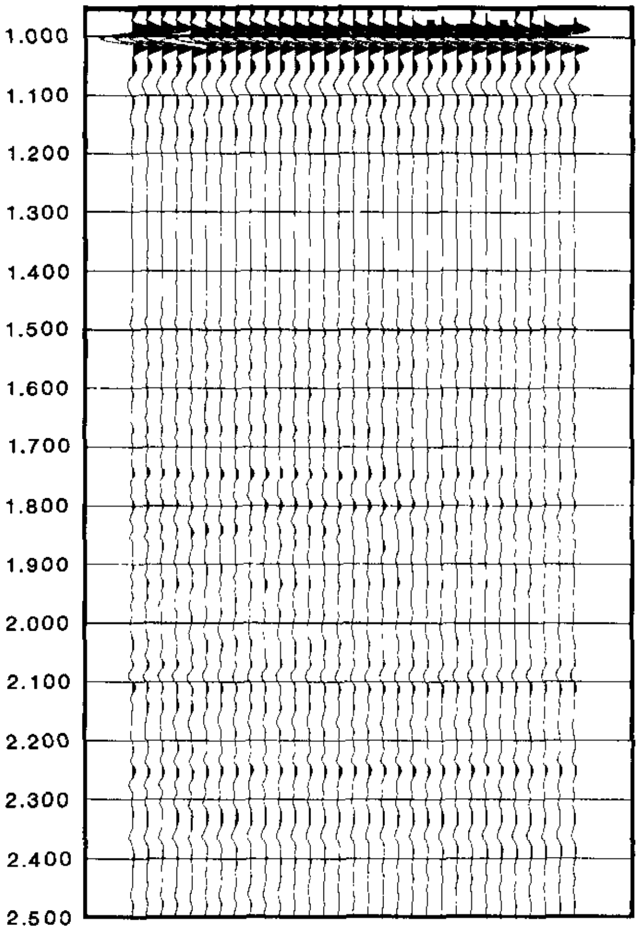

Fig. 8a. Downgoing waves (air gun, 200-ft offset) after application of predictive and zero-phase wave-shaping deconvolution.

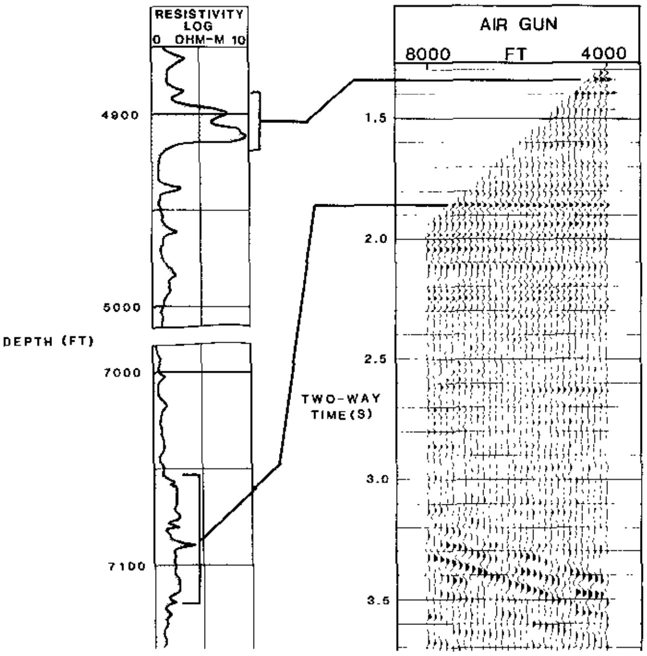

Fig. 8b. Upgoing waves after application of predictive and zero-phase wave-shaping deconvolution. Correlation with the open-hole resistivity log with a depth scale is shown.

COMPARISON OF SOURCES

The filtered and edited stacked sections for the air gun and vibrator for equal offset (200 ft) are shown in Figure 9. The vibrator traces are composed of three or four sweeps; each sweep was from 10 to 82 Hz for 12 s. The most prominent difference between the two is the amplitude of the reverberating tube wave, which appears significantly larger in relation to the direct signal for the vibrator than for the air gun. Especially prominent in the vibrator section is apparent constructive interference of the tube wave in the lower half of the section. The large tube wave in the vibrator section is not surprising, as the significant proportion of energy that a vibrator puts into surface wave generation is known.

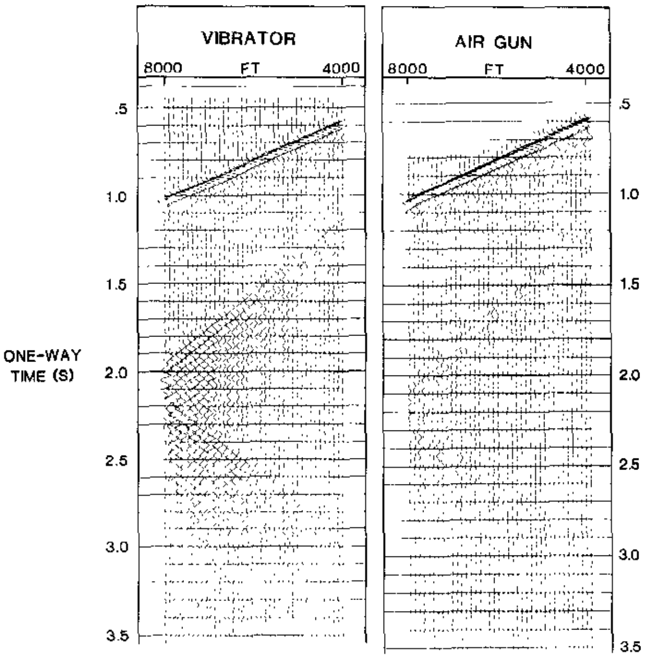

Fig. 9. Vibrator and air-gun stacked sections (200-ft offset).

Figure 10 shows the final processed upgoing events in two-way time for each source, and the tube waves provide the main difference. However, closer examination indicates possibly more detail on small reflection events on the vibrator section than on the air-gun section.

A simple comparison of the frequency content with depth of the two sources can be made by referring once again to the stacks. A 250-ms window was used for each of the edited, unfiltered stacked traces for the computation of a frequency spectrum. In all cases the 250-ms window preceded the arrival of a tube wave and, as the tool was not moved between source acquisitions, a comparison excluded the effect of tool coupling. The spectrums were computed in decibels at 3-db intervals, in relation to the peak energy in that trace. These spectrums were then contoured and colour-coded. The results for the air gun and vibrator are shown in Figures 11a and 11b respectively. The air gun's peak frequency is 10 to

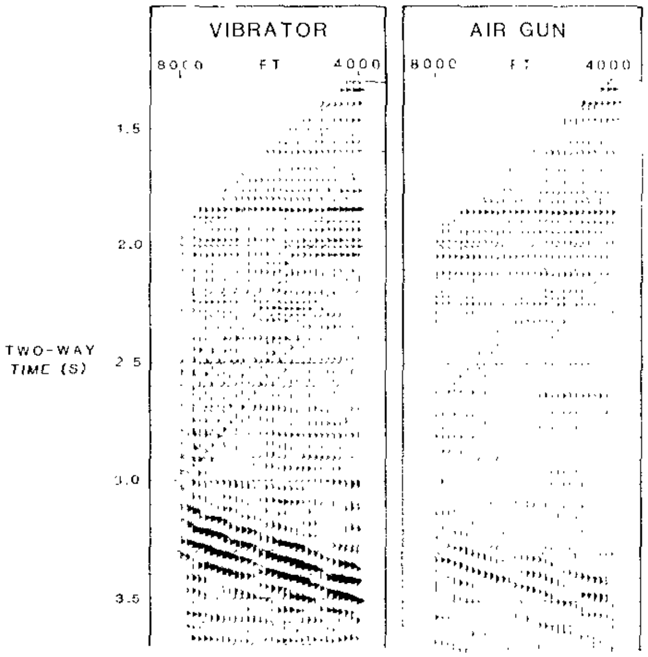

Fig. 10. Upgoing waves, vibrator and air-gun sources, after application of predictive and wave-shaping deconvolution.

20 Hz and, as is to be expected, there is a decrease in the high relative to the low frequencies as the depth increases. The same procedure applied to the vibrator's data shows a broader spectrum with the peak around 20 to *25 Hz, and a similar shift toward lower frequencies* with depth. Both plots show a notch around 40 to 50 Hz, which is evidently a characteristic of the site as it is not related to the source type.

A final point in the comparison is the apparent difference in transit times derived from applying conventional detection techniques, as might be done in a check-shot survey. Figures 12a and 12b show enlarged portions of the lowest five stacked traces for the air gun and vibrator respectively. Possible break picks are illustrated on each. The picks for the vibrator's signal, made on the assumption that it is zero phase, are about 12 to 14 ms later than those for the air gun. The difference appears to arise because the vibrator's signal is a significant departure from zero phase, exhibiting a notable asymmetry. The departure can be attributed to phase *shifts in the transmitted sweep received at the tool in* relation to the reference signal with which it is correlated. These phase shifts, in turn, could arise within the system composed of the vibrator/earth contact, the travel path through the earth, and the tool's coupling to the earth. In this context, it is difficult to be more specific in explaining the difference; however, it can be noted that the vibrator's wavelet changes very little in shape over the 4,000 ft of this VSP (Fig. 9), suggesting little effect of that portion of the earth's path. This might not have been the case in the more highly attenuating weathered zone but, unfortunately, this VSP was not continued to the surface. Phase shifts in a vibrator's signal arising for mechanical reasons have been discussed by Ward and *Hewitt (1977), Lerwill (1981), and Clymer and McEvilly* (1981).

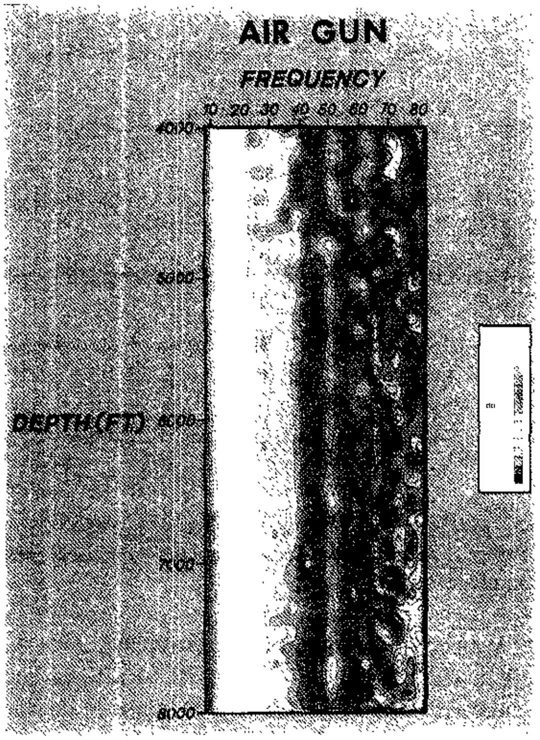

Fig. 11a. Coloured contour plot of level-normalized frequency trends for the air gun. The first 250 ms after the arrival time were used to eliminate tube-wave effects

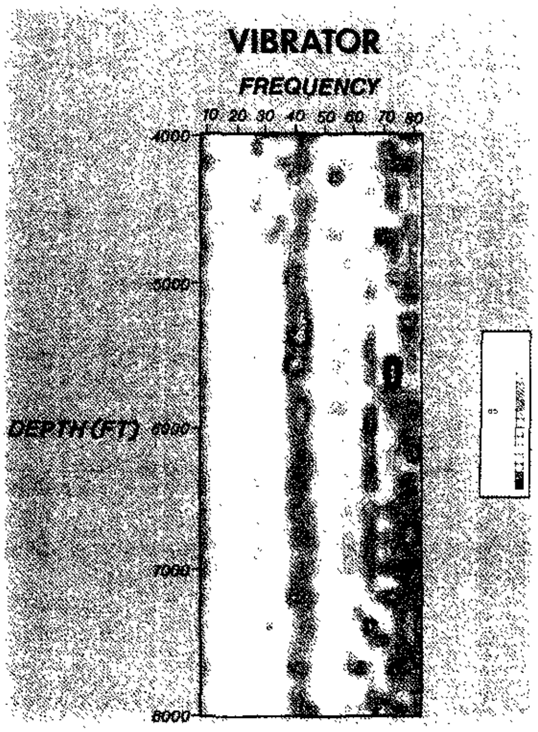

Fig. 11b. Same plot as 11a, for the vibrator.

That some reconciliation of the two times can be reached is illustrated in Figures 13a and 13b, which show the air gun arrivals with a processed version of the vibrator's arrivals. The vibrator's traces, obtained from the same levels and with the same tool position as for the air gun, have been deconvolved to a minimum-phase wavelet with the same frequencies as the vibrator's setting. This produces a signature from which a time break several milliseconds later than that of the air gun would be observed. Some of the residual difference is probably due to the positioning of the air gun in the pit, which was about 5 ft below the level of the vibrator. An appropriate static correction has not been applied to these stacks.

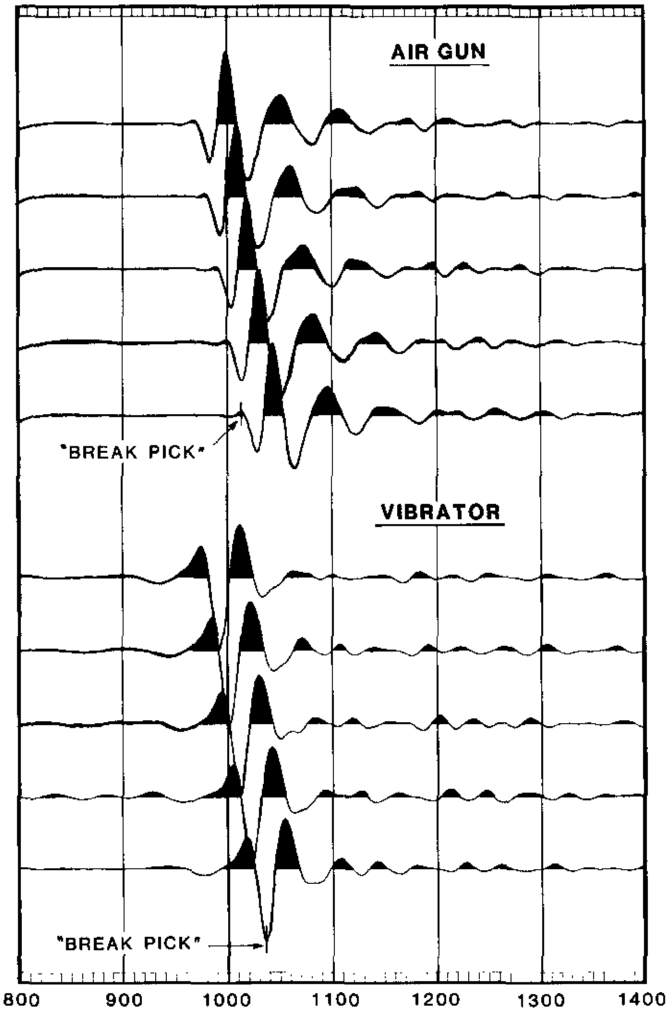

Fig. 12. Wavelets of bottom five band-passed stacks of VSPs for air gun (12a) and vibrator (12b) sources (200-ft offset).

Offset Sources

The effect of source offset on the magnitude of tube waves in the bore-hole has been described and documented (Riggs, 1955; Ward and Hewitt, 1977; Hardage, 1981). These authors relate the surface Rayleigh wave motion and other wave types encountering the well to the creation of a tube or mud wave, which travels through the fluid with a velocity of that medium. Movement of the source away from the well decreases the amplitude of the wave arriving at the well, and thus the amplitude of the tube wave.

The effect is illustrated in Figure 14 with the comparison of the filtered stacks for 200- and 500-ft offsets for the vibrator. With the diminished tube wave, several other less prominent events appear, such as upgoing reflections and downgoing multiples. The effect on the processed VSPs for these two positions and a third one at 1,500 ft is shown in Figure 15. At 1,500 ft the tube wave is no longer noticeable. The offset, however, has introduced a moveout delay in the VSP events which varies with tool depth and reflection time. This delay is notable on the reflections at 1.95 and 2.13 s. VSPs acquired with significantly large offsets in relation to the tool depth would have to be processed to correct for this moveout delay. In addition to reduction of the tube wave, the advantage of acquiring VSP data with large offsets is that as the tool moves from the reflector to the

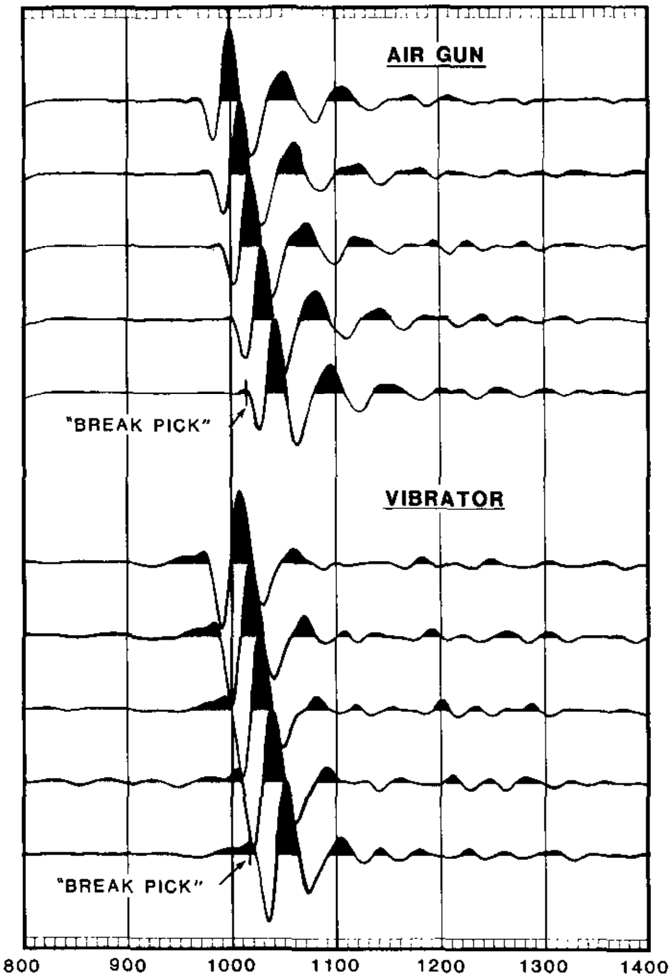

Fig. 13. Wavelets of bottom five band-passed stacks of VSPs for air gun (13a) and vibrator (13b). The vibrator wavelets have undergone minimum-phase wave-shaping.

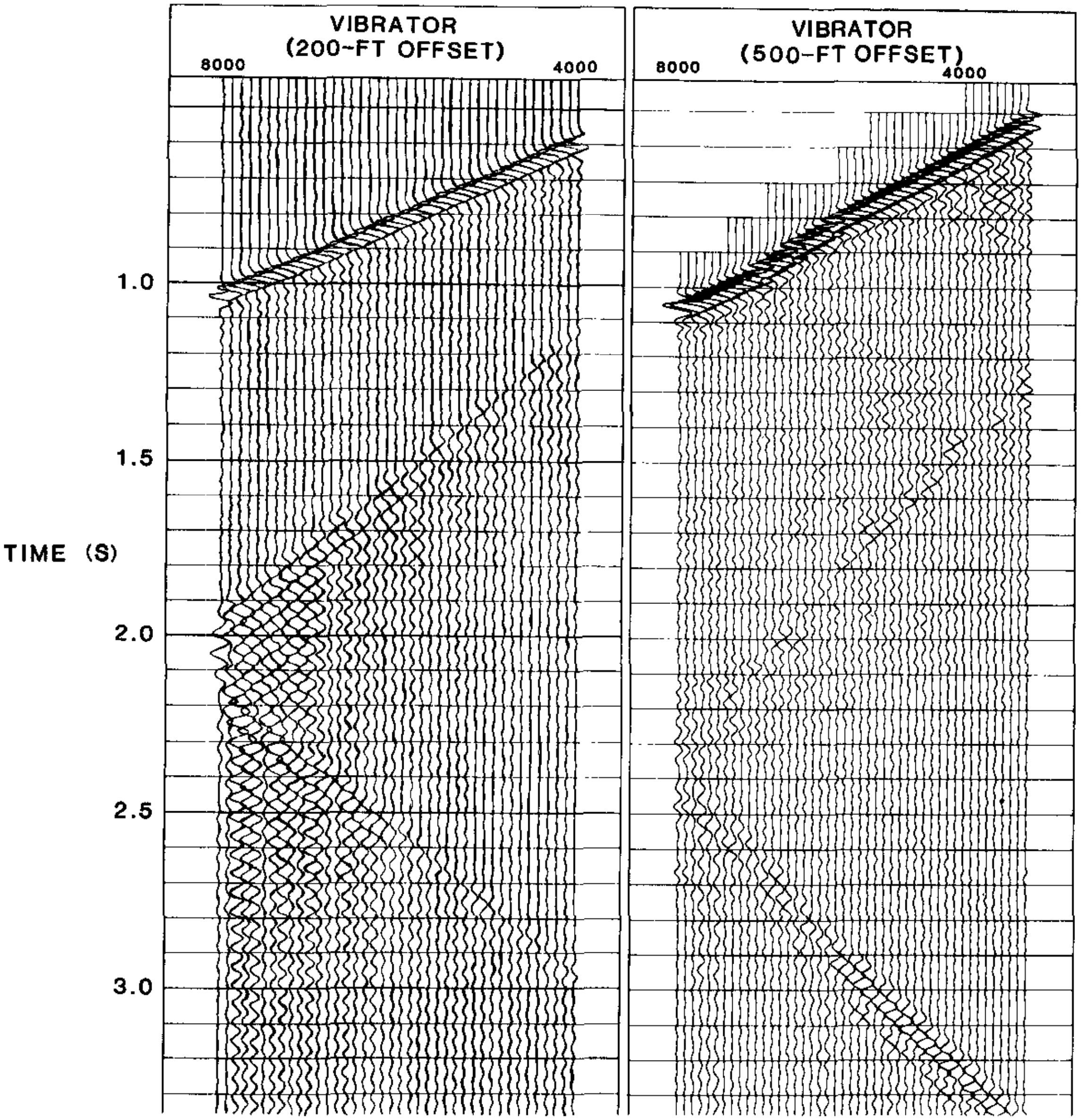

Fig. 14. Stacked sections band-passed 8-40 Hz for vibrator at 200-ft and 500-ft offsets.

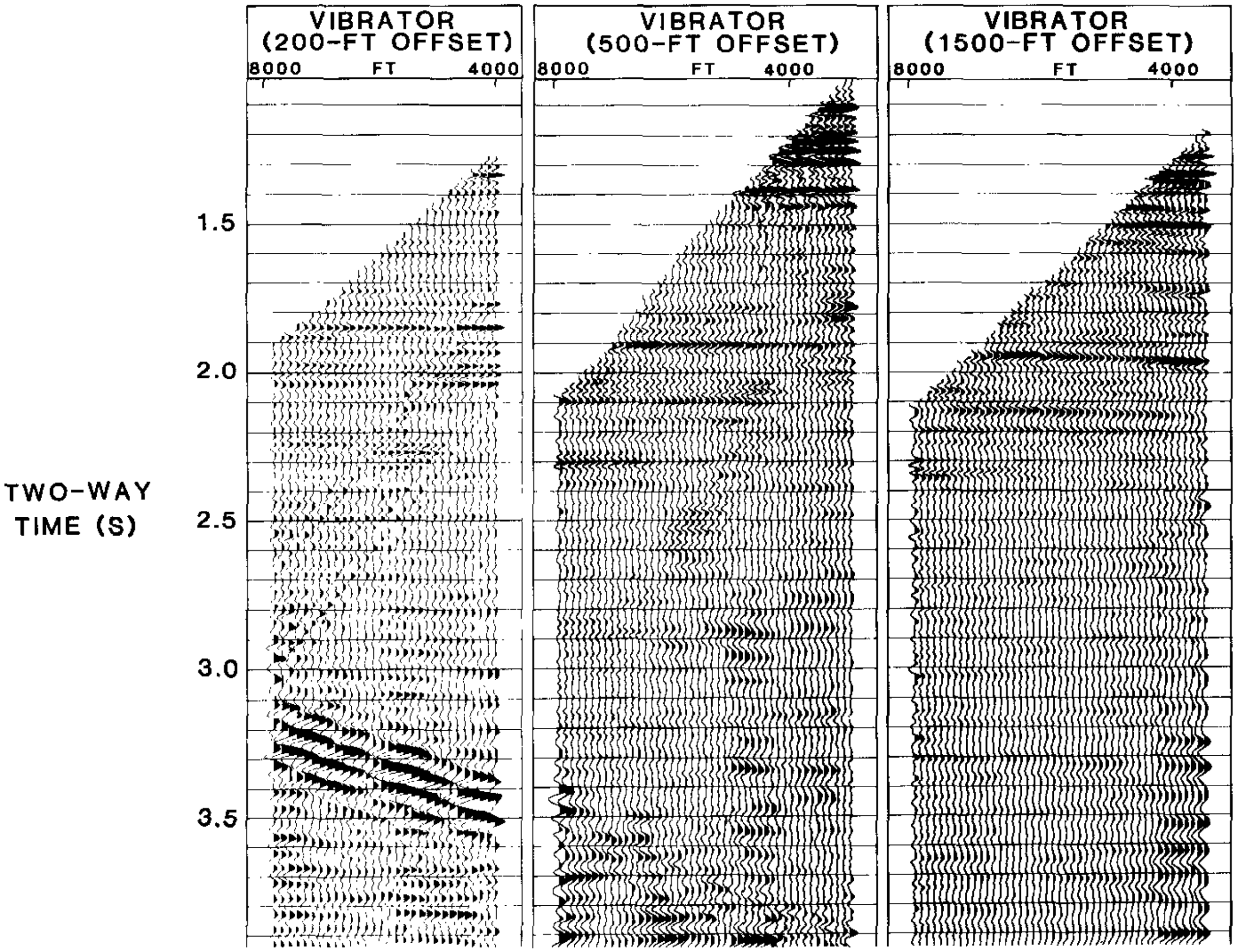

Fig. 15. Upgoing waves after application of predictive and wavelet deconvolution for variable vibrator offset positions.

surface, the reflection point moves out along a reflector from the wellbore to a distance of one-half the offset distance, thus providing a detailed image of reflectors around the well. Interpretation of such VSPs has been described elsewhere (Wyatt and Wyatt, 1981).

INTERPRETATION

For correlation of VSP seismic events to depth and logged data, it is common to model the seismic response of the earth by means of the logged acoustic impedance function (composed of the sonic and density logs) and compare it with the observed seismic response. This has been done here by calculating a primaries-only synthetic VSP from the through-casing sonic log only; the density log was not available. Figure 16 illustrates the comparison. The correlation of major events is reasonably good, and illustrates the potential for qualitative stratigraphic interpretation in old cased wells.

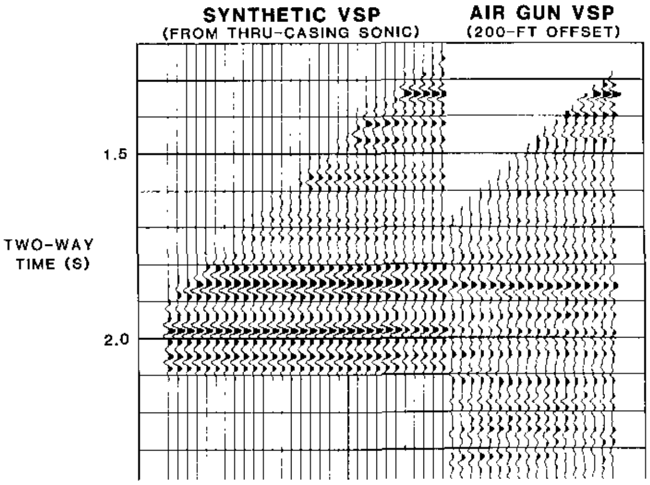

Fig. 16. Comparison of primary-only synthetic VSP computed from through-casing sonic with air-gun VSP (200-ft offset).

CONCLUSION

Considerable amounts of good-quality seismic data can be acquired from old cased wells with questionable cement bonding. This conclusion conforms to that made by Hardage (1981). If required, a detailed examination of the cement bonding in the well can be made with data from a sonic logging tool. In our experience, however, these data and other well seismic experiments indicate that, unless the casing is grossly uncoupled from the formation, such as at the loose end of a casing string, other factors such as the quality of the tool coupling will be more important than the cementation. In addition, development of through-casing logging tools can aid in the interpretation of VSP and surface seismic data gathered at these wells.

Vibrators and the Vibroseis® method have considerable potential for this type of work. Despite their significantly larger tube wave as compared with an impulse source, they have the capability for producing high-resolution results that may be of particular importance in studies of established reservoirs, in which wells such as these are common. In addition, their mobility enables multiple shooting positions to be easily established at large distances from the wellhead, again providing considerable information on the reflecting formations in the vicinity of the well.

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