

Seismic-While-Drilling in Kuwait Results and Applications

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ABSTRACT

During early 1994, Kuwait Oil Company and Schlumberger completed an extensive study of the Seismic-While-Drilling technique in two development wells in the Raudhatain field of North Kuwait. Seismic-While-Drilling records the energy radiated from a working drillbit (utilized as a seismic source), with receivers placed at the surface. This technology provides well seismic information such as checkshot and look ahead Vertical Seismic Profiling services at the wellsite, in real-time. The technique does not interfere with the drilling process nor does it require deploying any downhole hardware. The result of the study is that the Seismic-While-Drilling technique can work successfully in the Raudhatain field.

INTRODUCTION

The idea of using drillbit vibrations as an energy source for subsurface investigation dates back to the 1930s and cable drilling concepts. Three decades later, rollercone bit vibrations were analyzed, initially to assess their effects on the drillstring and the rig. Then in 1985, Elf Aquitaine patented the: "Method of instantaneous acoustic logging within a well bore" (US patent number 4,718,048), using a drillbit as the source. Since the initial Elf patent was filed, a Seismic-While-Drilling (SWD) service has been developed and offered under license as the TOMEX™ survey by Western Geophysical (Rector and Marian, 1991).

Despite offering real-time checkshot and Vertical Seismic Profile (VSP) data, SWD has rarely been used in the Middle East. In early 1994, Kuwait Oil Company and Schlumberger completed an evaluation of the SWD technique in 2 development wells in Kuwait's Raudhatain field. This experiment played an important part in the development of Schlumberger's SWD technique, DBSeis™.

In this paper we review the SWD technique and signal processing methods. The second section describes the test geometry, details of the wells and data acquisition. Next we present the results of the process and compare these to both wireline VSP and surface seismic methods. In the final section a brief discussion and conclusion is presented.

OVERVIEW OF THE SEISMIC-WHILE-DRILLING TECHNIQUE

The SWD technique has been developed as an aid to the drilling process. By providing checkshot information, in real-time, it allows the placement of the bit on the surface seismic section as the well progresses. By generating look ahead VSP images, the approach to critical horizons (e.g. casing points or overpressure zones) can be monitored. Such information, available in real-time at the wellsite, can have considerable value. It can help in the optimisation of the drilling operation and has obvious implications for safety.

The basic concept of SWD is quite simple (Figure 1). As a working drillbit breaks the rock at the bottom of the hole, it radiates acoustic energy into the surrounding formation. Some of this energy travels directly to the surface where it can be detected by geophones, or hydrophones if the well is offshore. Some of the energy radiates downwards ahead of the bit where it is reflected by impedance contrasts in the Earth. This reflected energy can also be detected at the surface.

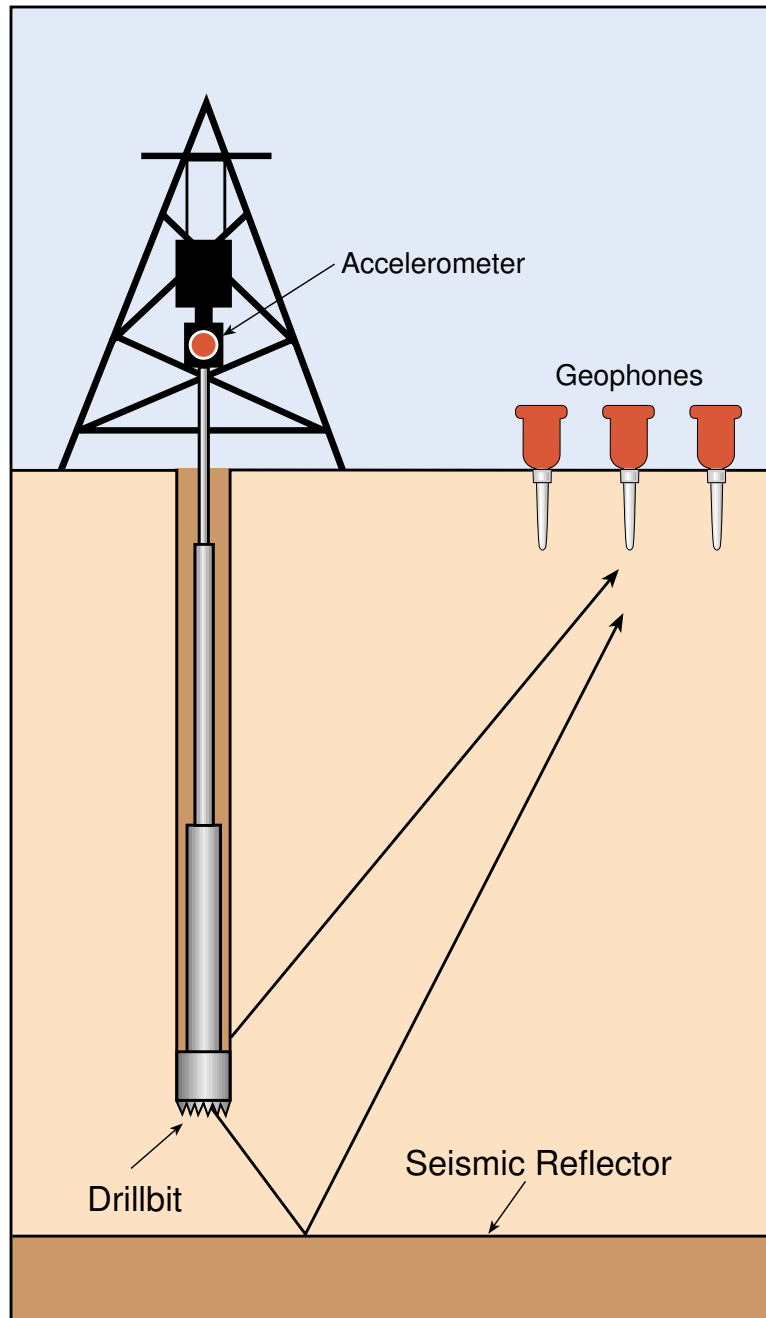


Figure 1: Basic concept of Seismic-While-Drilling. No downhole hardware required, all measurements are at the surface.

A rollercone bit generates axial vibrations in the drillstring. These vibrations are correlated with the energy radiating into the formation. The vibrations travel up the drillstring as axial waves. They can be detected by placing a sensor, such as an accelerometer, on the swivel.

The rollercone bit can be considered as a dipole source (Hardage, 1992). Although generally quite powerful, the characteristics of this source depend on many things:

- (1) drilling parameters (e.g. weight-on-bit, revolutions-per-minute),
- (2) formation properties,
- (3) bit type, and
- (4) drillstring and bottom hole assembly (BHA) geometry.

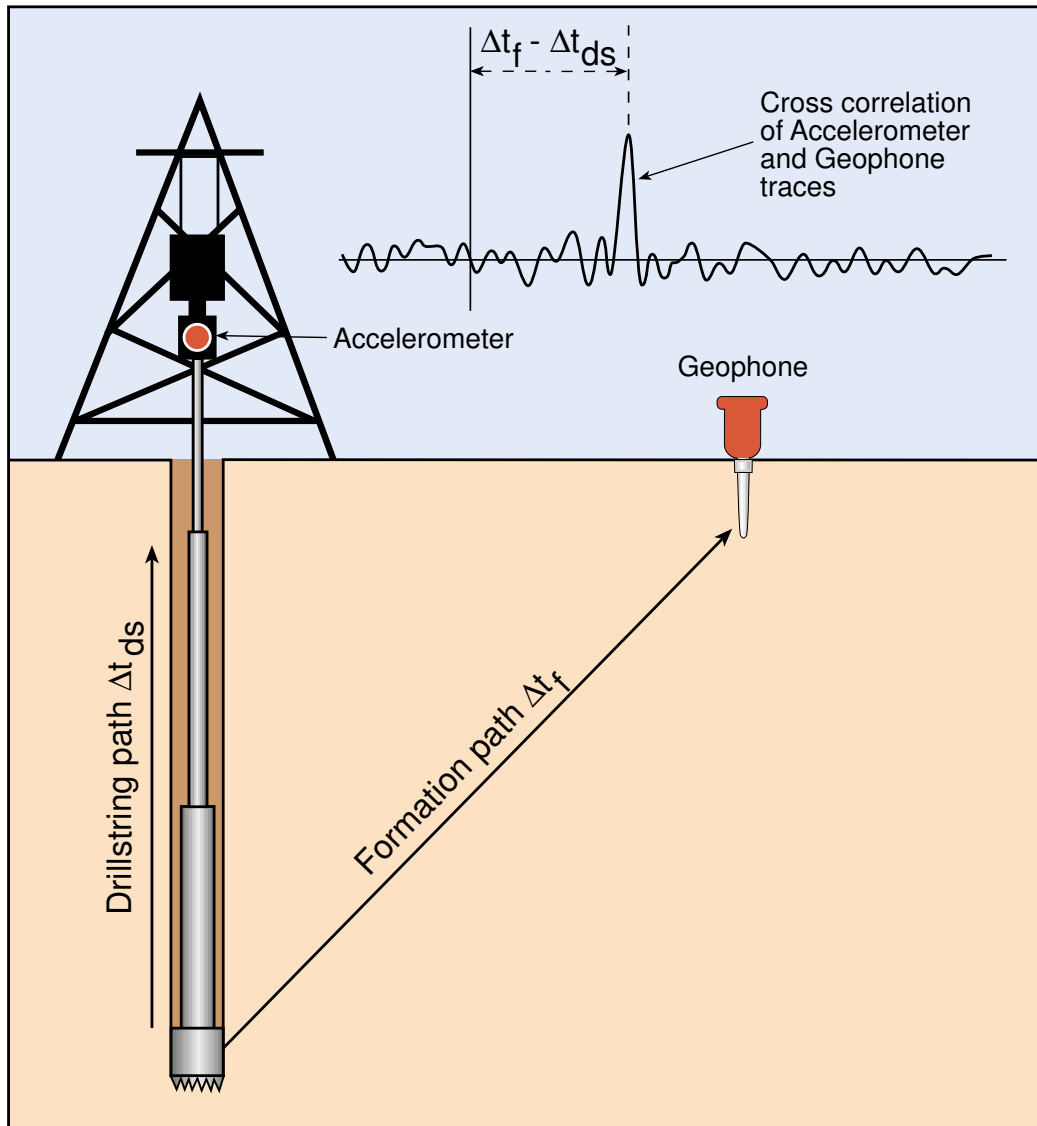


Figure 2: Extraction of timing data from Seismic-While-Drilling. Differential measurement between drillstring time Δt_{ds} and formation time Δt_f .

As a result the source is variable, both in amplitude and bandwidth. Typical bandwidths are from 5 to 100 Hertz, and the spectral shape depends to some extent on the drillstring.

Although the bit radiates energy continuously while drilling it is nevertheless possible to extract timing information (Figure 2). The acoustic energy is transmitted along the drillstring to the accelerometers, and through the formation to the geophone array. These two transmission paths usually have different acoustic velocities. Cross correlation of the accelerometer signal with the geophone signal gives the relative travel time difference between the drillstring path and the formation path. In order to find the absolute travel time from the bit to the geophones through the formation, i.e. the checkshot time, the travel time along the drillstring must be established.

In reality the situation is more complicated than the above description implies. Both the accelerometer and the geophone signals are influenced by their respective transmission paths, and the signal radiated into the formation by the bit is influenced by the drillstring geometry. This is so because some of the energy that travels up the drillstring is reflected back down by impedance changes (e.g. the transition between drill pipes and drill collars) and is re-radiated at the bit (Figure 3).

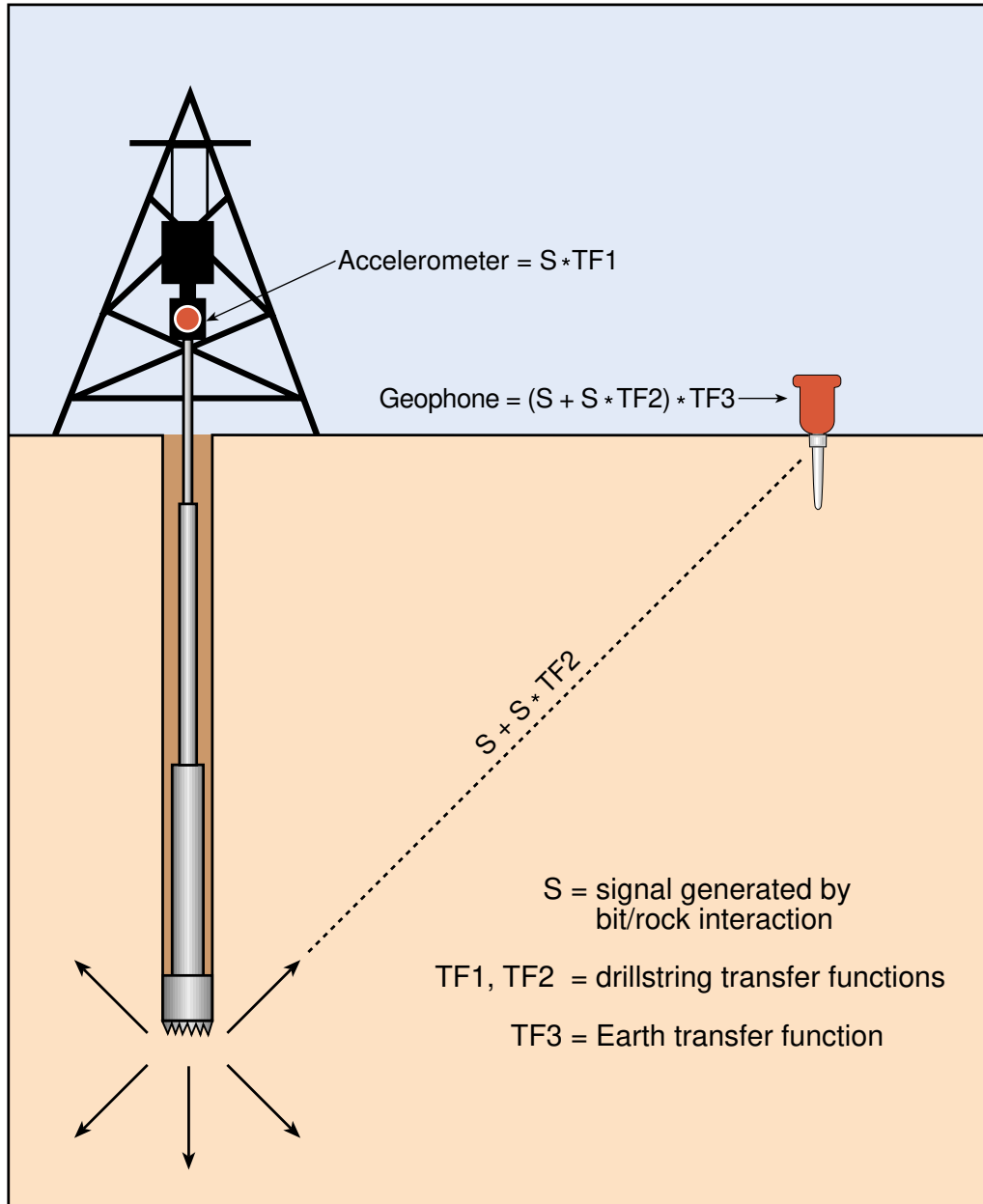


Figure 3: Transition paths and radiated signals. Absolute signature of drillbit will be affected by several transfer functions upon measurement at surface.

The re-emission of this reflected energy is governed by the boundary condition at the bit, which depends on the drilling parameters and the rock properties. In addition there is the problem of signal to noise ratio - a drilling rig is a very noisy place. The processing techniques to deal with some of these problems are described in the following section.

The Drillstring Measurement

The travel time of the signal from the bit to the accelerometer, along the drillstring, is needed to determine the checkshot time. This travel time can be determined if the acoustic velocity along the drillstring is known. Although the drillstring is essentially a long steel pipe, the acoustic velocity over the bandwidth of interest (approx. 16,900 feet/second), is not that of an extensional wave in a uniform steel pipe. This is due to the presence of the tooljoints.

Although the tooljoints are short (of the order of two feet) they have a considerably greater cross sectional area than the body of the drillpipe. The tooljoints add mass to the drillpipe without a corresponding increase in stiffness. This has several effects on the transmission characteristics of the drillpipe (Drumheller, 1995). For SWD the main consequence is to reduce the effective velocity. This reduction can be significant (up to 10%). The effective velocity can be calculated if the material properties and dimensions of all the drillpipes and tooljoints are known. In practice, however, such information is difficult to obtain. It is more practical to estimate the travel time from the data.

The drillstring consists of a series of steel cylinders of different cross sectional areas joined together. As such it can be modeled as a layered impedance system. Assume that the drillstring consists of a series of layers. The thicknesses of the layers are such that it takes the same amount of time for an axial wave to traverse each layer. Within each layer the material properties and cross sectional area remain constant. Changes in acoustic impedance (i.e. cross sectional area) from layer to layer can be represented as reflection coefficients at the layer boundaries. If the source (the bit) is at one end of the drillstring, and the receiver (the accelerometer) is at the other, then the resultant one dimensional transmission path has a transfer function that may be represented as an autoregressive (AR) process.

By processing the accelerometer signal it is possible to estimate the AR parameters. These parameters can be transformed into the reflection coefficients. It is then possible to produce an impedance map of the drillstring in terms of these reflection coefficients. A synthetic example of such a drillstring image is given in Figure 4. The larger reflection coefficients in this image correspond to changes in cross

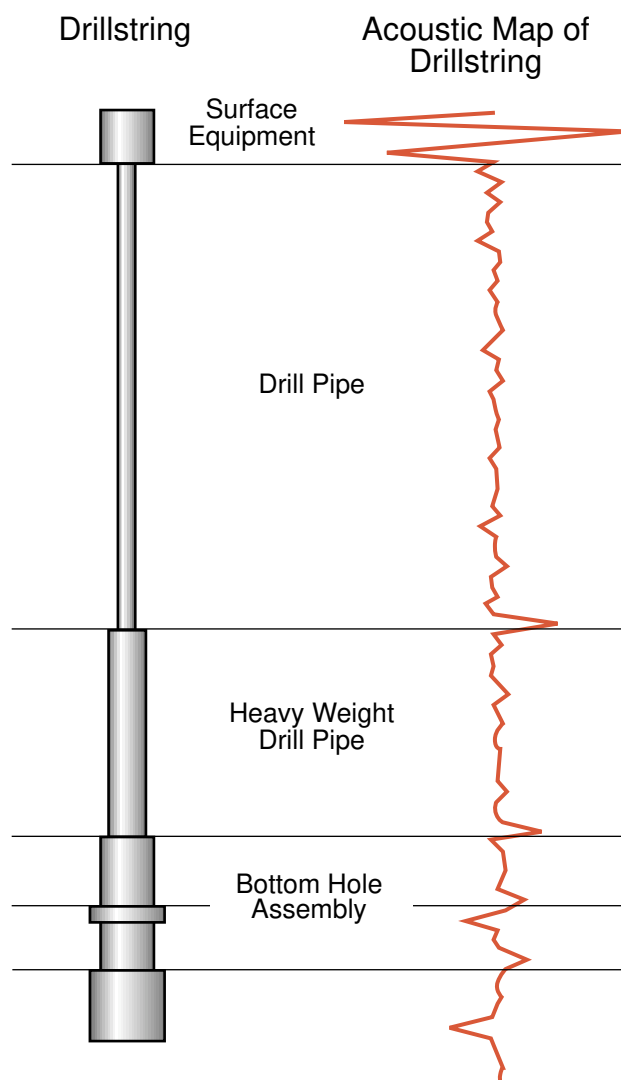


Figure 4: Synthetic example of a drillstring image, large reflection coefficients correspond to changes in cross-sectional area of the drillstring.

sectional area of the drillstring. The vertical axis of the image is travel time. This means that if a particular part of the drillstring can be identified in the image (e.g. the top of the drill collars) the travel time from that location, to the surface, is established. If the reflection coefficient corresponding to the impedance contrast between the bit and the formation can be identified, then the travel time along the drillstring has been determined.

In practice there are some additional complications. For operational reasons the accelerometer is not placed at the end of the drillstring (the traveling block), but on the swivel. This means that the receiver is embedded within the transmission path. The sensor output is therefore an autoregressive moving average (ARMA) process. The AR part depends upon the structure of the entire drillstring while the MA part depends only upon that part of the drillstring between the swivel and the traveling block. The effect of the MA part is significant but can be dealt with during processing.

A more serious problem occurs because the accelerometer measures both signal and noise. Since it is placed on the swivel it picks up noise from the mud pumps which travels along the mud line. This noise can cause significant degradation of the drillstring image and make it difficult to identify particular components.

In these situations the velocity of the drillstring signal can be determined by analyzing the moveout of the reflection coefficient series over a range of depths. Although this technique can give an accurate velocity estimate for the drillpipe section of the drillstring, it does not provide the velocity of the bottom hole assembly (BHA) or the heavyweight pipe section, and estimates for these velocities must be used. This will typically result in small errors, as the BHA is generally short compared to the total drillstring length.

The Geophone Measurement

The SWD technique utilizes a small array of geophones. On land this would usually be between 12 and 20 geophones. The geophones are usually placed between 6 and 13 ft apart in a line pointing towards the rig, with the first sensor typically 300 to 600 ft from the wellhead. Standard seismic acquisition practice would be to add all the geophone outputs together to produce a single channel. This procedure tends to attenuate surface waves traveling across the array while reinforcing any body waves coming from deep within the earth. However the amplitude of the surface waves generated by a working rig can be several orders of magnitude greater than the signal radiated from the bit. Simply summing the geophone channels together may not provide sufficient attenuation of the ground roll.

To overcome this problem each geophone channel is recorded separately with a high dynamic range. Digital grouping techniques can then be used to separate the bit generated signal from the groundroll. Such techniques are very versatile and may be applied in real time. Because individual sensor outputs are available, corrections for statics and normal moveout can be performed. This is particularly important when the bit is relatively shallow since the normal moveout across the array can be significant.

The Cross Correlation

Cross correlating the accelerometer signal with the geophone signal gives the relative travel time between the drillstring path and the formation path. However both signals contain multiples due to the drillstring. These multiples in the sensor signal result in multiple peaks in the cross correlation making time picking difficult.

The accelerometer signal is an ARMA process in which the AR order depends upon the length of the drillstring (for a drillstring 3,000 ft long the AR order is approximately 200) and the MA order depends upon the position of the accelerometer (typically it is less than 10). The ARMA parameters are estimated as part of the drillstring image processing. These parameters are used to remove the effects of the accelerometer drillstring multiples from the cross correlation. This reduces the multiple peaks in the cross correlation and makes time picking much easier.

The signal radiated into the formation from the bit is also an ARMA process. The AR part is the same as the accelerometer AR component but the MA part is different. It has the same order as the AR part. Estimating the parameters of such a large order MA process is extremely difficult to do in a robust manner. Accordingly the drillstring multiples radiated from the bit are left in the cross correlation and are treated as part of the source.

One more effect to be dealt with arises from the fact that the different types of sensors are used to measure the drillstring and formation signals. A phase compensation technique is applied correct for the different transfer functions.

KUWAIT DATA SET

Two vertical development wells, A and B, were drilled in the Raudhatain field in North Kuwait and were approximately 3 miles apart (Figure 5). Figure 6 shows the lithology column that the 2 wells traversed. Both wells bottomed in the Zubair clastics.

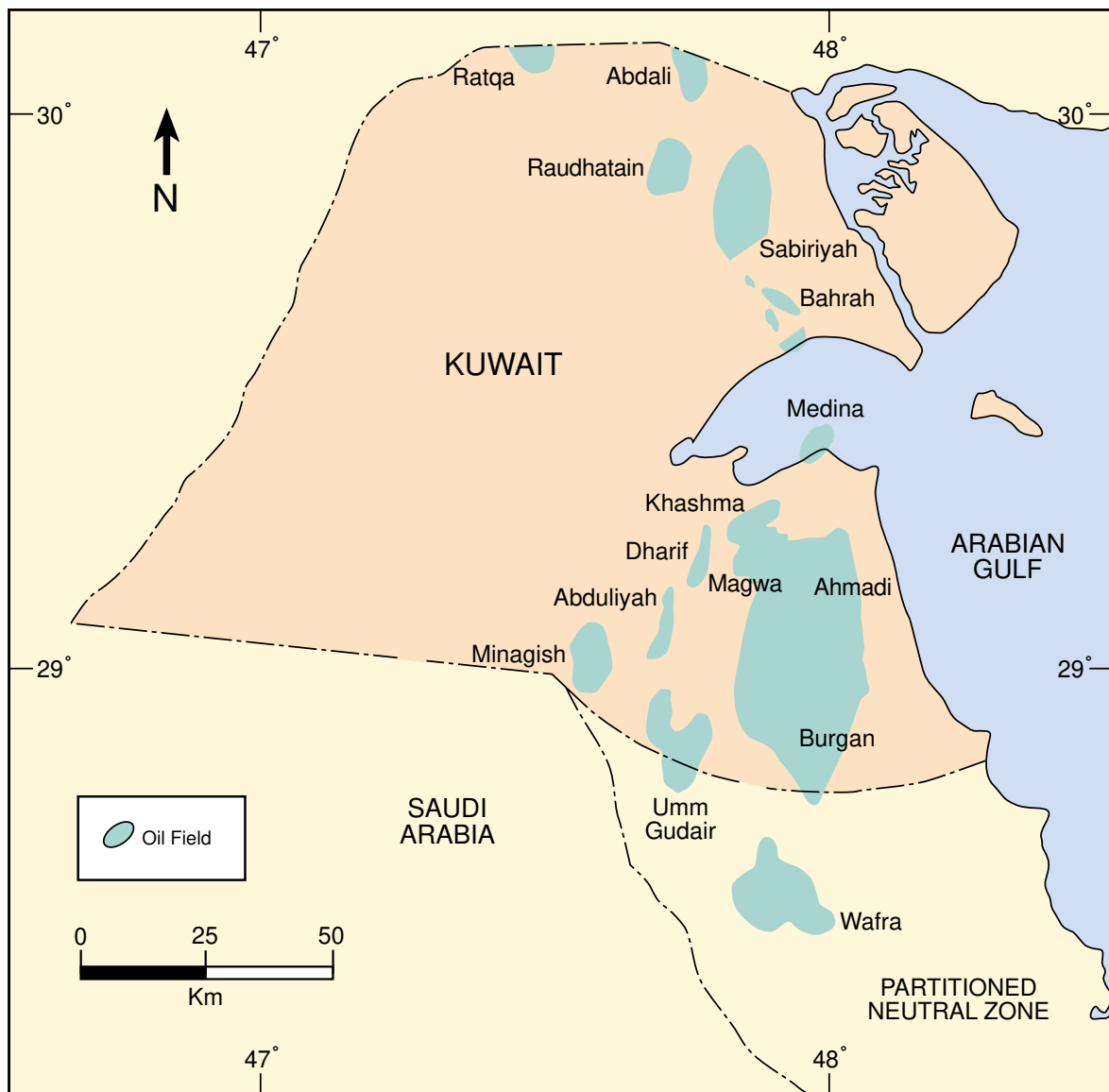


Figure 5: Kuwait map and field locations.

PERIOD / EPOCH / AGE		Ma	GP	FORMATION	THICKNESS (FEET)				
CENOZOIC	QUATERNARY	50	KUWAIT	Dibdibba	1,052				
				Lower Fars					
				Ghar					
	TERTIARY		OLIGOCENE	HASA	Dammam	717			
					Rus	444			
			PALEOCENE		Radhuma	1,442			
					MESOZOIC	CRETACEOUS	ARUMA	Tayarat	1,123
								Qurna	
	Hartha								
	Sadi								
	WASIA		Mutriba Khasib	435					
			Mishrif	188					
			Rumaila	466					
			Ahmadi	450					
	BERRIASIAN		VALANGINIAN	100	THAMAMA	Wara	0		
						Mauddud	308		
						Burgan	450		
						Shu'aiba	242		
						Zubair	1,385		
Shale Mbr									
Ratawi Limestone Mbr									
Minagish									
Makbul									

Figure 6: Kuwait lithologic column. Thicknesses are from Well B.

Well A

SWD logging was started at a depth of 128 ft below kelly bushing. The geophone array contained 18 single component sensors planted in a line pointing radially away from the rig. The geophones were spaced 14.5 ft apart, with the first geophone 215 ft from the wellhead. Two vertically oriented accelerometers were placed on the swivel to measure the drillstring signal.

Good quality data were obtained from a depth of 500 ft down to the casing point at 1,225 ft while drilling with a 26-inch bit. Unfortunately, hardware problems prevented data acquisition for the next 1,500 ft. Acquisition then resumed, however more equipment faults developed and the data quality from deeper sections of the well was so poor as to be unusable.

Figure 7 shows the cross correlations obtained down to 1,225 ft. The direct arrivals from the bit can be clearly seen. Each trace in Figure 7 is constructed as follows. For each drillpipe, data are acquired in 8 second (sec) segments from each individual geophone, cross correlated with the accelerometer signal, and stacked. The multiples in the accelerometer signal that are due to the drillstring structure are removed. The data are then digitally beamformed to remove surface waves, and corrected for the offset geometry.

An example of this can be seen in Figure 8, which shows the beamformed cross correlations for a bit depth of 1,225 ft. The top trace is from the geophone closest to the rig. The direct arrival from the bit

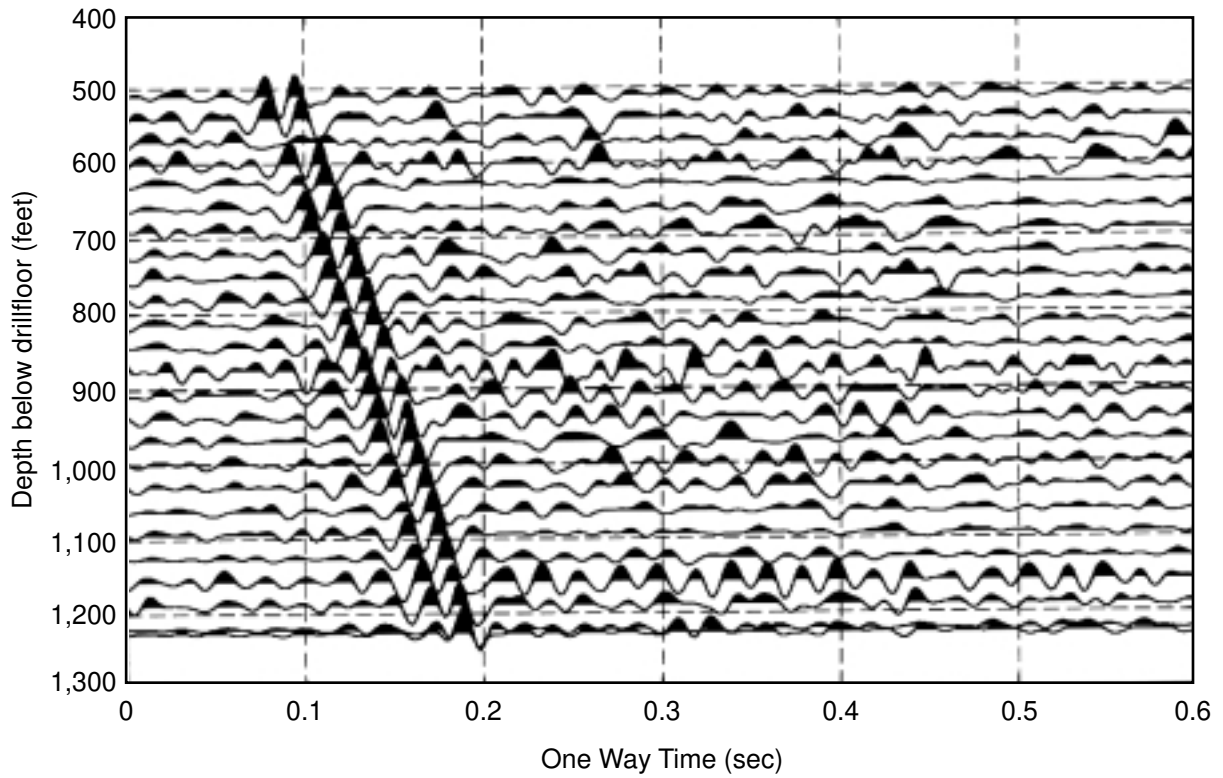


Figure 7: Cross correlations from shallow section of well A.
The direct arrival from the bit can be clearly seen.

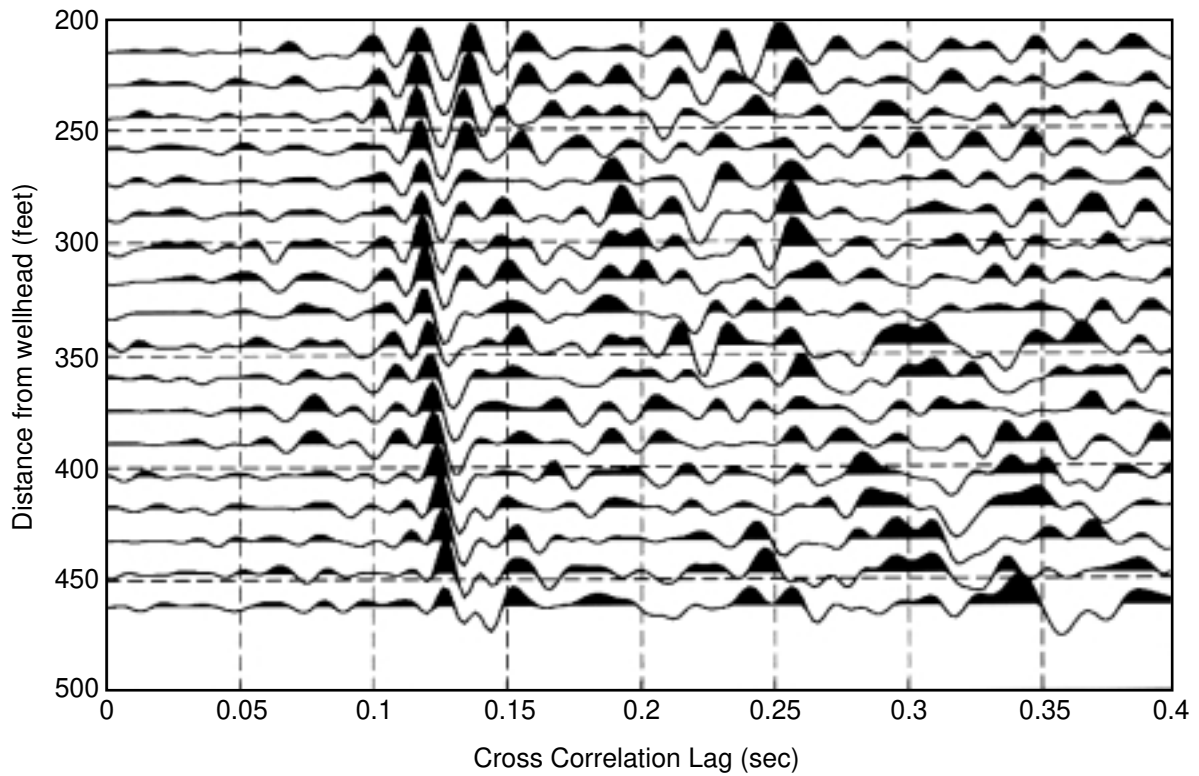


Figure 8: Individual geophone cross correlations from one depth level (1,225 ft) of well A.
The hyperbolic moveout of the direct arrival is visible from 0.115 sec to 0.127 sec.

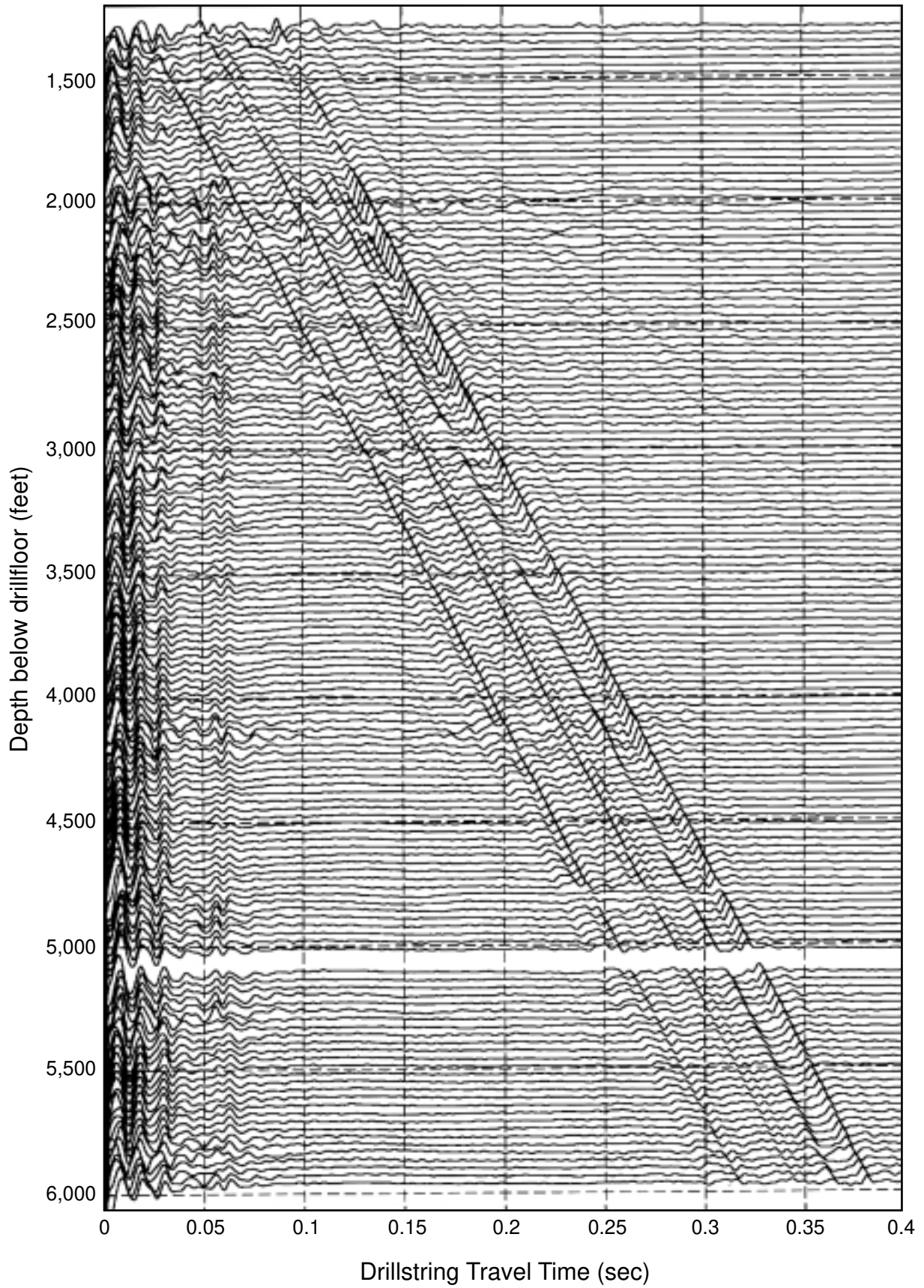


Figure 9: Drillstring image for the 17^{1/2} inch section of well B. The reflection coefficients corresponding to the bottom hole assembly moveout with depth.

exhibits a hyperbolic moveout across the array from 0.115 sec down to 0.127 sec. The traces are then stacked along this moveout and corrected to zero offset. A phase operator is applied to compensate for the different sensor responses. Finally the traces are shifted to one way time by adding on the drillstring travel time.

Although hardware problems prevented a usable data set from being obtained for most of the well, the results in the shallow part of the well were very encouraging.

Well B

Acquisition from this well started at a depth of approximately 1,000 ft and continued until the start of the Polycrystalline Diamond Compact (PDC) bit section at 8,700 ft (the SWD technique is limited to rollercone bits). This covered a time period of several weeks and traversed the Tertiary and Cretaceous systems of North Kuwait, terminating in the Zubair clastics of Barremian age.

Initially the geophone array contained 12 single geophones spaced 13 ft apart with the first geophone 250 ft from the wellhead. As acquisition progressed the array was lengthened and moved to increase signal to noise ratio. Eventually the array consisted of 27 geophones spaced 13 ft apart, with the first geophone 530 ft from the wellhead. Two vertically oriented accelerometers were placed on the swivel.

The data quality was good throughout the depth range of the well. The drillstring image for the 17^{1/2} inch section, calculated from the accelerometer signal, is shown in Figure 9. The structure due to the BHA can be seen to move out with depth. A close up of part of this image is shown in Figure 10. The reflection coefficient at the bit is clearly visible. Picking this reflector for each level gives the drillstring travel time. The drillstring image for the 12^{1/4} inch section is shown in Figure 11. The signal to noise ratio is slightly lower here, however the BHA and bit reflections are still clear.

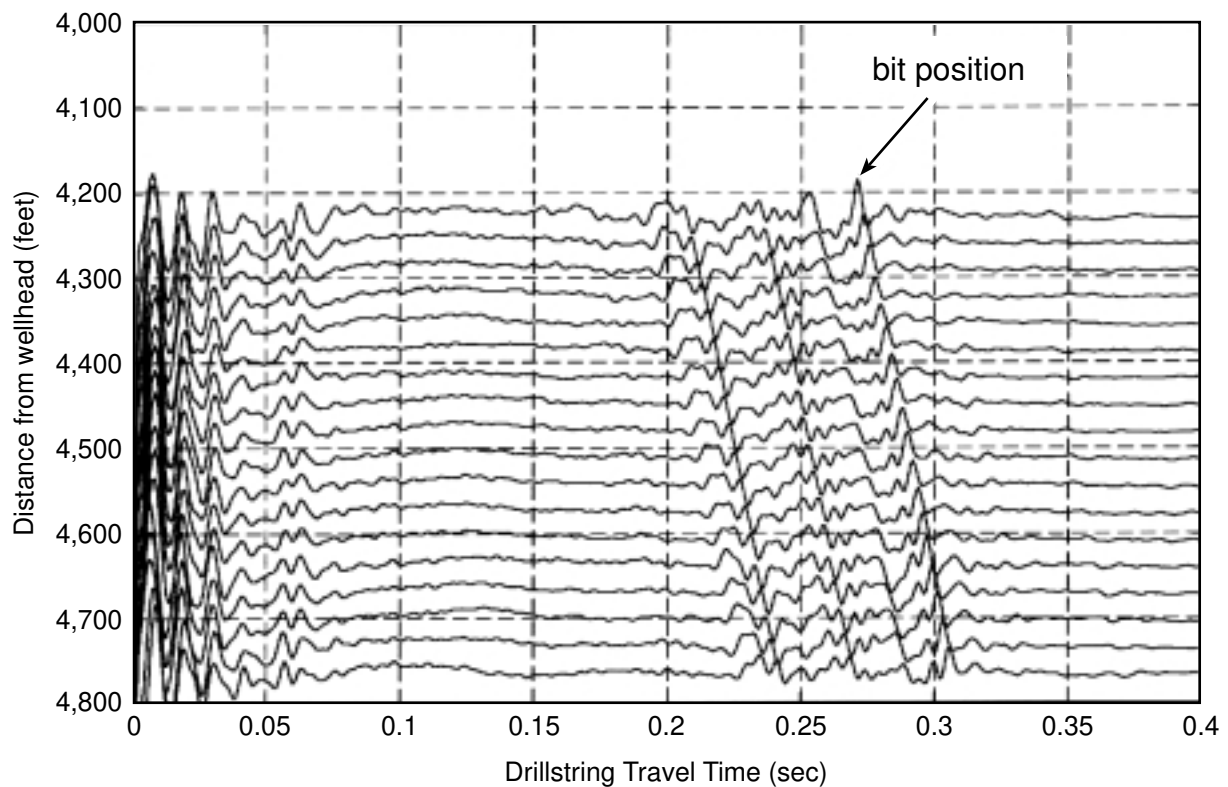


Figure 10: Close up of part of Figure 7. The reflection coefficient due to the bit/rock interface is indicated. Identifying this interface gives the drillstring travel time.

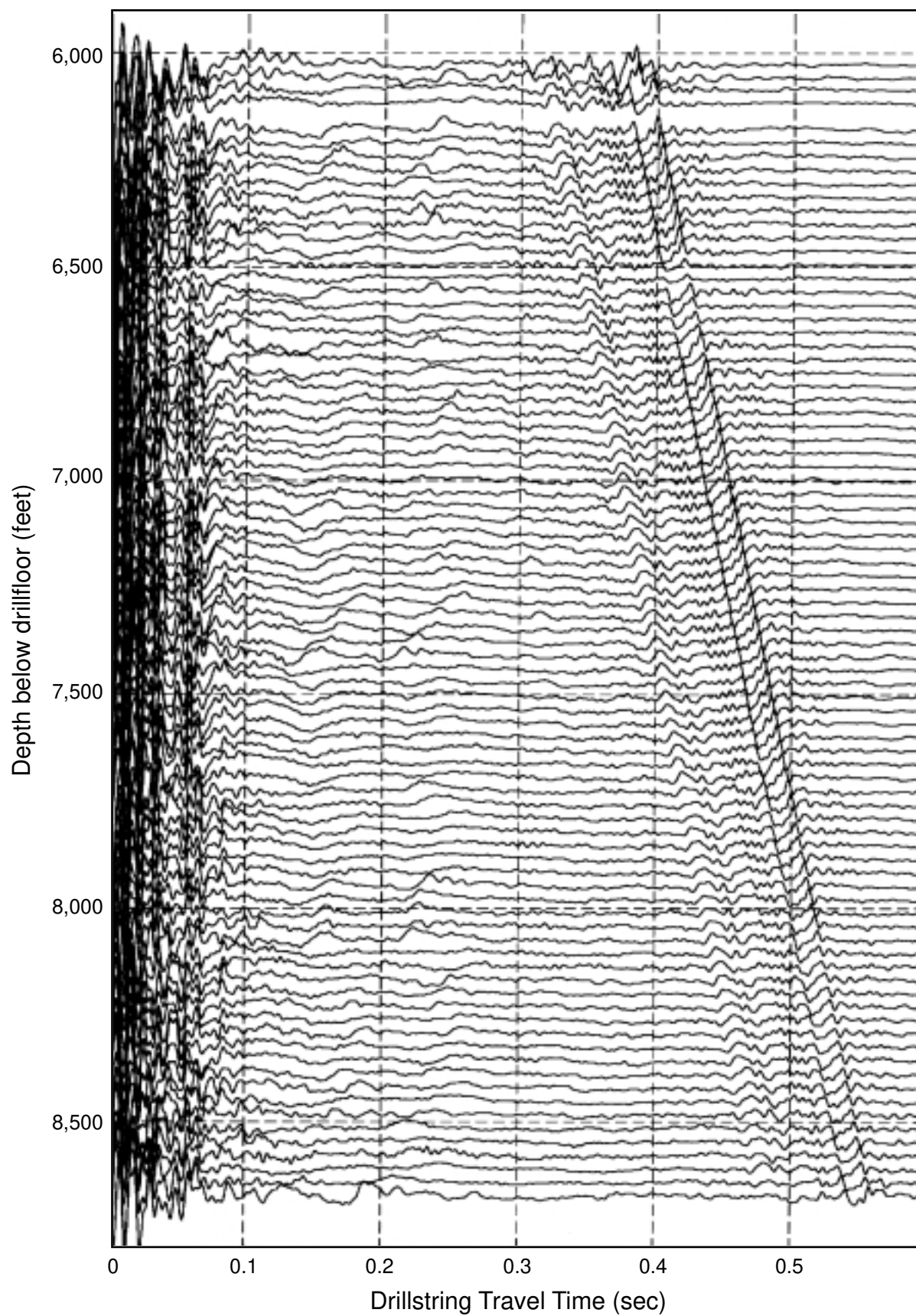


Figure 11: Drillstring image for the 12^{1/4} inch section of well B.

Figure 12 shows the cross correlations between the accelerometer and the geophones after drillstring multiple removal, beamforming to remove the surface waves and application of the phase operator. The data have been corrected for the drillstring travel time and are plotted in one way time. The direct arrival can be seen over the whole depth range. In addition there are several other features, notably tube waves, and some faint evidence of reflected energy.

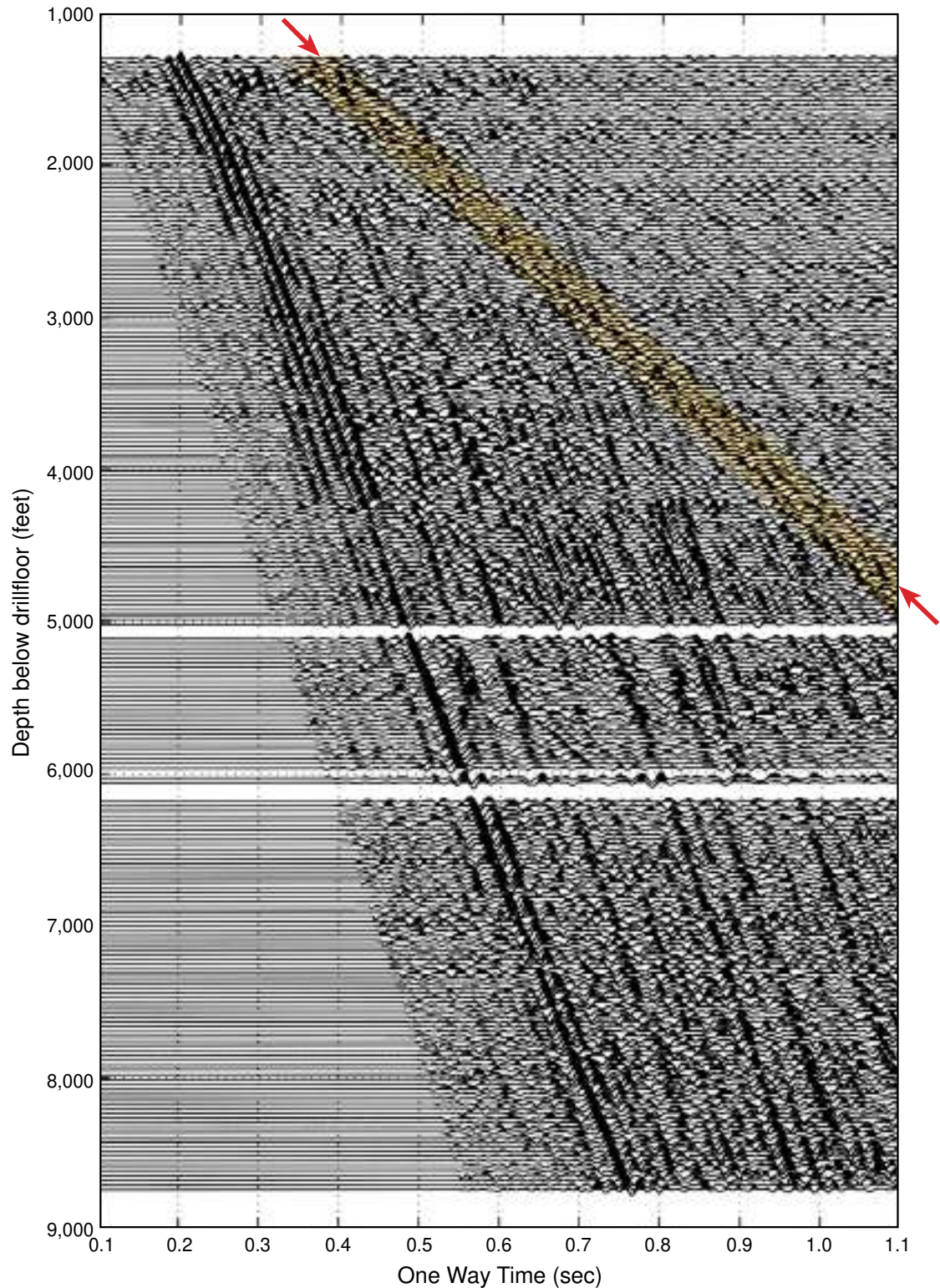


Figure 12: Cross correlations for well B. The drillstring multiples have been removed and the data have been corrected to zero offset and one way time. Note tube wave indicated by arrows.

Figure 13 shows the same data after tube wave removal. It is obvious that the character of the direct wavefield changes with depth. The signal generated by the bit depends on a variety of factors such as weight on bit, rotation speed, lithology, bit wear, mud weight, etc. Since the amplitude of the direct signal can vary widely with different drilling conditions it is instructive to look at how the energy is distributed over the frequency range.

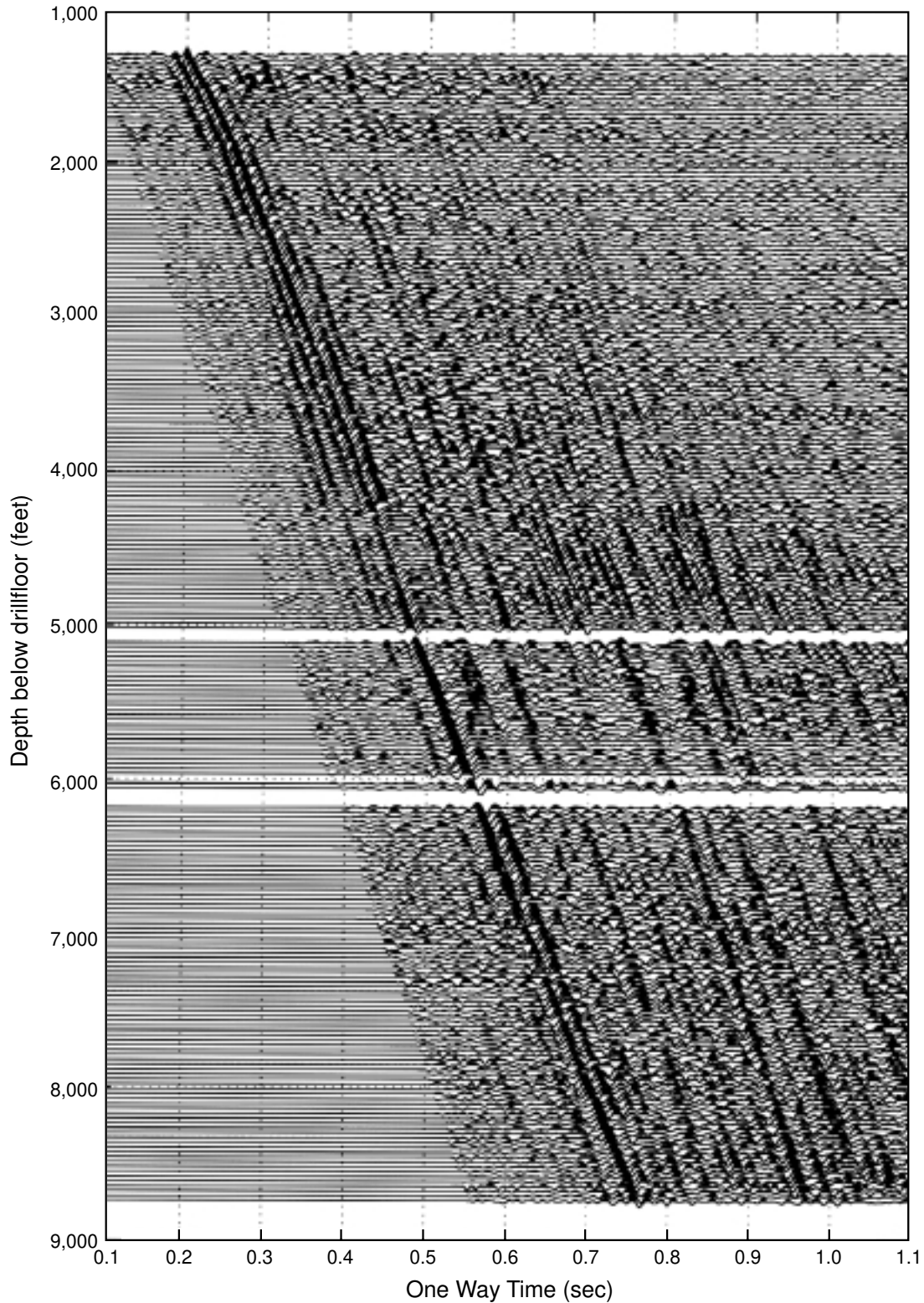


Figure 13: The data of Figure 12 after tube wave removal.

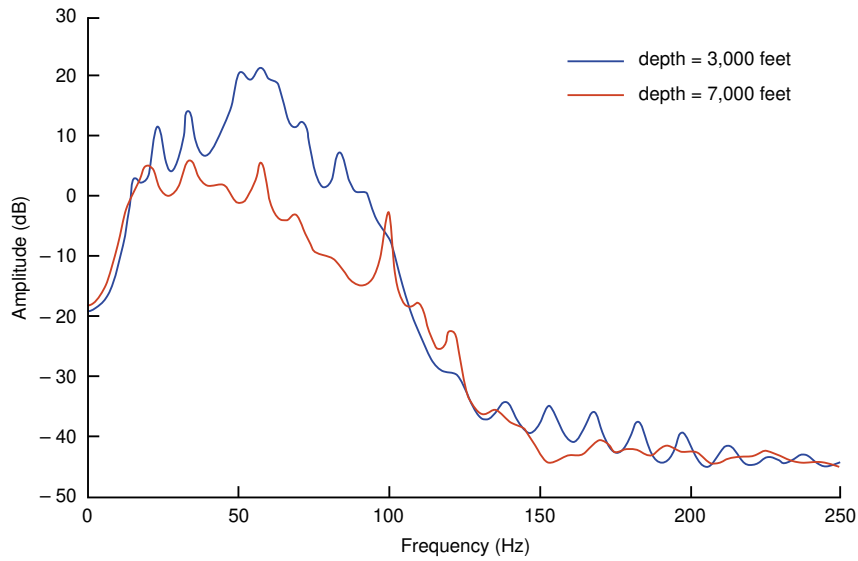


Figure 14: Smoothed source spectra for two different depths. Bandwidth decreases with depth.

Figure 14 shows the smoothed source spectra for two depths. The data from the shallower depth has a wider bandwidth. This is to be expected, since the effect of attenuation increases as the well gets deeper. It should also be remembered that the geophone array was lengthened and moved periodically during acquisition in an attempt to improve the signal to noise ratio. Changing the position and coupling of the sensors has an effect on the recorded wavefield.

Figure 15 shows the comparison between the time to depth resulting from the SWD data, and those from a conventional wireline VSP that was acquired in well A. There is a time difference of approximately 11 milliseconds one way time. There could be several reasons for this discrepancy. The data are from different wells, although the wells are close and should have similar time to depth curves. There may be errors in the offset correction applied to the SWD data (straight raypaths were assumed). The wireline data were acquired with an airgun source in the mudpit, which was some 20

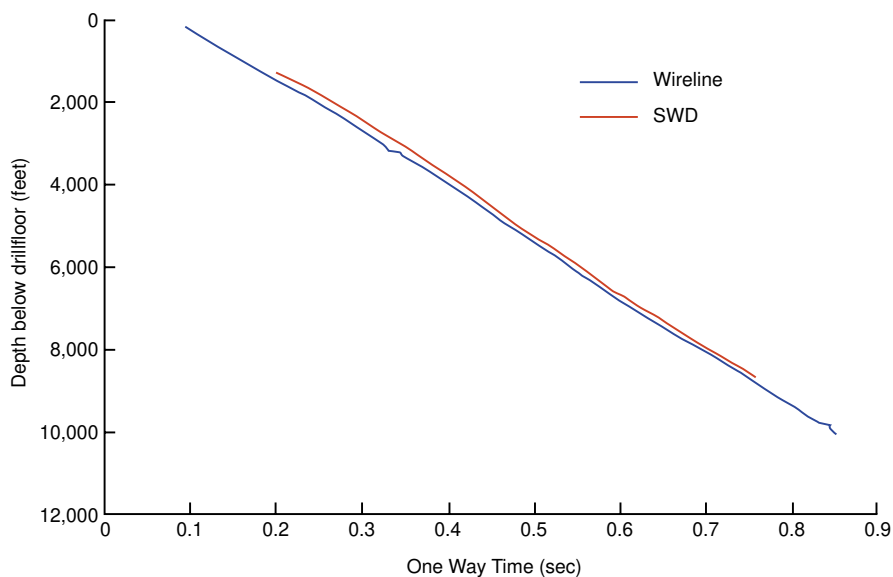


Figure 15: Comparison between Seismic-While-Drilling (SWD) time to depth data from well B and wireline checkshot data from well A. There is a difference of approximately 11 milliseconds one way time.

ft below the surface, while the SWD geophones were placed on the surface. In addition, we would normally expect to see some difference in travel time between an impulsive type source such as an airgun, and a correlation technique, such as SWD.

The data from Figure 13 were processed using the optimal deconvolution technique (Haldorsen et al., 1993, 1994) and a 17 trace (approximately 500 ft depth aperture) median filter was applied to the reflected wavefield. The resulting VSP is shown in Figure 16.

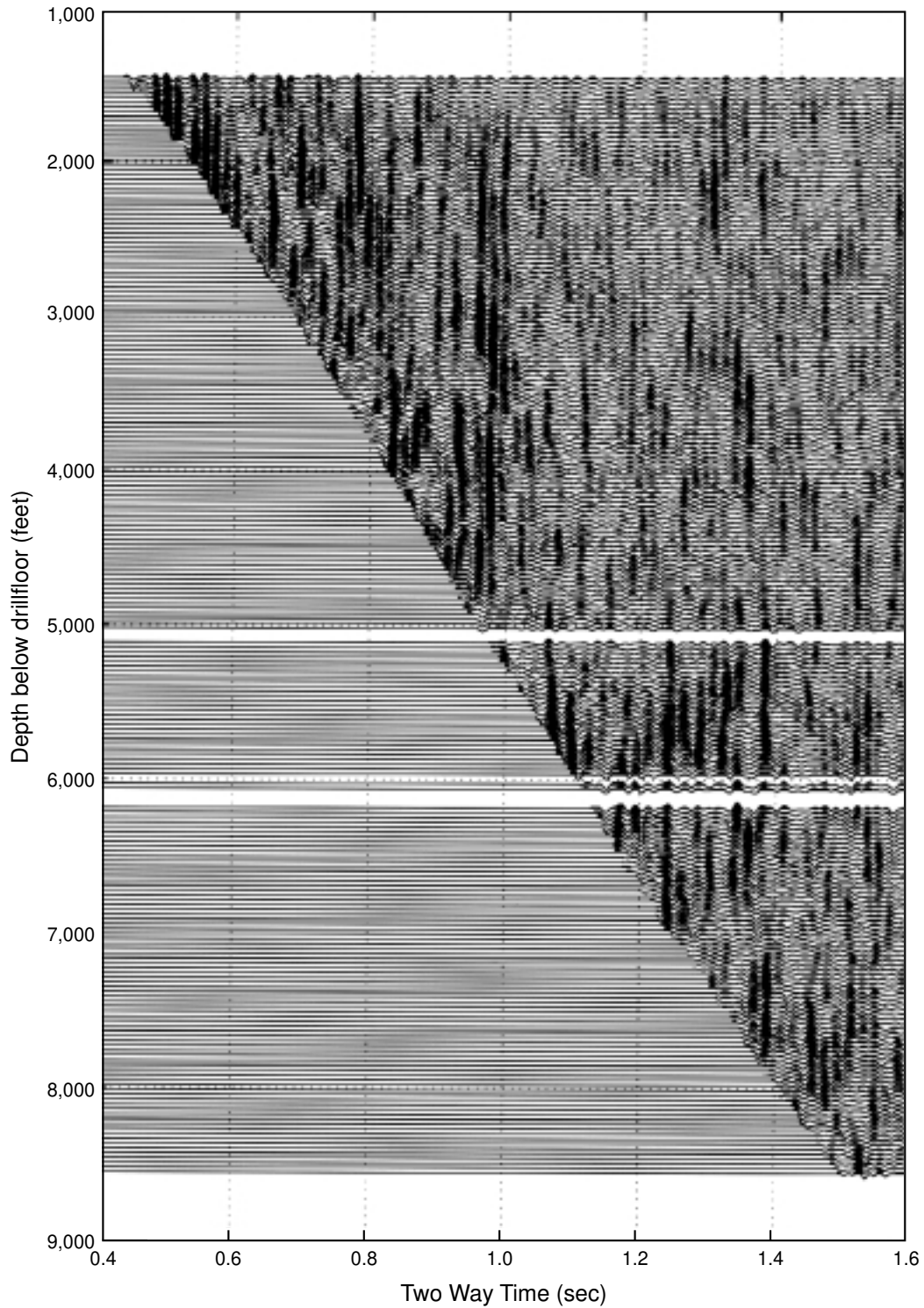


Figure 16: VSP image produced from the Seismic-While-Drilling data in well B.

COMPARISON

Figure 17 shows the image obtained from a conventional wireline VSP in well A. The data set was of excellent quality and exhibits a better signal to noise ratio than the SWD VSP; however, the major features, such as the strong reflection at 5,000 ft, are common to both.

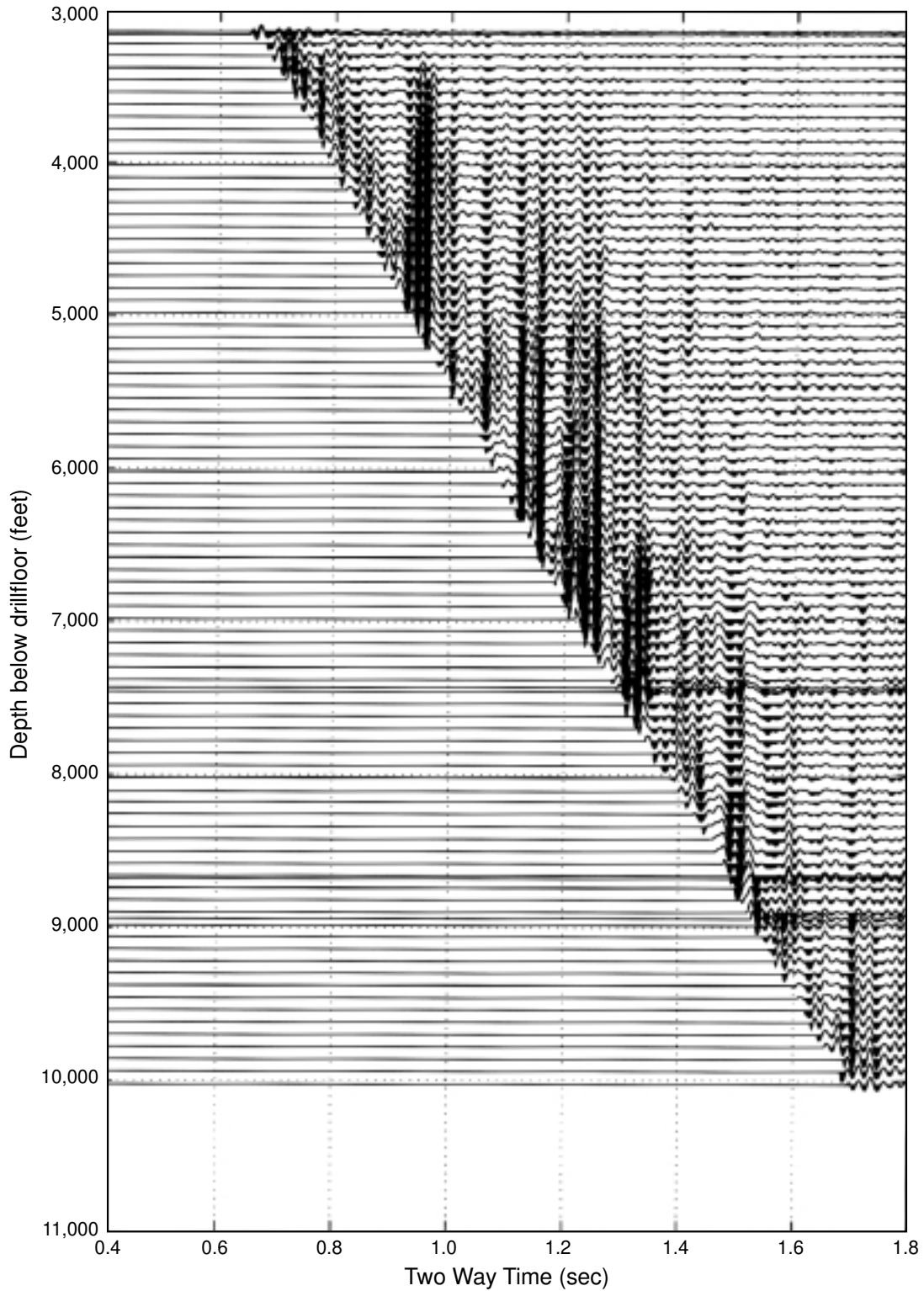


Figure 17: VSP image produced from a conventional wireline VSP in well A.

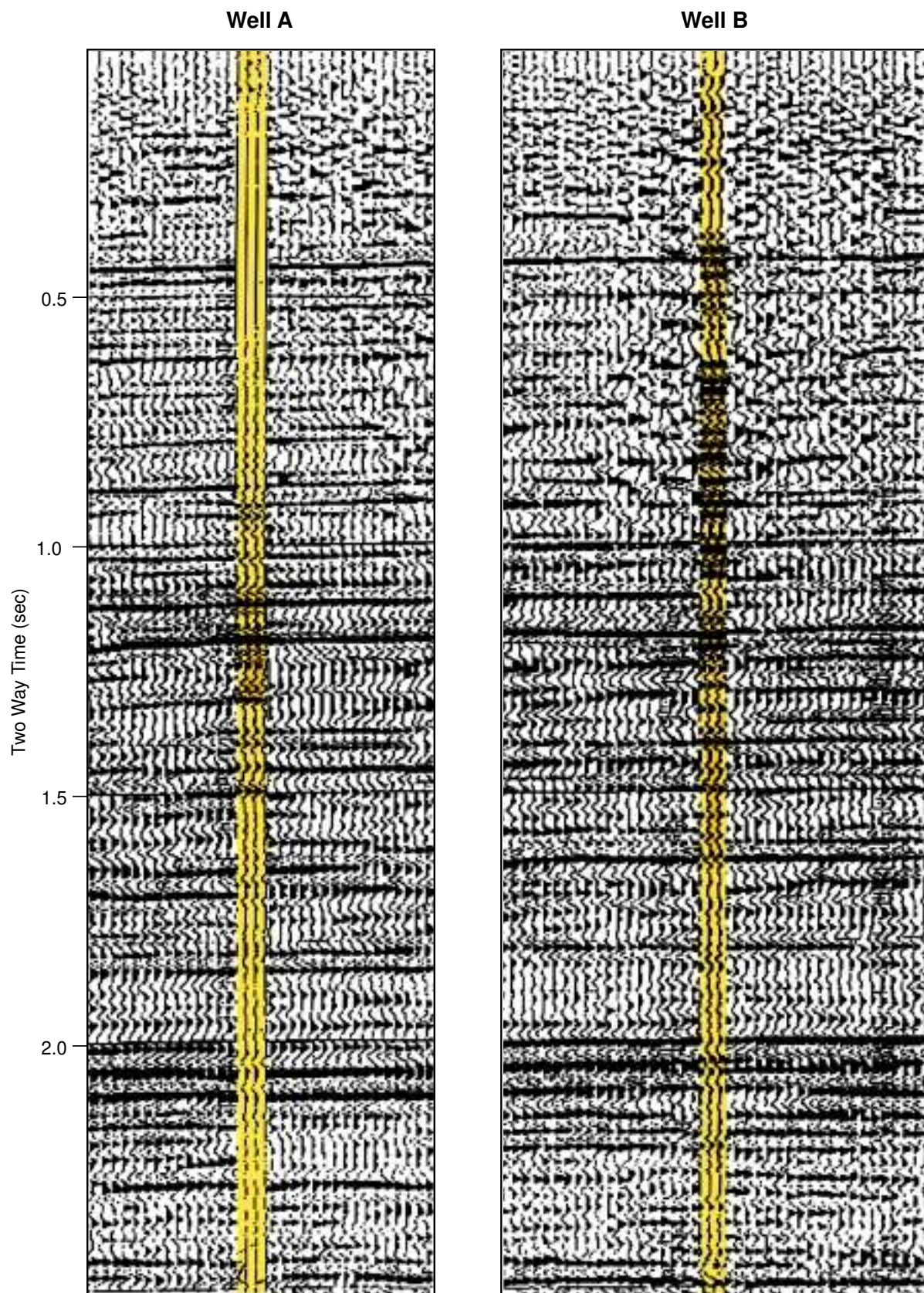


Figure 18: Parts of a surface seismic line passing close to both wells. A corridor stack from the wireline data has been inset at the location of well A, while a corridor stack from the Seismic-While-Drilling data has been inset at the location of well B (shown in yellow).

Figure 18 shows part of a surface seismic line that passes close to both wells. Well A is approximately 1,200 ft from the line, while well B is about 2,500 ft away. The two well locations are marked. At the well A position a corridor stack produced from the wireline VSP data has been inset into the surface seismic section. At the well B position a corridor stack produced from the SWD data has been inset. There is a good match to the region below 0.9 sec two way time. The region between 0.5 and 0.9 sec two way time is poorly resolved in the surface section.

DISCUSSION AND CONCLUSIONS

The introduction stated that the SWD technique had been very seldom used in the Middle East. It is the opinion of the authors that this is due to three main factors:

- (1) The real-time benefits of the technique are of lower value in development drilling campaigns where horizons and targets are well known.
- (2) In general, high quality surface seismic data is readily available, specially in the Gulf areas.
- (3) Technical limitations, such as bit type, deviated wells and rig noise.

The SWD technique can work successfully in the environments encountered in the wells of North Kuwait. Although hardware problems on well A restricted the amount of usable data, the results from the shallow section proved that the technique works. It is unlikely, however, that the SWD technique could ever produce results of such a high quality as the wireline VSP data in well A.

In well B the SWD results could be used to produce a "real time" look ahead image at the rig-site, i.e. formations can be identified before drilling through them. This has obvious operational advantages as, for example, selecting casing point.

REFERENCES

- Drumheller, D.S. 1995. *The Propagation of Sound Waves in Drill Strings*. Journal of the Acoustical Society of America, v. 97, p. 2116-2125.
- Haldorsen, J., D. Miller, J. Walsh and H. Zoch 1993. *Optimal Array Focusing Deconvolution for VSP*. Presented at the 55th European Association of Exploration Geophysicists Meeting and Technical Exhibition, Stavanger, 1993. Expanded Abstracts, Paper C005.
- Haldorsen, J., D. Miller and J. Walsh 1994. *Multichannel Wiener Deconvolution of Vertical Seismic Profiles*. Geophysics, v. 59, p. 1500-1511.
- Hardage, B.A. 1992. *Crosswell Seismology and Reverse VSP*. Geophysical Press Ltd. 304 p.
- Rector III, J.W. and B.P. Marian 1991. *The Use of Drill-bit Energy as a Downhole Seismic Source*. Geophysics, v. 56, p. 628-634.

ACKNOWLEDGEMENT

Permission to publish has been granted by the Kuwait Oil Ministry and the Kuwait Oil Company. Dr. B. Cassell, Dr. M. Hussein and Mr. A. Rivett are thanked for their reviews and useful comments.

The development of the Schlumberger Drill-Bit Seismic technique was partially funded by the Thermie program of the European Community under contract OG 046/93.

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Paper presented at the 2nd Middle East Geosciences Conference and Exhibition, GEO'96, Bahrain, 15-17 April 1996

Manuscript Received 1 April 1996

Revised 30 September, 1996

Accepted 7 October 1996