GEOPHYSICS, VOL. 56, NO. 5 (MAY 1991); P. 628–634, 9 FIGS.

The use of drill-bit energy as a downhole seismic source

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ABSTRACT

A new wellbore seismic technique uses the vibrations produced by a drill bit while drilling as a downhole seismic energy source. The technique is described as "inverse" VSP because the source and receiver positions of conventional VSP are reversed. No downhole instrumentation is required to obtain the data and the data recording does not interfere with the drilling process. These characteristics offer a method by which borehole seismic data can be acquired, processed, and interpreted while drilling. Interchanging the conventional VSP source and receiver positions improves the efficiency of recording multioffset surveys for imaging a 3-D data volume in the borehole vicinity. The continuous signals generated by the drill bit are recorded by a pilot sensor attached to the top of the drillstring and by receivers located at selected positions around the borehole. The pilot signal is crosscorrelated with the receiver signals to compute traveltimes of the arrivals and to attenuate incoherent noise. Deconvolution and time shifts of the pilot signal compensate for the effects of propagation from the drill bit to the top of the drillstring. By repeating this process for an interval of the well, a VSP-equivalent data set is generated. Results from a test well demonstrate that the processed drill-bit data are comparable to conventional VSP data.

INTRODUCTION

Since the emergence of vertical seismic profiling (VSP) as a subsurface imaging tool (Hardage, 1985), there has been widespread interest within the exploration and production community in the development of a downhole seismic energy source. A downhole energy source can be used to perform an "inverse" VSP, interchanging the source and receiver positions. Receivers are deployed at the surface while the energy source is activated in the borehole. The efficiency of acquiring multiple-offset surveys is improved over conventional VSP acquisition methods, and surveys can be performed in locations inaccessible to conventional VSP.

In this work, we introduce a technique for acquiring inverse VSP surveys that uses the vibrations produced by drill-bit impacts on the formation during drilling as a downhole seismic energy source. The technique is termed seismic-while-drilling, or drill-bit, VSP. Drill-bit VSP holds several advantages over other downhole energy sources used for inverse VSP surveys. Specifically, drill-bit VSP surveys are acquired without any downhole instrumentation, which means there is no interruption to drilling, no lost rig time, and no risk to the borehole while the seismic data are being acquired. By using the drill bit as the energy source, measure-while-drill (MWD) seismic surveys are possible. Subsurface conditions ahead of the drill bit can be predicted at any time during drilling without tripping out of the hole, and seismic data are available at the well site for real-time drilling decisions.

The idea of using drill-bit vibrations as the energy source for subsurface imaging was first discussed by B. B. Weatherby (1936). He proposed using the discrete impulses generated by a cable-tool drilling assembly as the seismic energy source. (Unlike current rotary drilling, in which the drill bit is in semicontinuous contact with the formation, early cable tool drilling applied force to the formation through discrete impacts of the drill bit on the formation.) Later, drill-bit vibrations from a rotary drilling assembly were analyzed by drilling engineers concerned with their effects on the drillstring and on the rig. Vibrations associated with downhole forces can be felt while standing on the rig floor in addition to being observed in the movement of the swivel. The work of Deily et al. (1968) indicated that longitudinal and axial vibrations recorded by strain gauges at various locations within the drillstring were produced by the interaction of the

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drill-bit teeth with the formation. The vibrations exhibited a wide-band spectrum with a dominant frequency three times the rotary-table rate. A study by Lutz et al. (1972) showed that sensors at the top of the drillstring were measuring signals generated at the drill bit. The amplitude of the vibrations was often related to the lithologies drilled, e.g., higher amplitude vibrations were observed in harder rocks. From these studies, it appeared that the vibrations produced by the drill bit could have sufficient energy and bandwidth to be used as an energy source for inverse VSP.

DATA ACQUISITION AND PROCESSING

The signal paths exploited to process drill-bit vibrations for inverse VSP are shown in Figure 1. The vibrations travel up the drillstring and also radiate into the earth. A pilot sensor is positioned at the top of the drillstring to receive the upward traveling waves. Receivers are deployed on the earth's surface or on the ocean bottom to receive the seismic waves traveling in the earth. A downhole receiver can also be placed in a nearby borehole to perform crosswell imaging. The signal received by the pilot sensor is crosscorrelated with each of the receiver signals. This step is analogous to the Vibroseis method where a sweep signal is crosscorrelated with a geophone signal.

The crosscorrelation function provides a reference frame in which the arrival times of drill-bit energy can be measured. Where $R(t)$ is the signal recorded by the pilot sensor at the top of the drillstring and $G(t)$ is the signal recorded by the receiver, an unnormalized estimate of the crosscorrelation function in discrete time is

$$cc(\tau) = \sum_{n=1}^{N} R(nt)G(nt + \tau), \tag{1}$$

where τ is the time shift between the signals R and G, n is the number of recording samples, N is the total recording length (in samples), and t is the sampling interval. The time lag τ between the signals R and G is the traveltime difference between an event recorded at both locations. A wideband event from the drill bit will occur at a discrete time lag τ_0, provided that the drill-bit depth is stationary during the recording time. If the drill bit moves during the recording time, the event will be smeared around a range of time lags near τ_0.

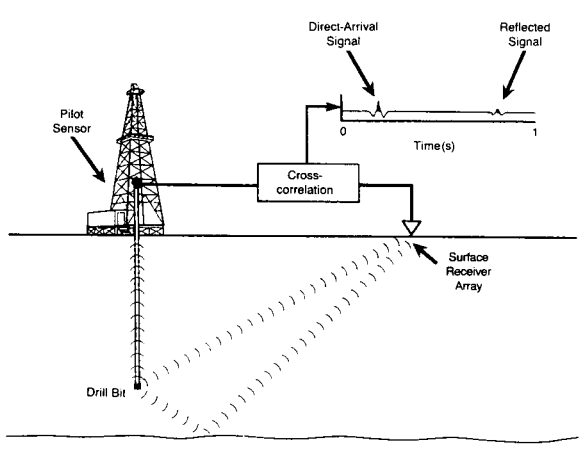

FIG. 1. Acquisition geometry and crosscorrelation processing used in the drill-bit VSP technique.

Unlike conventional Vibroseis crosscorrelations, the time lags of events in this crosscorrelation function do not correspond to the actual traveltimes of waves from drill bit to the receiver through the earth. For example, suppose the drill bit generates an impulsive event at time $t = t_0$. This event will be received by the pilot sensor at time $t = t_0 + t_p$, where t_p is the traveltime from the drill bit to the top of the drillstring. The geophone will receive this same event at time $t = t_0 + t_e$, where t_e is the traveltime from the drill bit to the receiver. For simplicity, assume we have single, primary, direct-arrival signal in the drill string and also in the earth from a single drill-bit depth. For a continuous, white drill-bit signal with unit amplitude, the unnormalized estimate of the crosscorrelation function between the pilot signal and the receiver signal is

$$cc(\tau) = \delta(t_e - t_p). \tag{2}$$

The continuous drill-bit signal is compressed into a delta function δ occurring at a crosscorrelation time lag τ equal to the traveltime difference or "relative" traveltime between drill-bit energy recorded at the pilot sensor and the same drill-bit energy recorded at the receiver. For a constant drillstring velocity, t_p is equal to the drillstring length divided by the drillstring velocity. This value will change every time a new joint of drill pipe is added and the drillstring length increases. The delay of drill-bit arrivals generated in the crosscorrelation function is converted to their "earth" traveltime τ' by adding t_p to the time axis of the crosscorrelation:

$$\tau' = \tau + t_p, \tag{3}$$

and

$$cc(\tau') = \delta(t_e). \tag{4}$$

Assuming that the drill-bit signal and the incoherent noise are white and stationary, the crosscorrelation process enhances the signal-to-noise (S/N) power ratio by a factor proportional to the recording time (Aki and Richards, 1980). The recording time is typically chosen to be the time needed to drill a 10-m joint of drill pipe, representing a tradeoff between the improvement in drill-bit S/N due to recording time and attenuation of drill-bit signal through movement of the drill bit. For drill-bit energy in the seismic band (<100 Hz), a drill-bit movement of 10 m is less than the smallest vertical wavelength, and there is little attenuation of drill-bit energy through movement of the drill bit. If higher frequency energy is desired, the recording time is shortened. Penetration rates achieved in drilling can vary from 1 to 100 m/h depending upon the depth and properties of the formation, with 10 m/h being a fairly typical penetration rate. Therefore, the recording time can vary anywhere from 6 minutes to 30 hours, with 1 hour being a typical value. The crosscorrelation function resulting from such long recording times has improved S/N compared to the typical recording times used in Vibroseis (20 to 30 s), and low-amplitude drill-bit signals can be detected.

Figure 2 is a field data example showing a series of computed crosscorrelation functions between the pilot signal and the geophone signal. The receiver channel at the surface consisted of an array of 24 10-Hz geophones with an array aperture of 60 m centered at a distance of 732 m from the wellhead. Data were recorded from a drilling depth of 1250 m to 1550 m. The data are displayed with a time axis of relative traveltime τ. The strong, broadband arrival at 285 ms is primary direct-arrival energy from the drill bit. The weaker energy arriving after the direct arrival, with negative moveout, is a reflected arrival. These data are typical of drill-bit VSP data in that a strong direct arrival is usually observed. The time delay and moveout of the direct arrival as a function of drill-bit depth is less than a delay and moveout of a direct arrival in a conventional VSP, due to the traveltime in the drillstring. Figure 3 shows the data after adding the drillstring traveltime t_p to the time axis of each of the crosscorrelation functions of Figure 2. The data are now positioned in earth traveltime τ', where the primary events have traveltimes of the type that would be recorded by a conventional VSP.

The positioning of the pilot sensor at the top of the drillstring introduces the filter response of the drillstring into the crosscorrelation function. To explain this transfer function, we can model the configuration in Figure 1 as a linear, time-invariant system. The resulting crosscorrelation function $cc(\tau)$ for this system is

$$cc(\tau) = [S(t) * D(t)] ** [S(t)*E(t)], \tag{5}$$

where $S(t)$ is the drill-bit source signal, $D(t)$ is the impulse response of the drillstring, $E(t)$ is the impulse response of the earth, $*$ denotes convolution, and $**$ denotes crosscorrelation. For a pilot sensor at the drill bit, the crosscorrelation function for the system would be similar to Vibroseis

$$cc(\tau) = S(t) ** [S(t) * E(t)]. \tag{6}$$

The difference between the two crosscorrelation functions is attributable to the term $D(t)$, the response of the drillstring to an impulse generated at the drill bit.

The drillstring is made up of two sections: the bottom-hole assembly (BHA) and the drill pipe (dp). These sections have the following characteristic frequency resonances due to multiple reflections at the top and bottom of the drillstring and at the interface between the bottom-hole assembly and the drill pipe:

$$f_{\mathrm{BHA}} = nV/4L_{\mathrm{BHA}}, \qquad n = 1, 3, 5 \ldots, \tag{7}$$

and

$$f_{\mathrm{dp}} = nV/2L_{\mathrm{dp}}, \qquad n = 1, 2, 3 \ldots, \tag{8}$$

where V is the velocity of propagation in the drillstring, L_{BHA} is the length of the bottom-hole assembly, and L_{dp} is the length of the drill pipe.

The drillstring resonances can be investigated by computing the autocorrelation function of the pilot signal $ac_p(\tau)$

$$ac_p(\tau) = [S(t) * D(t)] ** [S(t)*D(t)]. \tag{9}$$

If $S(t)$ is broadband, the drill-bit arrivals at time lags other than $\tau = 0$ are caused by multiple reflections in the drill-

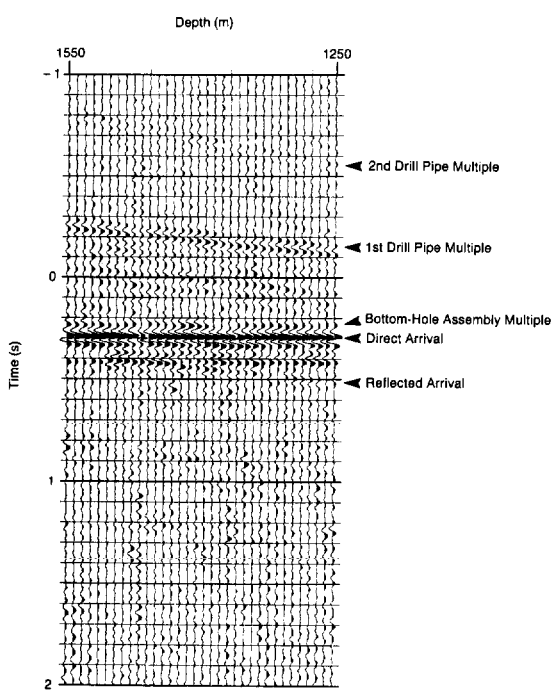

FIG. 2. Crosscorrelated drill-bit VSP field data. Each trace represents a crosscorrelation function between the pilot signal and a group of geophones located 732 m from the wellhead. The vertical axis measures the relative traveltime τ between coherent energy sensed at the pilot sensor and at the group of geophones.

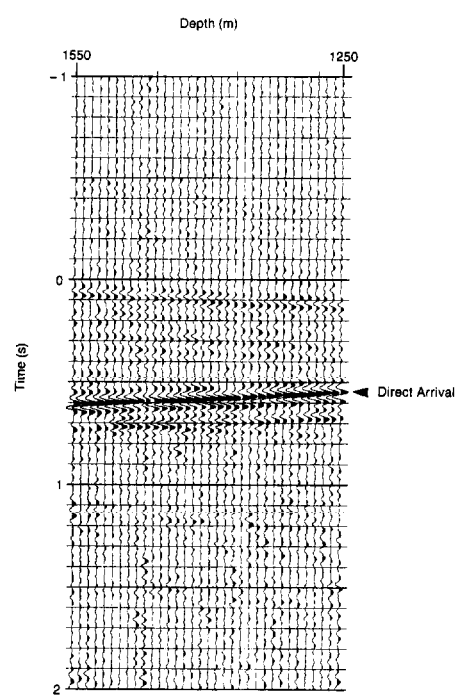

FIG. 3. Crosscorrelated drill-bit VSP data after correcting for the traveltime within the drillstring. The data are now positioned in earth traveltime τ', where the primary arrivals occur at the same traveltimes as a conventional VSP.

string. Figure 4 shows the pilot-signal autocorrelation functions corresponding to the crosscorrelated data of Figures 2 and 3. Although it is difficult to distinguish from an autocorrelation side lobe, the energy at 50 ms occurs at the expected time of an arrival that travels up and then down the length of this particular bottom-hole assembly. This bottom-hole-assembly multiple has a constant period because the length of the bottom-hole assembly is fixed. The second event after the zero lag of the autocorrelation, whose period increases with increasing depth, occurs at the expected time of an arrival that travels up and down the entire length of drill pipe. The period of the drill-pipe multiple increases as drill pipe is added. Higher order drill-pipe multiples are also apparent. The drill-pipe multiples appear in the frequency domain as resonances at frequencies given by equation (8). Figure 5 shows an example of a pilot-signal spectrum where the drill-pipe resonances are present.

From the period and moveout of the drill-pipe multiples, we have computed the average and interval velocity of the drill pipe. Both of these velocities are 4860 m/s, or approximately 200 m/s less than theoretical values for the velocity of propagation in a steel rod, which can vary between 4960 and 5140 m/s (Roark, 1954). Assuming that the velocity is the same in the bottom-hole assembly, the drill-pipe velocity can be used to compute t_p.

The drillstring multiples in the autocorrelation function of Figure 4 are equivalent to the arrivals observed in Figures 2 and 3 preceding the direct arrival. These events appear to be anticausal because the crosscorrelation process time reverses the pilot signal prior to convolution with the receiver signal. These multiples pose a deconvolution problem, requiring that an anticausal filter be applied to the crosscorrelation function to attenuate the pilot-signal multiples. As in conventional VSP deconvolution, the earth reverberations are filtered using a deconvolution operator derived from the direct arrival.

The drillstring multiples in the crosscorrelation function are attenuated through a processing step referred to as reference deconvolution. Reference deconvolution filters the crosscorrelation function to obtain a function that is equivalent to the crosscorrelation between a whitened version of the pilot signal and the signal received through the earth:

$$cc_w(\tau) = W(t) ** [S(t) * E(t)], \tag{10}$$

where $W(t)$ is the whitened pilot signal and $cc_w(\tau)$ is the crosscorrelation function with pilot signal drillstring multiples removed.

Reference deconvolution assumes that the pilot signal $P(t)$ recorded at the top of the drillstring can be represented as

$$P(t) = W(t) * H(t), \tag{11}$$

where

$$H(t) = B(t) * D(t),$$

and $B(t)$ is the impulse response of an individual impact of the drill bit on the formation. Assuming that $H(t)$ is minimum-phase, the pilot signal can be inverted to yield $W(t)$ by performing predictive deconvolution (Peacock and Treitel, 1969) on the pilot signal with a unit prediction distance:

$$W(t) = P(t) * H^{-1}(t), \tag{12}$$

where $H^{-1}(t)$ is the prediction error filter. Hence, reference deconvolution can be written as

$$cc_w(\tau) = H^{-1}(-\tau) * cc(\tau). \tag{13}$$

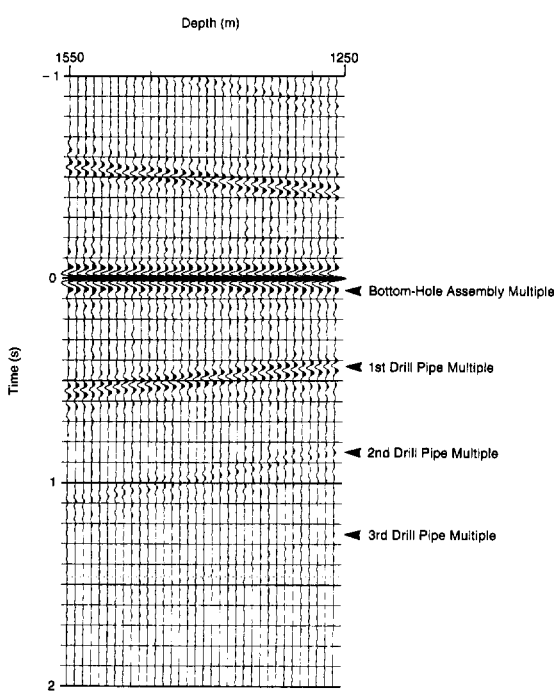

FIG. 4. Pilot signal autocorrelations corresponding to the drill-bit VSP data in Figures 2 and 3.

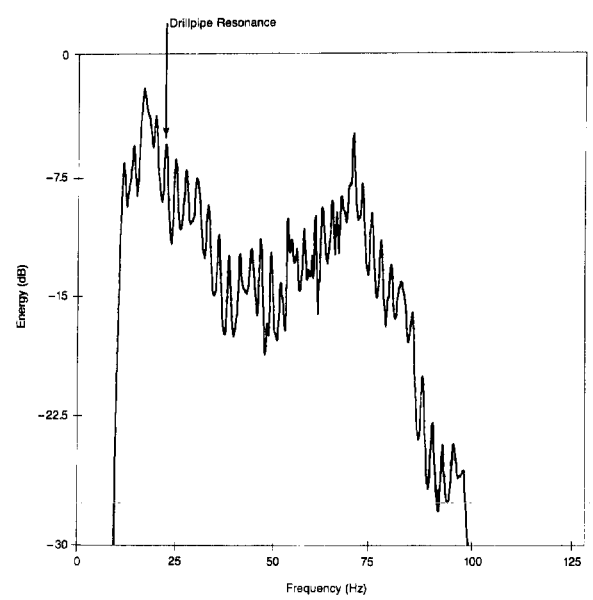

FIG. 5. Pilot signal spectrum from a driller's depth of 900 m averaged over 10 minutes. Resonance peaks at intervals of 2.5 Hz are due to drill-pipe multiples.

Assuming that the signals are stationary, by filtering the crosscorrelation function with the prediction error filter reversed in time, the drillstring multiples in the pilot signal are removed from the crosscorrelation function. This process is much less computationally intensive than deconvolving the pilot signal prior to crosscorrelation. Figure 6 shows the crosscorrelated data after reference deconvolution. Note the disappearance of the drillstring multiples preceeding the direct arrival.

DATA COMPARISON BETWEEN DRILL-BIT VSP AND CONVENTIONAL VSP

A well in the Sabine Uplift region of west-central Louisiana was selected to compare data recorded using drill-bit VSP and conventional VSP. Drill-bit VSP data were recorded from 1370 to 2600 m in a clastic and carbonate zone.

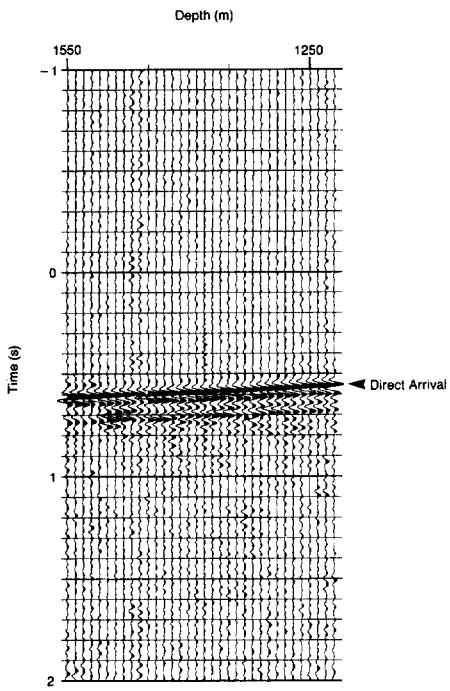

FIG. 6. Crosscorrelated drill-bit VSP data corrected for traveltime within the drillstring after applying reference deconvolution. Compare with Figure 3.

A receiver group of surface geophones was deployed for comparison with a single-offset VSP. The group consisted of 24 10 Hz geophones spaced at 1.5 m intervals, resulting in a total array length of 36 m. The center of the array was 778 m from the wellhead.

A real-time acquisition system specifically constructed for drill-bit signal logging was used to record the data continuously during all periods of drilling. Data were not recorded during connections and trips. The time duration required to drill a joint of drill pipe was designated as the precorrelation record length. Early in the drilling process, when drilling rates were high, the precorrelation record lengths were 25 to 75 minutes. At the conclusion of the drilling where drilling slowed, the precorrelation record lengths were 210 to 270 minutes. Data were logged over a period of one month.

After the well was completed, a VSP survey was conducted using an air-gun energy source suspended in a pit. The source was located at the same offset distance from the wellhead as the center of the geophone array used in acquiring the drill-bit VSP data. An LRS 1300 three-component downhole receiver was used to record the VSP data. Only the vertical component data were processed for comparison. The downhole receiver occupied discrete depths along the same depth zone over which the drill-bit vibrations had been recorded during the drilling of the well. The VSP depth sampling interval was 20 m. With the receiver locked to the borehole wall, five air-gun pops were vertically stacked to generate a single data trace at each level.

Figure 7 shows the processed drill-bit VSP data and the conventional VSP data. Every other data trace in the drill-bit VSP data is shown to emulate the 20 m sampling interval used in the VSP. Both data sets exhibit strong direct-arrival energy and weaker reflection energy. There is a phase difference between the two data sets. The impulsive air-gun source theoretically generates a minimum-phase wavelet, whereas the correlative technique used to extract the drill-bit VSP wavelet theoretically results in a zero-phase wavelet. Figure 8 shows a comparison of the direct-arrival traveltimes computed for the two data sets. The direct-arrival traveltimes for the drill-bit VSP data were computed by picking the peak of the direct-arrival wavelet, whereas the direct-arrival traveltimes for the conventional VSP data were computed by picking the onset time of the direct-arrival wavelet.

The traveltime differences were generally within ±2 ms or 0.3 percent of the total traveltime. These differences are

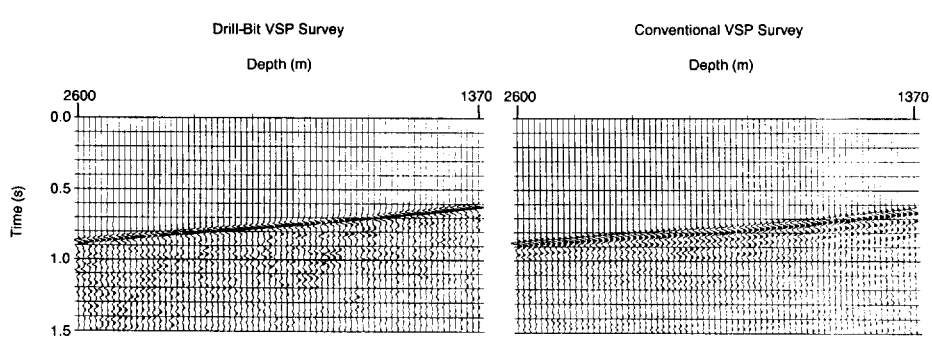

FIG. 7. Comparison of data recorded at the same offset with drill-bit VSP and with conventional VSP.

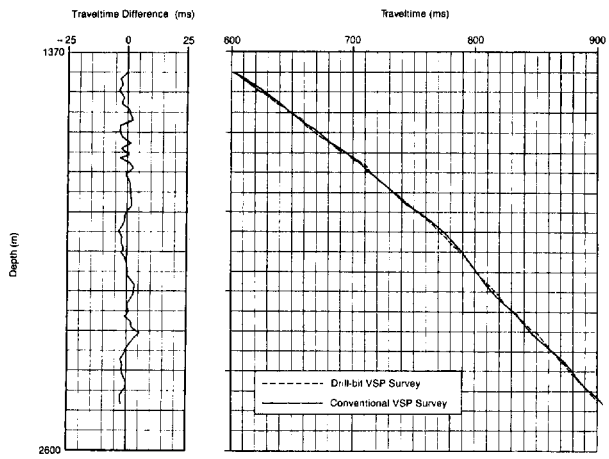

FIG. 8. Comparison of direct-arrival traveltimes computed from drill-bit VSP data and conventional VSP data.

comparable to the traveltime differences observed when impulsive source onset times are compared to correlated Vibroseis wavelet peak times (Hardage, 1990).

The reflection energy obtained from the two surveys was compared after performing conventional VSP processing consisting of wavefield separation of direct and reflected arrivals and then deconvolution of the reflected arrivals using a filter derived from the direct arrival. The data were transformed to the domain of two-way time versus wellhead offset using a VSP-CDP transform similar to the one described by Wyatt and Wyatt (1981). The resulting images are shown in Figure 9. Most of the major reflectors tie well, and the overall frequency content is similar. There are some differences between the images, particularly below 1.5 s. Wavelet and radiation pattern differences between the airgun source and the drill-bit source may contribute to subtle differences in the reflection images.

CONCLUSIONS

Energy originating at the drill bit can be detected at the surface by crosscorrelating a top-of-drillstring pilot signal with a signal from receivers placed on the surface. By repeating this process for a series of drilling depths, a drill-bit VSP data set is obtained. The use of recording times that are much longer than conventional Vibroseis sweep

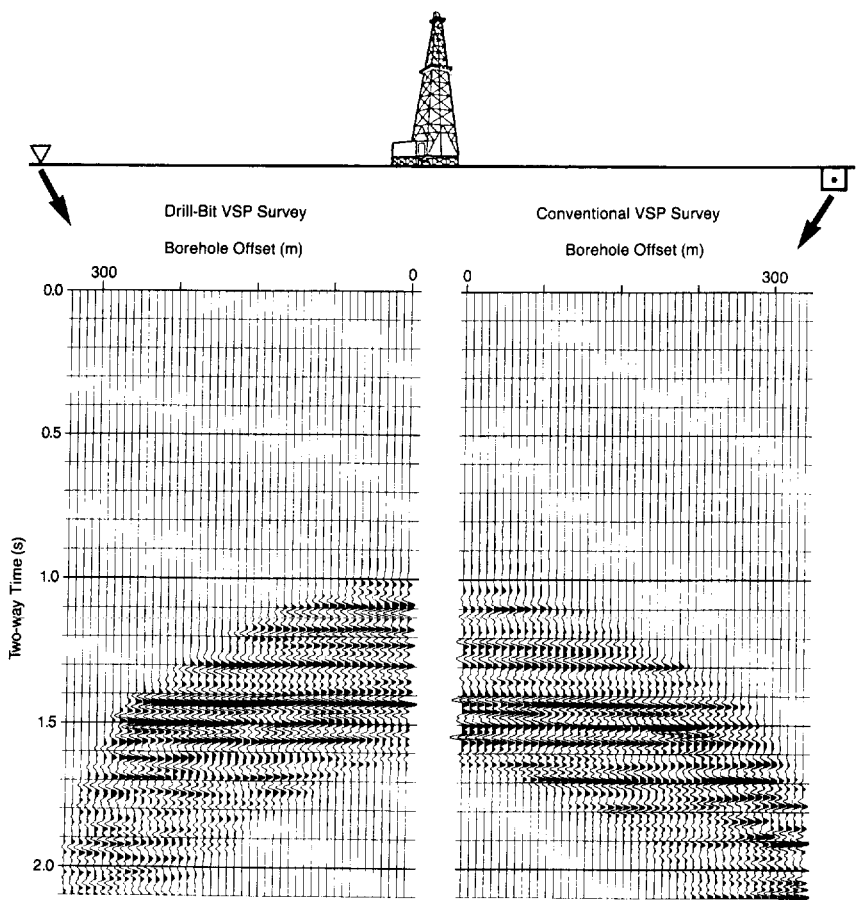

FIG. 9. Comparison of the subsurface reflection images generated from drill-bit VSP data and from conventional VSP data.

times means that weak drill-bit signals can be detected. The crosscorrelated data contain both the response of the earth and the response of the drillstring. The drillstring response is removed through time shifts and deconvolution.

Test well results indicate that the drill bit generates detectable energy over a frequency range that is similar to conventional seismic data. The traveltimes of drill-bit VSP and conventional VSP direct arrivals compared to within ±2 ms (0.3 percent), and the S/N of the crosscorrelated drill-bit VSP data was sufficient to detect reflected arrivals, as well as direct arrivals.

With drill-bit VSP, data are acquired without any downhole instrumentation, and the costs of lost rig time when conducting conventional wireline VSP are eliminated. As a measure-while-drill technique, drill-bit VSP provides real-time seismic data for use at the well site. This can aid the driller by indicating the position of the drill bit within the seismic section and providing a look at reflecting horizons yet to be encountered by the drill bit. Furthermore, the ease with which surface receivers can be deployed makes multi-offset VSP economically feasible.

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REFERENCES

Aki, K., and Richards, P. G., 1980, Quantitative seismology, Theory and methods: W. H. Freeman & Co.

Deily, F. H., Dareing, D. W., Paff, G. H., Ortloff, J. E., and Lynn, R. D., 1968, Downhole measurements of drill string forces and motions: Trans. Am. Soc. Mech. Eng. of Eng. for Ind., 217–225.

Hardage, B. A., 1985, Vertical seismic profiling, Part A: Principles, Geophys. Press.

Lutz, J., Raynaud, M., Stalder, S. G., Quichaud, C., Raynal, J., and Muckelroy, J. A., 1972, Instantaneous logging based on a dynamic theory of drilling: J. Pet. Tech., **10**, 750–758.

Peacock, K. L., and Treitel, S., 1969, Predictive deconvolution: theory and practice: Geophysics, **34**, 155–169.

Roark, R. R., 1954, Formulas for stress and strain: McGraw-Hill Book Co.

Weatherby, B. B., 1936, Method of making sub-surface determinations: U.S. Patent no. 2,062,151.

Wyatt, K. D., and Wyatt, S. B., 1981, The determination of subsurface structural information using the vertical seismic profile: presented at the 51st Ann. Internat. Mtg., Soc. Expl. Geophys.