TEMPRESS®

Seismic-While-Drilling Source for Real-Time Pore Pressure Prediction

Phase II SBIR Final Report

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Contents

Abstract

This Phase II project was directed towards meeting the objectives of the Deepstar consortium project entitled: "Seismic-while-drilling to improve pore pressure prediction ahead of the bit." The objective is a real-time display of the formation from the bit to 300 m (1000 ft) below the bit at a resolution of 15-m. A downhole hydraulic impulse tool for reverse vertical seismic profiling and look-ahead seismic while drilling was developed and demonstrated successfully in a well. The HydroSeis™ tool generates a stream of powerful impulses below the bit by periodically blocking mud flow to the bit. The tool utilizes a mud-activated poppet valve, located directly above the bit, that rapidly closes for about 3 ms and then rapidly reopens for about 50 to 100 ms. The valve creates pressure pulses at frequencies from about 10 to 20 Hz. The HydroSeis™ tool is equipped with a frequency modulator device that varies the pulse frequency from minimum to maximum over a period of about 5 seconds. This provides a periodic broad-band point seismic source at the bit.

Downhole HydroSeis™ drilling tests were conducted at the Baker-Hughes Experimental Test Area (BETA) in September 2003 in an existing 2200 foot deviated well. Over 11 hours of drilling and 99 feet of well were completed with HydroSeis™ tools. A Baker-INTEQ CoPilot measurement-while-drilling system located directly above the HydroSeis™ tool was used to record downhole drilling parameters. Seismic testing was carried out while drilling with a PDC bit. The HydroSeis™ tool generated a strong, continuous point signal originating at the drill bit while drilling. The seismic signals were received with arrays of surface geophones and with the CoPilot system. The surface seismic signal were used for seismic profiling while drilling. These tests represent the first demonstration of reverse vertical seismic profiling while drilling with a PDC bit or while drilling in an inclined well. Profiling resolution of ±1 ms was demonstrated with the HydroSeis™ source – exceeding the Deepstar objective. The surface signals also appear to include reflections from formations up to 1000 feet ahead of the bit representing the first demonstration of look-ahead seismic while drilling. Look-ahead seismic reflections were also obtained by the CoPilot sensors.

Durability of the tool was demonstrated by a 3-hour continuous run in the flow-loop facility and a 5-hour run in the BETA field test. Longer run times are possible based on the wear rates of the HydroSeis™ components. On-going development of the diverter poppet valve components in a separately funded program will also increase tool life.

Introduction

Offshore blowouts during oil and gas drilling operations represent a significant economic, personal and environmental cost to the U.S.. Deepwater drilling operations are carried out using drillships and platforms with capital costs now approaching $500M and day rates of over $250K to $350K[1]. Drilling is taking place in water depths of over 2 km (6560 ft). Drilling over-pressurized formations in deep sediments represents a critical challenge for deepwater operations. Penetration of an unanticipated pressurized formation may lead to loss of well control; a blowout of gas and oil; and, in extreme cases, loss of the rig. Between 1960 and 1996 there were over 30 blowouts per year in Texas, Louisiana and the GOM[2]. The economic costs of an offshore blowout average $50M and can approach $1B. Blowouts also incur a severe cost in human life and damage to the environment. The risk and cost of a blowout increases both with well depth and water depth. A reliable seismic-while drilling source would provide the ability to image formations ahead of the bit during deepwater drilling operations. This capability would greatly reduce the risk of blowouts due to gas kicks and formation fracture.

The problem of drilling over-pressurized formations is not limited to deepwater offshore resources – all of the major onshore gas basins have geo-pressurized formations with increased costs related to the inability to predict pore pressure ahead of the bit. Present success rates in deep (>16,000 ft) onshore wells are under 20%. The size of the producing zone is typically small. The uncertainty of seismic profiles is 15% or more, which leads to large depth errors in deep wells (3000 ft in a 20,000 ft deep well). Seismic-while drilling would allow geosteering to production targets – resulting in greater success rates in deep wells. Greater operational safety and improved seismic depth accuracy will open up over 100 TCF of pressurized gas reserves onshore and even greater reserves offshore.

The cost of SWD service on a shallow offshore well in 1997 was $75K to $100K for a two or three month well[3]. Well savings in this study resulted primarily from elimination of casing and liners and ranged from $500K to $3M. The seismic-while-drilling technique competes with conventional VSP checkshot surveys that cost $10K for the service[4] plus rig costs for a trip and time to run the wireline survey. On deepwater offshore rigs, the rig time costs are high and operators are reluctant to run openhole wireline surveys. If the wire fails it will typically collect in the BOP stack where it may disable the BOP and loss of the well and loss of well control[1]. In any event, checkshot surveys do not provide real-time information on pore pressure or horizons ahead of the bit.

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[1] Von Eberstein , W. (2000) Shell Exploration and Production Company presentation at DeepTrek Planning meeting, Houston.
[2] Skalle, P. and A.L. Podio (1998) "Trends extracted from 1200 Gulf Coast blowouts during 1960-1996," World Oil, June, pp. 67-72.
[3] M. Jackson and C. Einchcomb (1997) "Seismic while drilling: Operational experiences in Viet Nam," *World Oil*, March, pp. 50-53.
[4] J. Rector (2001) personal communication.

This Phase II project was directed towards meeting the objectives of the Deepstar consortium project entitled: “Seismic-while-drilling to improve pore pressure prediction ahead of the bit.” Deepstar is a consortium of major deepwater operators in the Gulf of Mexico who have pooled resources to enhance operational safety, environmental performance and economics of deepwater drilling operations. The project champions have identified two major incentives for this work. The first is the potential cost savings in the drilling process as discussed above. The second is enabling in that “pore pressure uncertainty often results in an unacceptable risk profile, and contingency costs that could make a project uneconomical. Improved pore pressure prediction should in many cases reduce these risks sufficiently for the project to proceed.” The Phase II project objective is a real-time display of the formation from the bit to 300 m (1000 ft) below the bit at a resolution of 15-m. This display would indicate the range to reflection horizons, formation velocity gradients and provide the magnitude of deviation from normal pore pressure gradients as an indication of the mud density required to control formation pressures.

Tempress has developed a hydraulic pulse (HydroPulse™) tool that generates intense cyclic suction pulses to enhance drilling rates of roller cone and PDC bits. The HydroPulse™ tool generates suction impulses around the bit at a constant rate, which limits the bandwidth and utility of the source for seismic applications. The HydroSeis™ sweep mechanism was developed in the course of this Phase II SBIR project. The sweep mechanism modulates the pulse frequency from minimum to maximum over a period of about 5 seconds. This provides a periodic broad-band point seismic source at the bit.

The moving valve components are subject to erosive wear and high-cycle impact loading. Design optimization and endurance testing was conducted at a Tempress flow-loop test facility. The facility simulates downhole pressure and flow conditions using a test chamber and choke valve located at the end of 60 feet of heavy wall drill pipe. Various tool configurations and material combinations were tested here in preparation for downhole testing. A total of 39.1 hours of testing was carried out in the flow loop. The HydroPulse™ and HydroSeis™ tools ran (pulsed) for a total of 23.6 hours during the BETA tests and participated in drilling 651 feet of well. Most of the parts in these tools survived without significant wear.

The HydroSeis™ was tested at the Baker Experimental Test Area (BETA) located near Mounds Oklahoma as part of a test of both HydroSeis™ and HydroPulse™ tools. A surface seismic array was deployed during the tests to demonstrate reverse vertical seismic profiling (rVSP) while drilling with a PDC bit in the deviated section of the well. The Baker-Inteq CoPilot tool was also deployed on the BHA to receive seismic signals reflected from formations ahead of the bit.

Phase II Technical Objectives

The project objective was to develop a seismic-while-drilling source and processing techniques to allow real-time display of the formation 1000 ft ahead of the bit with a resolution of 50 ft. This display would indicate the range to reflection horizons, formation velocity gradients and predicted pore pressure. Specific Phase II objectives and progress were as follows:

1. *Demonstrate continuous broadband signal generation from 10Hz to 200Hz*. This objective was met.
2. *Demonstrate 100 hours of continuous operation on drilling mud*. The seismic tool has only been operated for 5 hours continuously as of this report.
3. *Demonstrate seismic-while-drilling without affecting drilling operations*. Field testing demonstrated both look-ahead and reverse vertical seismic profiling while drilling in an inclined wells with a PDC bit.
4. *Characterize the radiation pattern of the source under a variety of drilling conditions*. The field tests demonstrated that the source is a point pressure source.
5. *Evaluate different pilot sensor configurations*. Both accelerometer and pressure pilots were evaluated.
6. *Demonstrate VSP equivalent velocity measurements while-drilling with an accuracy within 5% of a conventional checkshot survey.* This objective was met.
7. *Demonstrate reflection imaging of features at a range of 1000 ft*. This objective was met.
8. *Demonstrate the ability to generate VSP data within one hour of taking data. (ie within Deepstar real-time definition).* Real time processing was not demonstrated, however the processing steps are straightforward and could be implemented easily in the field.

Background

Hydraulic pulse drilling technology is specifically designed to overcome problems encountered during deep drilling in over-pressurized formations. The hydraulic pulse valve, shown schematically in Figure 1, periodically stops the flow of mud through the drillstring. As shown in Figure 2, a high-speed flow course housing is provided around the valve. Stopping the flow of mud through the flow courses generates an intense suction pulse around the bit. A typical pulse profile is shown in Figure 3. The pulse width is about 3 milliseconds corresponding to the acoustic wave travel time in the flow courses.

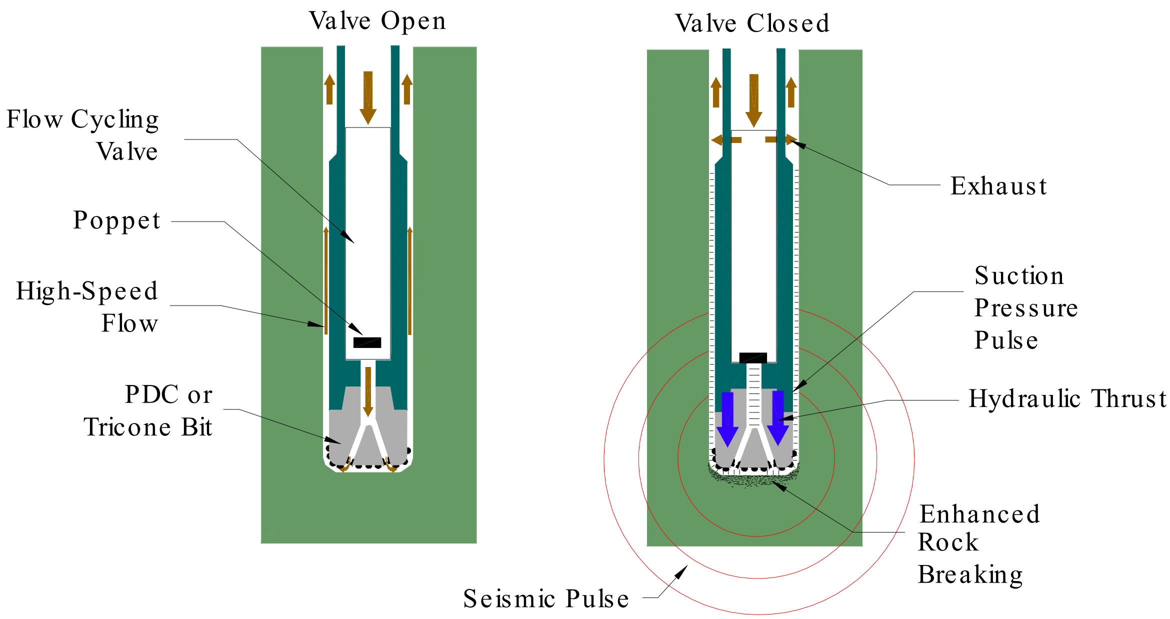

Figure 1. Hydraulic pulse drilling.

Figure 2. Hydraulic pulse tool housing with high-speed flow courses.

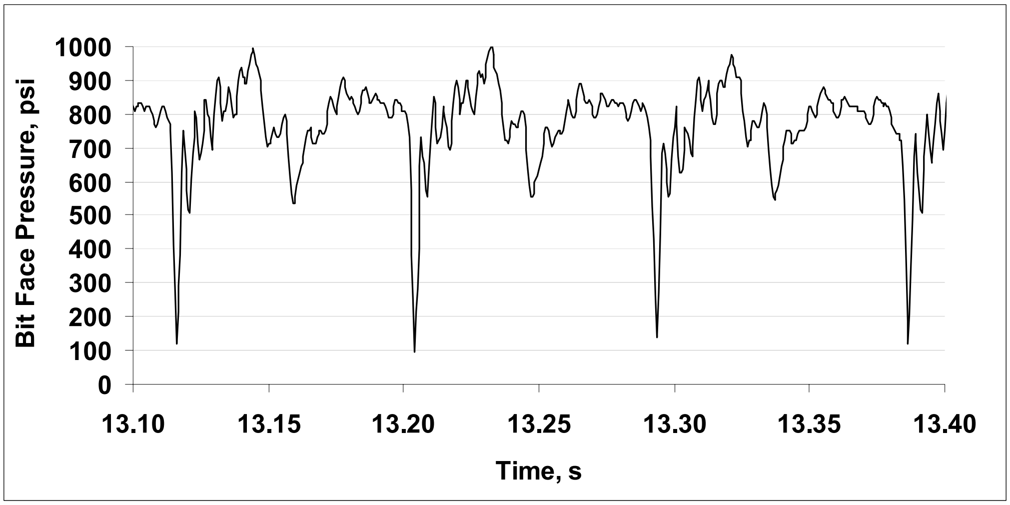

Figure 3. Bit face pressure profile generated by hydraulic pulse drilling tool. (Flow loop; 400 gpm water, no bypass, 8.75" test vessel).

The suction pulse amplitude is proportional to flow rate and mud density. Suction pulse amplitude comparisons for the various tool configurations used in testing are listed in

Table 1. Since the tool is capable of stopping all of the mud flow, a series of bypass ports may be incorporated to ensure circulation in the event that the valve fails and stops in the closed position. The bypass ports reduce the pulse amplitude by 33%. A diverter valve version of the tool, which maintains circulation without bypass ports, is currently under development.

Two valve housings have been tested. The first prototype incorporated relatively small flow slots plus an annular flow area, which caused relatively high torque when cuttings were large. The second housing incorporated flow slots with a area seven times larger to slots to ensure that no torque issues were encountered. The tool diameter wore by 0.2" during testing at BETA. Wear of the OD of the tool increases the flow area and has the effect of reducing pulse amplitude by a further 100 psi.

The combined effect of the circulation bypass and increased flow course area is to reduce pulse amplitude by a factor of three relative to the pressure drilling tests. Larger pulses may be required to affect hard rock drilling rate of penetration or improper bit motions. A flow course housing with two, smaller slots is planned for the next generation tool housing. This housing will increase the suction pulse amplitude to the levels obtained during pressure drilling tests which showed substantial drilling rate increases while drilling with roller cone bits in shale at high overbalance and with high mud weight.

Table 1. Suction pulse amplitude comparison at 400 gpm.

Test	Tool Configuration	Flow Area, in^2	Mud Density, ppg	Pulse Amplitude, psi (MPa)
Pressure Drilling	8.1” OD 3x 1”x.38” slots in 8.5” bore	6.3	10 14	1460 (10.1) 1740 (12.0)
Flow Loop	8.3” OD 3x 2.75”x1” slots in 8.75” ID vessel with and without bypass ports	14.3	8.4	630 (4.4) 400 (2.8) w/bypass
BETA	8.3” OD 3x 2.75”x1” slots in 8.5” bore, with bypass ports 8.1” OD worn	10.9 13.5	9.5	550 (3.8) 445 (3.1)
Next Generation	8.3” OD 2x 1.75”x1” slots	6.1	10	1500 (10.3)

A section view of the HydroPulse™ tool is shown in Figure 4. The tool consists of a valve cartridge located in a housing that is located immediately above the bit. The valve periodically stops the flow of mud to the bit. Flow courses on the outside of the housing accelerate the return mud velocity. When the mud flow stops, an intense suction pulse is generated around the bit. Simultaneously, a water-hammer pulse is generated in the drill collars upstream of the bit. The suction pulses around the bit have been shown to increase drilling rates in pressure sensitive shales. Upstream pressure pulses cause the drill collars to vibrate and induce a cyclic load on the bit.

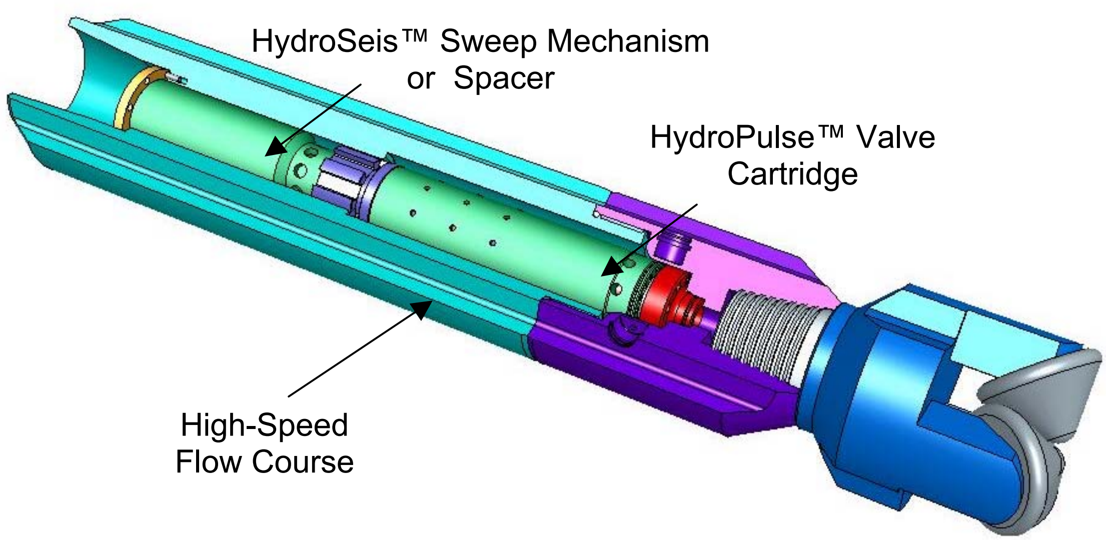

Figure 4. HydroPulse™/HydroSeis™ tool with high-speed flow course housing and roller cone bit.

When the sweep mechanism is installed, the HydroSeis™ tool generates a swept impulse signal consisting of 3 ms impulsive suction pulses at a cycle rate that varies from 5 to 10 Hz. This signal is designed to be used for reverse vertical seismic profiling-while drilling and look-ahead seismic imaging-while drilling. The source-receiver configuration is shown in Figure 5. A swept impulse function generates a seismic signal with a broadband power spectrum. Since the HydroSeis™ source operates continuously, the received signal can be correlated with the source using techniques common to other swept sources such as Vibroseis or the swept impulse seismic technique[5]. This approach differs from conventional swept sinusoidal sources because the spectrum is not limited by the swept cycle rate. Data acquisition is carried out by sweeping the source for a period of around 100 seconds. Signals may also be stacked to reduce noise. Seismic profiling and reflection imaging are carried out by correlating the signal received by geophones with a pilot signal coupled directly to the source.

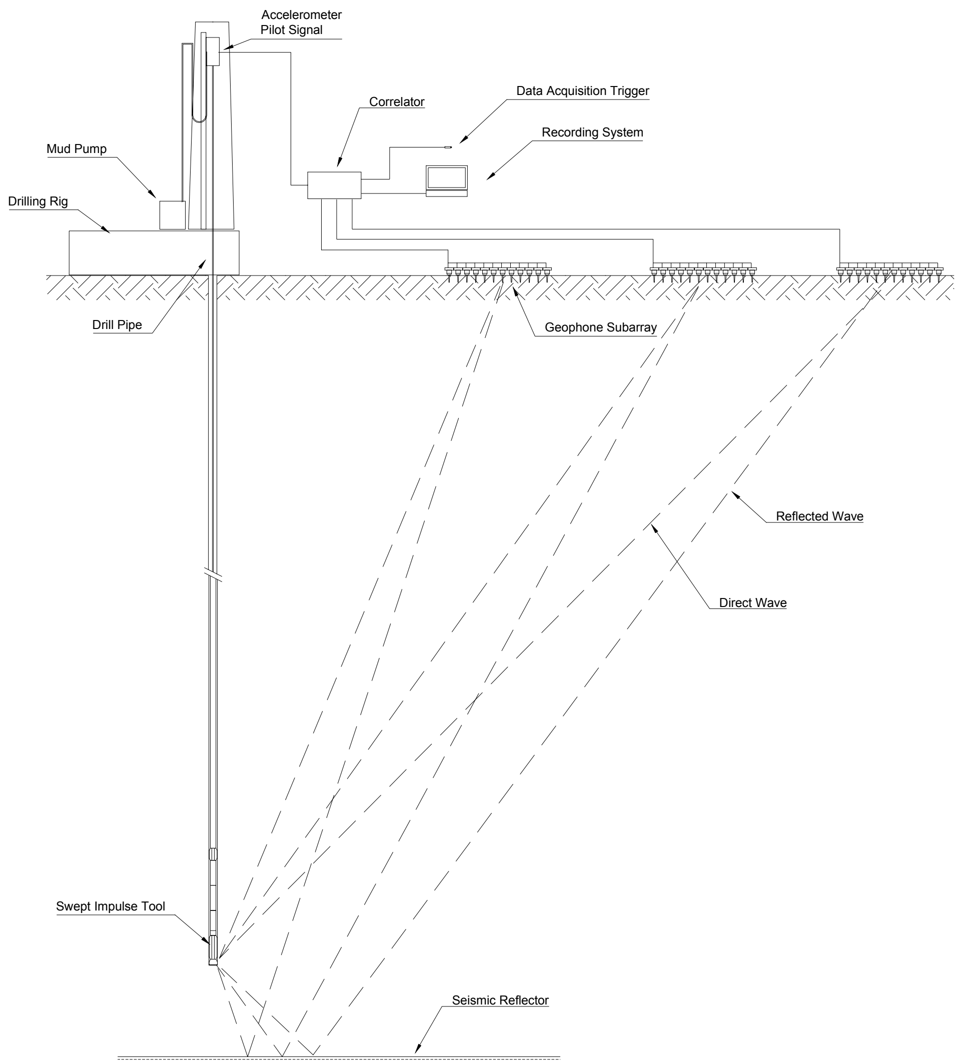

Figure 5. Seismic source and receiver configuration for reverse vertical seismic profiling rVSP), and look-ahead seismic imaging while drilling (SWD).

[5] Park et al. (1996) "Swept impact seismic technique (SIST)," *Geophysics,* **61**(6), pp. 1789-1803.

BETA Test Summary

The general configuration of the BHA used for BETA testing is shown in Figure 6. The BHA composition is listed in Table 2.

Table 2. BHA composition

Name	OD, inch	ID, inch	Length, ft	Total, ft
HC406 PDC bit (IADC M333) or HX20 roller cone bit (IADC 517)	8.5		0.88	0.88
HydroSeis™ or HydroPulse™	8.3		3.34'	4.22
Crossover	6.5	2.81	1.59'	5.81
Stop sub	6.81	2.25	2.35	8.16
Copilot	7.25	2.25	5.45	13.61
Battery sub	7.31	1.88	10.98	24.59
Stop sub	7	2.25	1.55	26.14
PBL bypass sub	6.5	2.63	7.24	33.38
Stabilizer – 8.44" OD,	8.44	2.38	5.96	39.34
Drill collars .	6.5	2.81	615	654
Drill pipe	4.5	3.83	to surface	

The Copilot tool provided measurement-while-drilling (MWD) of BHA acceleration, loads and pressure. The tool was used to record data throughout the testing.

The bypass sub includes a ball drop mechanism that opens a valve to allow circulation in the event that the HydroPulse™ tool fails in the closed position. A stabilizer was located on top of the BHA. The stabilizer was included to backream filtercake during trips out of the hole.

The HydroSeis™ tool configuration was tested with the HC406 PDC bit (IADC M333). The bit was operated with six 11/32" nozzles for a total flow area of 0.60 in^2. The HydroPulse™ tool was tested with both the HC406 PDC bit and the HX20 roller cone bit (IADC 517) with three 16/32" nozzles- total flow area = 0.59 in^2 (0.00038 m^2). All drilling was carried out using 9.3 ppg bentonite gel/barite mud (PV 11 to 15, YP 12 to17).

A summary of test runs is provided in Table 3. A well trajectory showing deviation to the northeast at an inclination of around 40 degrees from vertical is shown in Figure 7.

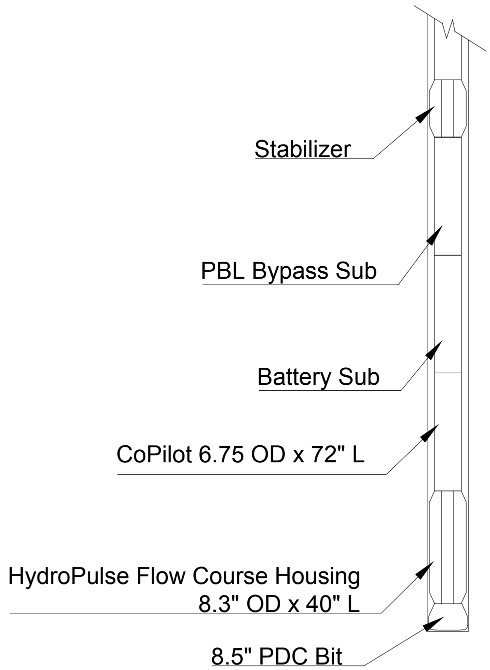

Figure 6. BHA used for BETA testing

Table 3. Summary of BETA test runs of HydroPulse™ (HP) and HydroSeis™ (HS) tools .

Test	Measured Depth In, feet	Interval, feet	TVD In, feet	Drilling Time, hr	Bit	Tool	Comment
1	2214	35	2020	2:29	PDC	HS	Seismic-while-drilling Erratic tool cycle rate
2	2246	168	2045	5:36	PDC	HP	HydroPulse™ Drilling
3	2414	52	2178	1:58	PDC	HS	Seismic-while-drilling
4	2466	22	2210	0:28	PDC	No	PDC Baseline stick-slip test 2 stalls
5	2488	77	2238	1:57	PDC	HP	HydroPulse™ Stick-Slip 2 stalls
6	2565	149	2301	4:40	RC	No	Roller Cone Baseline Bit Bounce
7	2714	101	2425	3:37	RC	HP	HydroPulse™ Bit Bounce
8	2815	15	2511	3:13	PDC	HS	Seismic-while-drilling
9	2830	184	2524	2:36	PDC	HP	PDM motor run

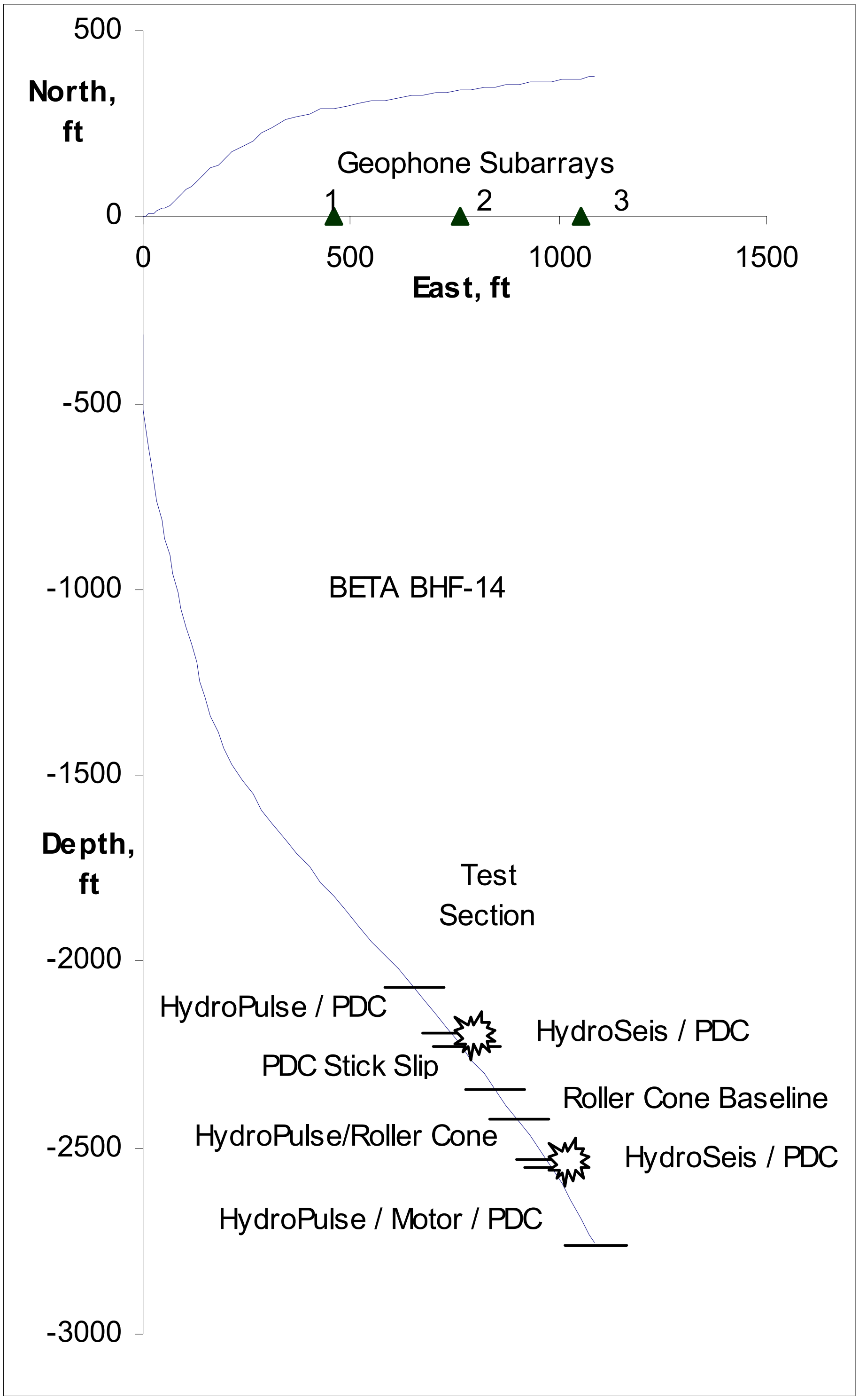

Figure 7. BETA test well trajectory, test sections and geophone layout.

Pulse Characteristics

The seismic signal generated by the HydroSeis™ is a swept impulsive suction pulse that is localized around the bit. Details of a raw pulse profile as measured using the CoPilot are shown in Figure 8, both internal pressure and annulus pressure are shown. The suction pulse propagates in the annulus around the BHA and is recorded by the MWD tool as a reduced amplitude impulse. The CoPilot battery sub acts as a flow restriction with a flow area of 14.8 in^2, which is comparable to the flow restriction around the HydroPulse™ tool (11 to13.4 in^2). In comparison the flow area around the drill collars is 23.6 in^2. The annulus pressure pulse has a primary and secondary pulse of lower amplitude. The secondary pulse may reflect the influence of the CoPilot flow restriction. The presence of a second pulse with a delay of 10 ms will introduce a strong 10 Hz component to the source spectrum.

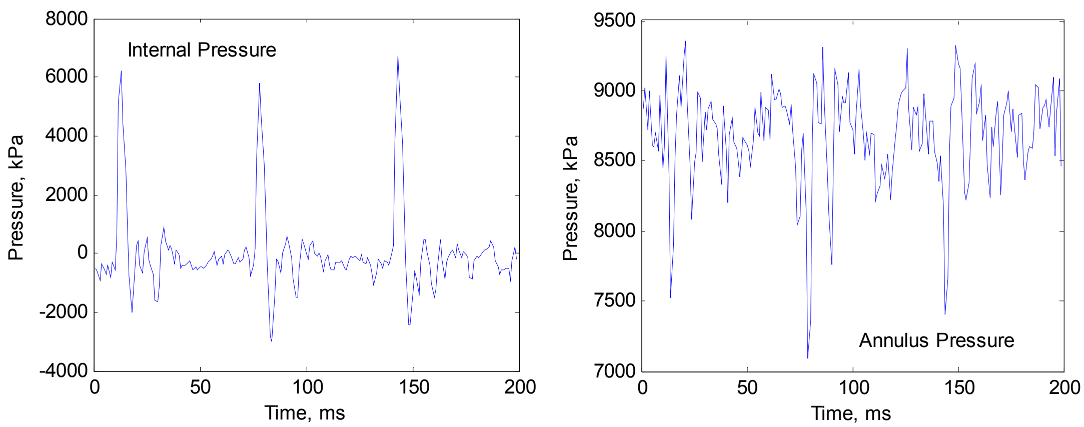

Figure 8. Raw pressure pulse data recorded on BHA at 1 kHz data rate.

The internal pressure pulse signal can be converted to an impulse function consisting of a series of delta functions at the time when the internal pressure crosses a threshold. An example impulse function is shown in Figure 9. Each sweep consists of 60 impulses with a decreasing period between pulses. These pulses correspond to the 60 steps taken by the sweep mechanism.

The impulse function was used to calculate the cycle rate as shown in Figure 10. The cycle rate varies from 11 to 19 Hz and the impulse cycle period sweeps over a period of about 4 seconds. The impulse function spectrum is shown in Figure 11 and Figure 12 along with the power spectra of the other MWD data. The spectrum shows only 35 discrete impulse frequencies in the signal although there are 60 positions of the sweep mechanism. The data shows that the cycle rate at both the low and high end of the range is relatively constant. The impulse spectra is broadband to well over 250 Hz, however the internal pressure is attenuated at high frequencies and the axial acceleration is attenuated at low frequencies.

The impulse function may be cross-correlated with the MWD signal to generate an average pulse profile. This process eliminates flow noise and noise associated with drilling loads. Figure 13 shows average impulse profiles obtained by averaging over the entire 40 second record. When the valve closes a 6 MPa (870 psi) pressure pulse is observed inside the MWD tool. This pulse propagates up the drillstring as a pipe wave. The annular suction pulse amplitude around the MWD tool is 1.5 MPa. A secondary suction pulse with about half the amplitude occurs about 10 ms after the first. The weight on bit variation has an amplitude of 45 kN (10,000 lbf) in phase with the annular pressure. The weight on bit variation is comparable to the applied weight on bit.

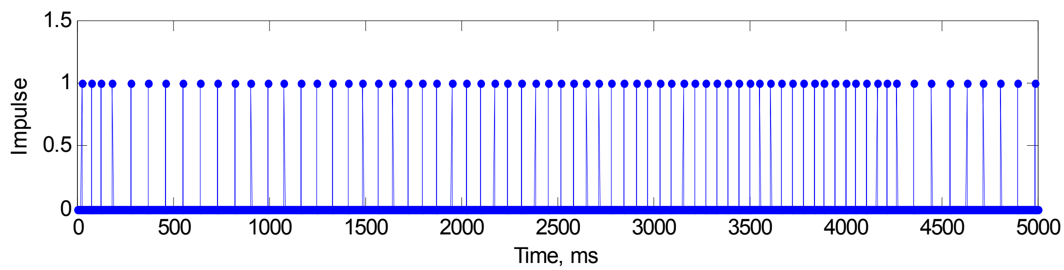

Figure 9. Impulse function showing one full sweep.

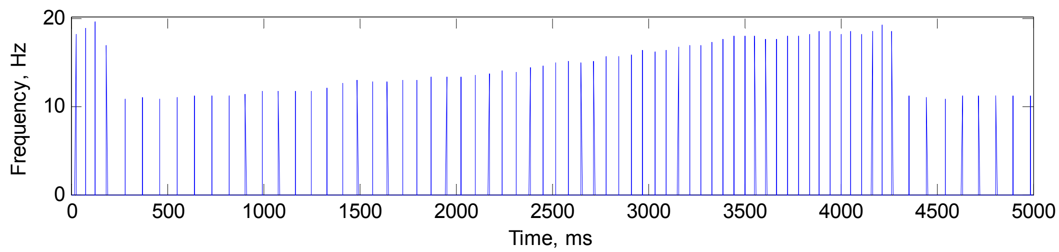

Figure 10. Internal pressure frequency time sample – impulse function times cycle frequency.

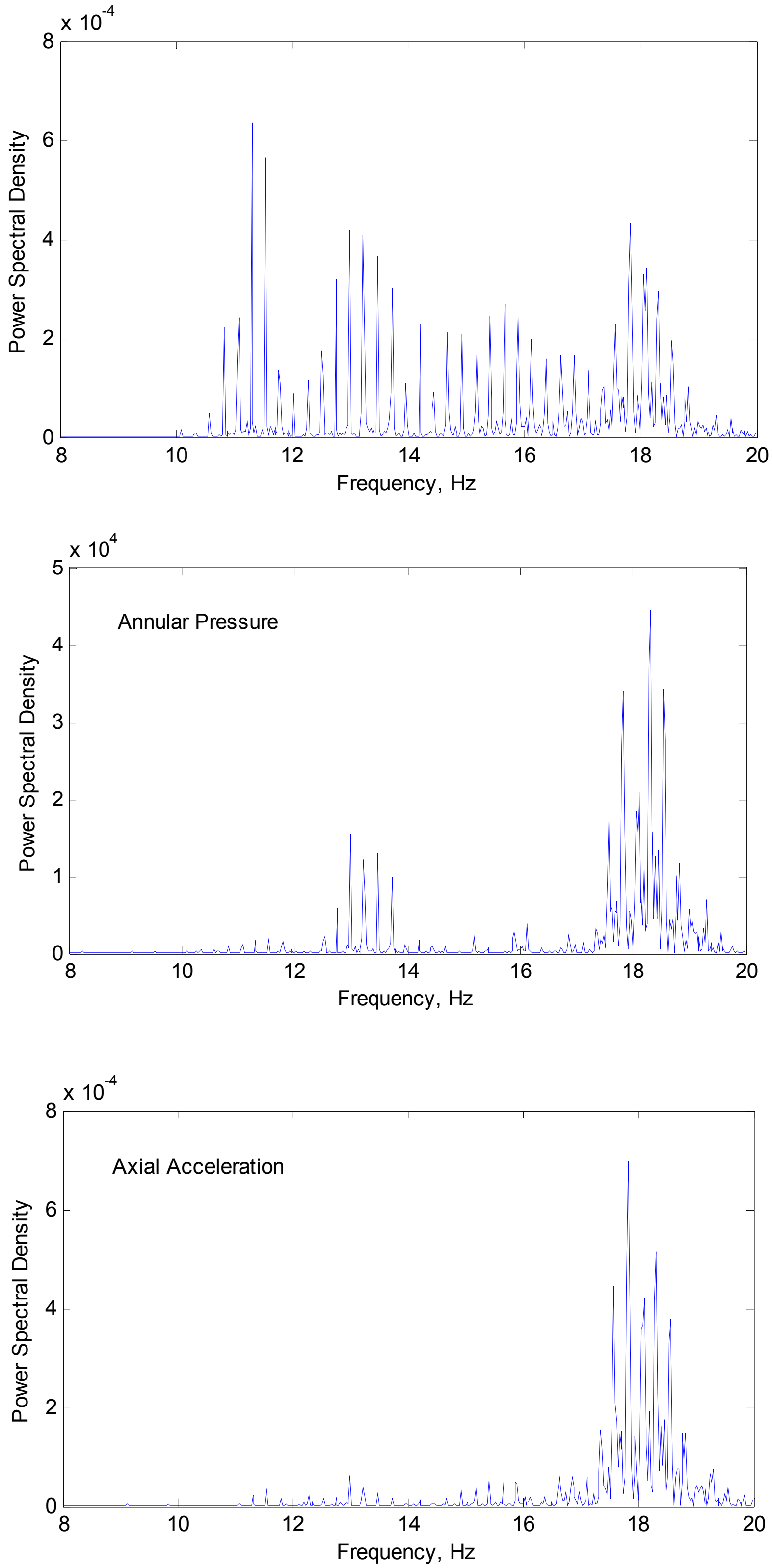

Figure 11. Power spectrum of impulse function from MWD data showing discrete frequencies from 11 to 19 Hz.

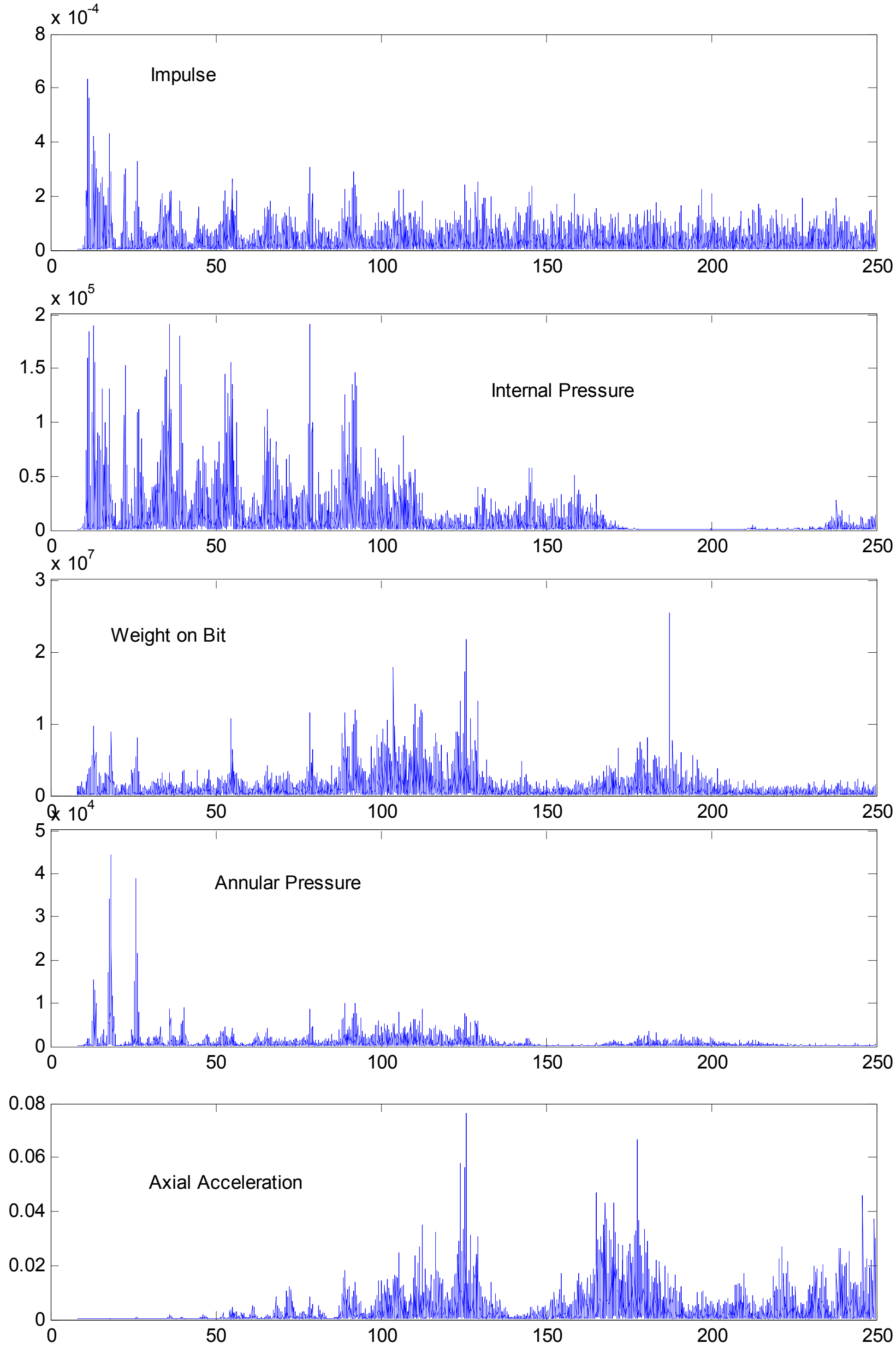

Figure 12. Power spectra of Copilot data showing higher harmonics of impulse signal.

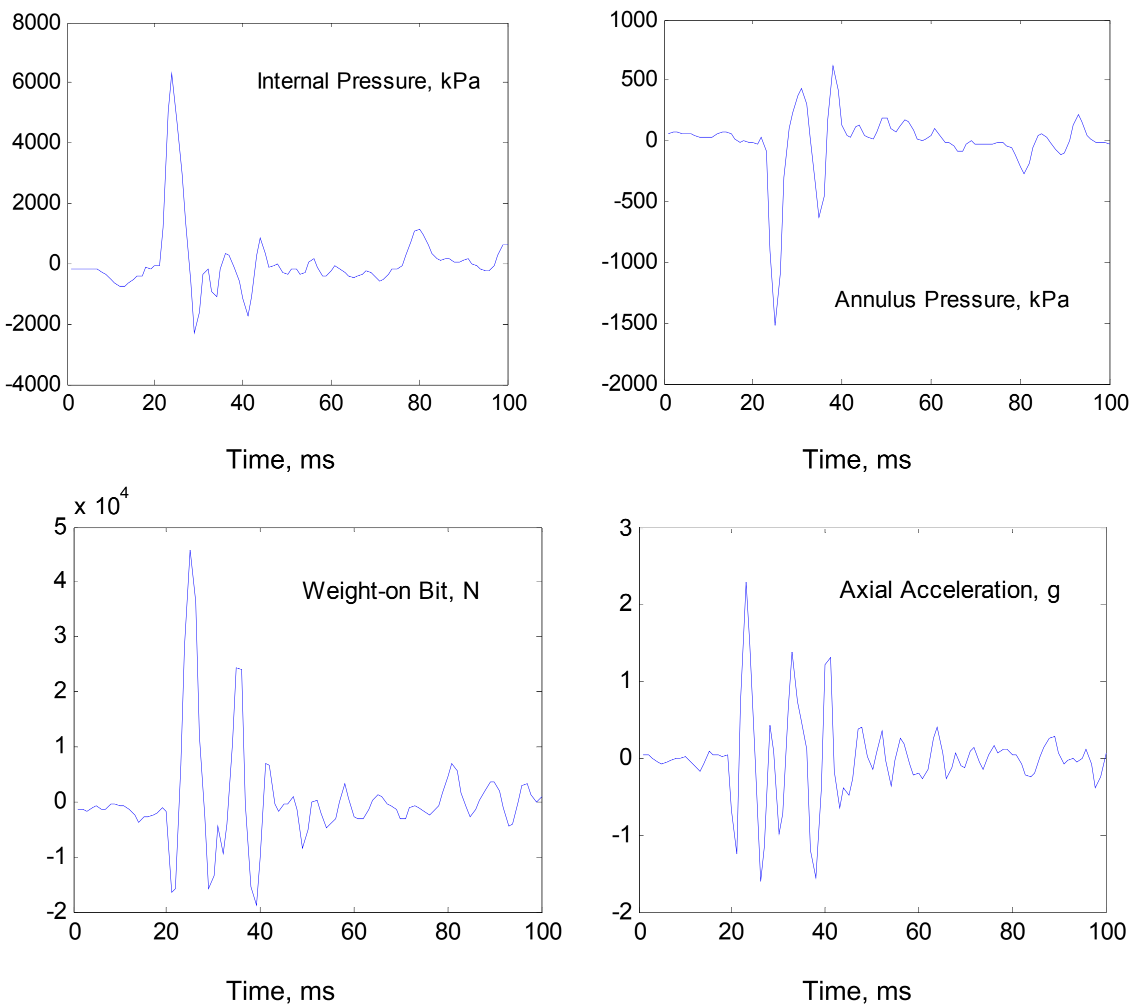

Figure 13. Average pulse profiles obtained by cross-correlation with impulse function, impulse occurs at 20 ms.

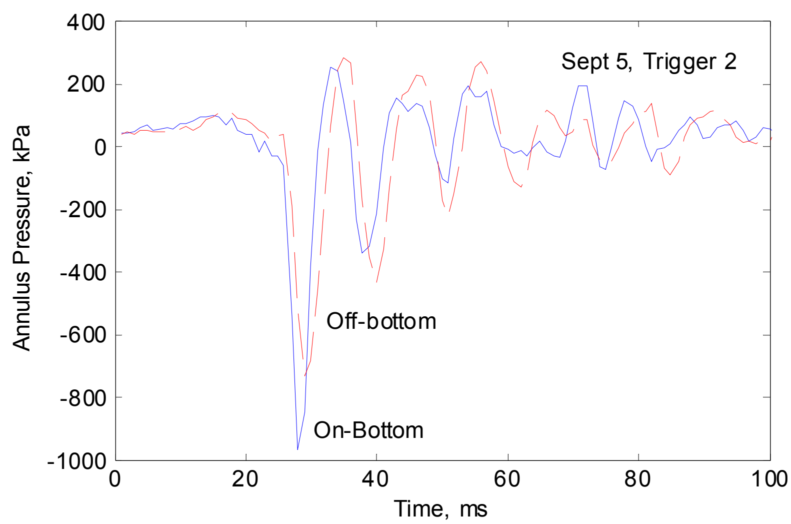

Figure 14. On- and off-bottom annulus pressure.

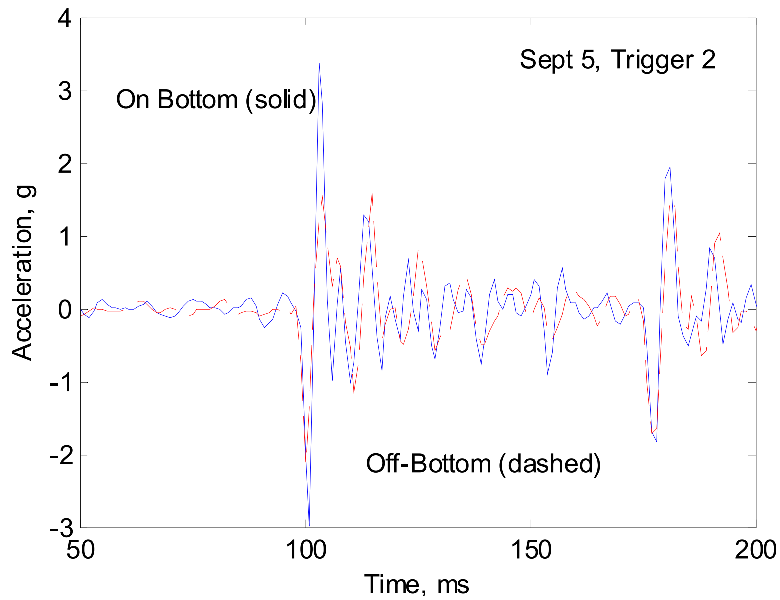

Figure 15. On- and off-bottom axial acceleration. Note drill collar reflection at 80 ms after primary impulse.

Seismic Receiver Configuration

Seismic profiling tests were carried out at BETA as part of the drilling program. The tool was operated while drilling with a PDC bit in a deviated well. The seismic source and receiver configuration for these tests is shown in Figure 7. Three geophone subarrays were located on surface, roughly inline with the deviated well at radial distances of 460', 760' and 1060' from the drill rig.

Two pilot signals were recorded at the wellhead, 1) standpipe mud pressure, 2) topdrive vertical acceleration. Both signals had a DC offset so an AC coupler was devised to allow input to the seismograph. The seismograph is a low impedance instrument and the effect of the AC coupler was to create a high-pass filter with a natural frequency of 8 Hz.

Seismic velocities in the drillpipe and formation are listed in Table 4. Observed velocities are based on seismic profiling while drilling data discussed in subsequent sections of this report. A vertical seismic profile supplied by Baker-Atlas is shown in Figure 16. Intermediate velocities were calculated based on the two-way average travel times from the VSP data.

Table 4 . Seismic velocities at BETA

	Calculated ft/s	Observed, ft/s
Pipe wave, 9.3 ppg mud	4427	4608
Drill collar steel	16,840	17,180
Average P-wave 2200' to 2500'	9400 to 9800	9615 to 10,090
Ground Roll		1500

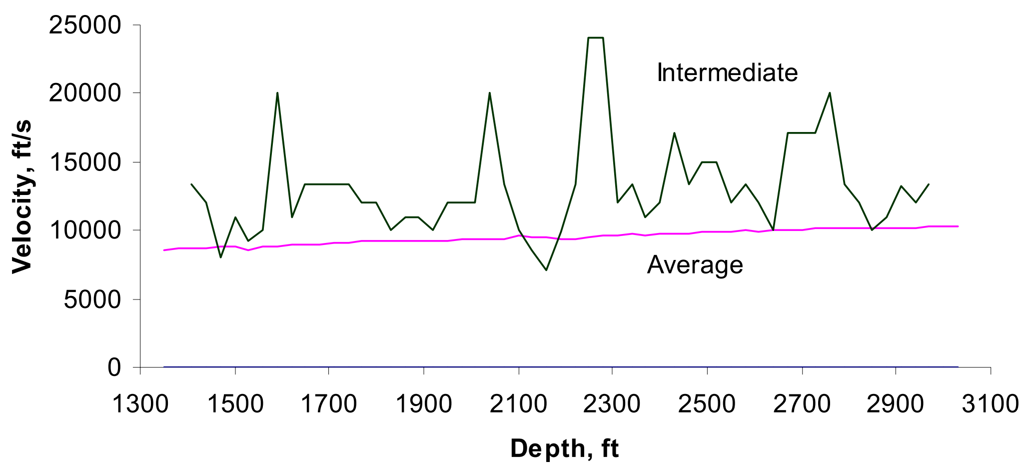

Figure 16. Seismic velocity profile at BETA.

Correlation of MWD with Surface Seismic

As a first step in evaluating the use of the HydroSeis™ tool for seismic profiling, the MWD fast data files were correlated with surface seismic data taken at about same time. The fast MWD files were triggered by raising the tool off-bottom and increasing rotation rate to over 100 rpm. The record length was 85 seconds of 1 kHz data which included 30 to 50 seconds of drilling data and 55 to 35 seconds of off-bottom data. The seismic records were triggered manually anticipating the MWD trigger so the synchronization was imperfect. There were nine fast MWD files obtained in concert with surface seismic. Of these, four were synchronized with the surface seismic enough to obtain cross correlations. In all cases the upstream pressure signal was converted to an impulse function as discussed earlier (see Figure 9). The surface seismic signals were then cross correlated with the impulse function.

Pressure Pilot

Surface seismic cross-correlations with the MWD signal are shown in Figure 17. The pressure signal received at the surface shows a strong impulse. The cross-correlations show clear near-simultaneous P-wave arrivals at the geophone arrays with a ground roll moving across the array. The ground roll interferes with the P-wave arrival at the first array but not at the outer arrays. The impulse correlation reproduces the negative character of the suction pulse. The pressure pilot signal arrives after the surface arrivals consistent with lower velocity of the pipe wave. In this case:

pipe wave travel time 2495/4427 =	564-ms	calculated
travel time difference	330 ± 5-ms	from record
formation travel time	234-ms	
ray length	2250 feet	
P-wave velocity	9615 ft/s	

which is consistent with the velocity obtained from the VSP (Figure 16)

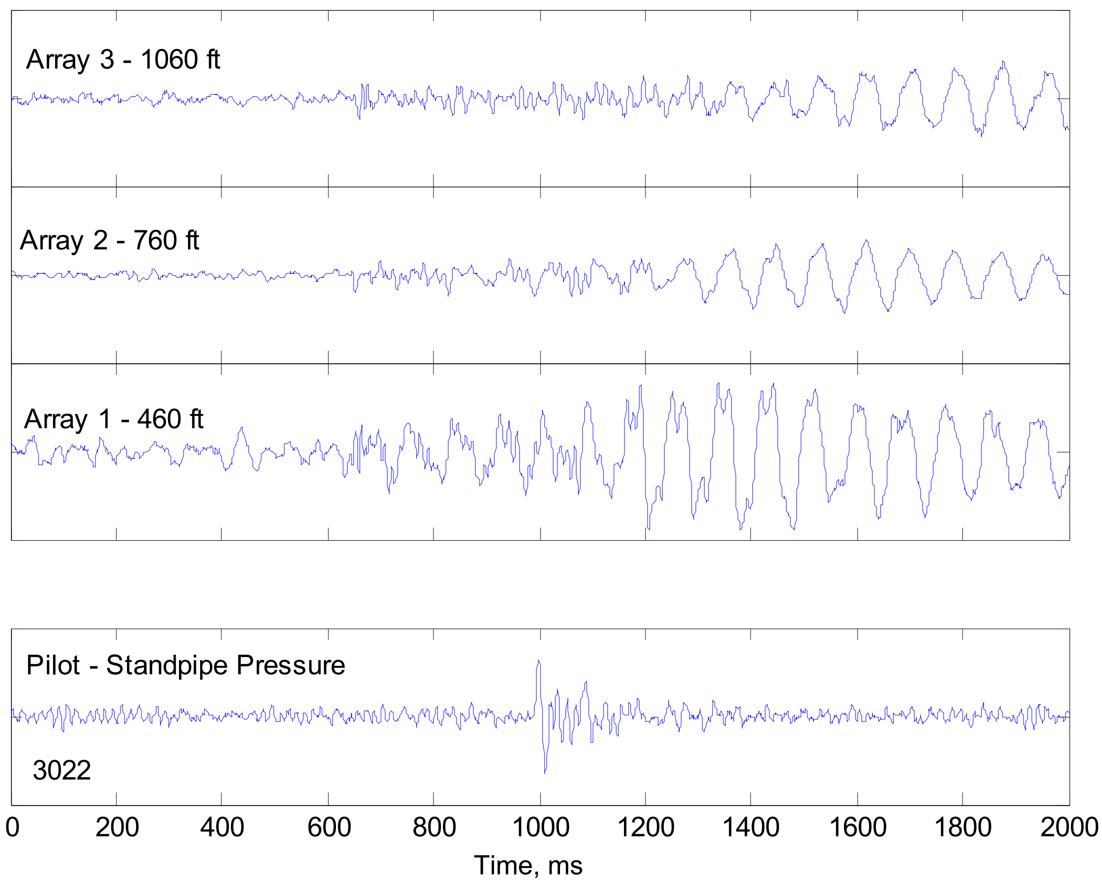

Figure 17. Surface seismic correlation with MWD impulse signal while drilling, Drill string length = 2495', MD=2446, TVD=2204'.

A similar plot obtained at greater depth is shown in Figure 18. In this case:

pipe wave travel time 2871/4427 =	649-ms estimated
travel time difference	405-ms from record
formation travel time	254-ms
ray length	2540 ft
P wave velocity	10,000 ft/s

which is also consistent with the VSP.

The time delay between the P-wave and pipe wave arrivals increases by 65 ms as seen on the record. Again, the signal received at the far array is the strongest. The ground roll wave is very broad and obscures the P-wave signal at the nearest array. The ground roll velocity is 1500 ft/s based on this data. As depth increases the ground roll will become further delayed and less significant in seismic profiling.

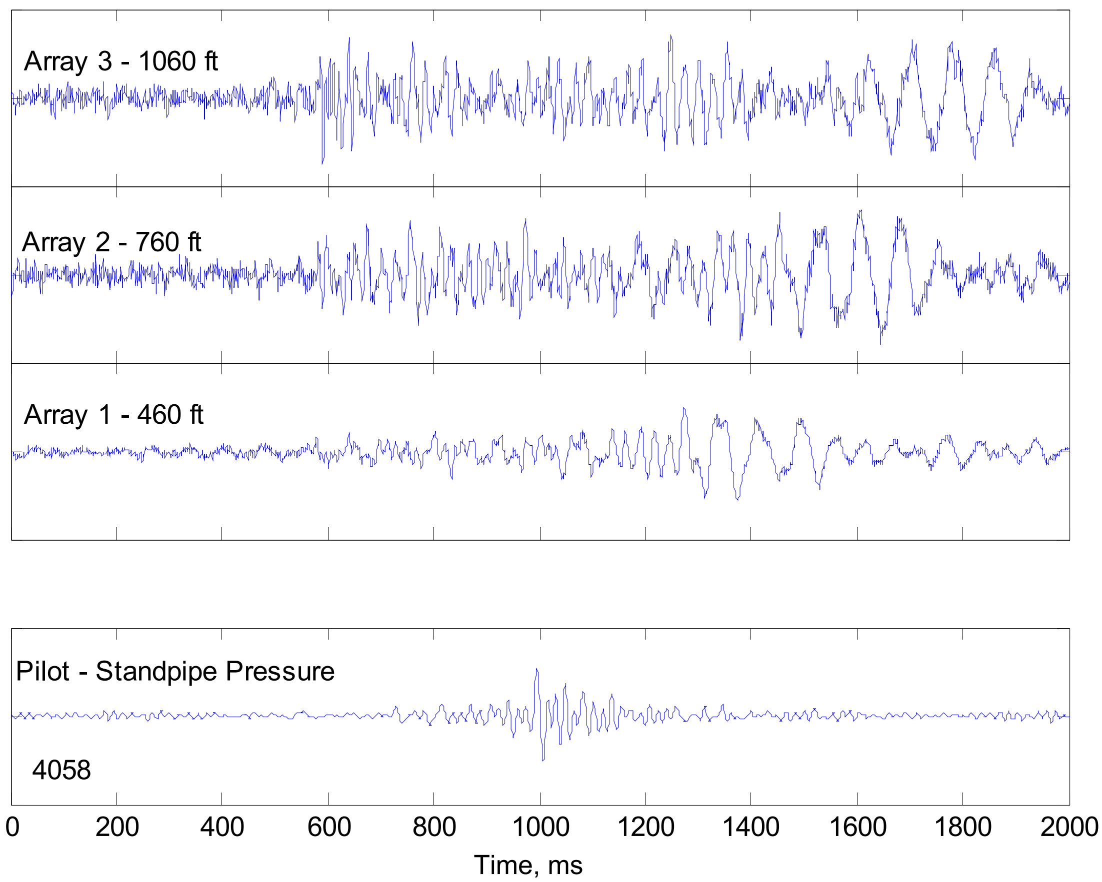

Figure 18. Surface seismic correlation with MWD impulse signal while drilling, Drill string length = 2871', MD=2816, TVD=2512'.

Accelerometer Pilot

Figure 19 shows an MWD correlation with an accelerometer pilot and the geophone subarrays. The accelerometer signal arrives at the same time as the pipe wave signals discussed above. This signal is presumably the motion of the top drive caused by the pipe wave. The acceleration signal is broader than the pressure impulse and less useful for timing. The geophone signals are not as strong as those shown in Figure 18, even though the depth is similar. Data was taken with the bit on bottom and no rotation. With the drillstring stationary, multipath waves coupled from the collars into the borehole may obscure the P-wave arrival. Drillstring rotation may reduce this phenomenon. The ability to take seismic data while drilling is a substantial advantage.

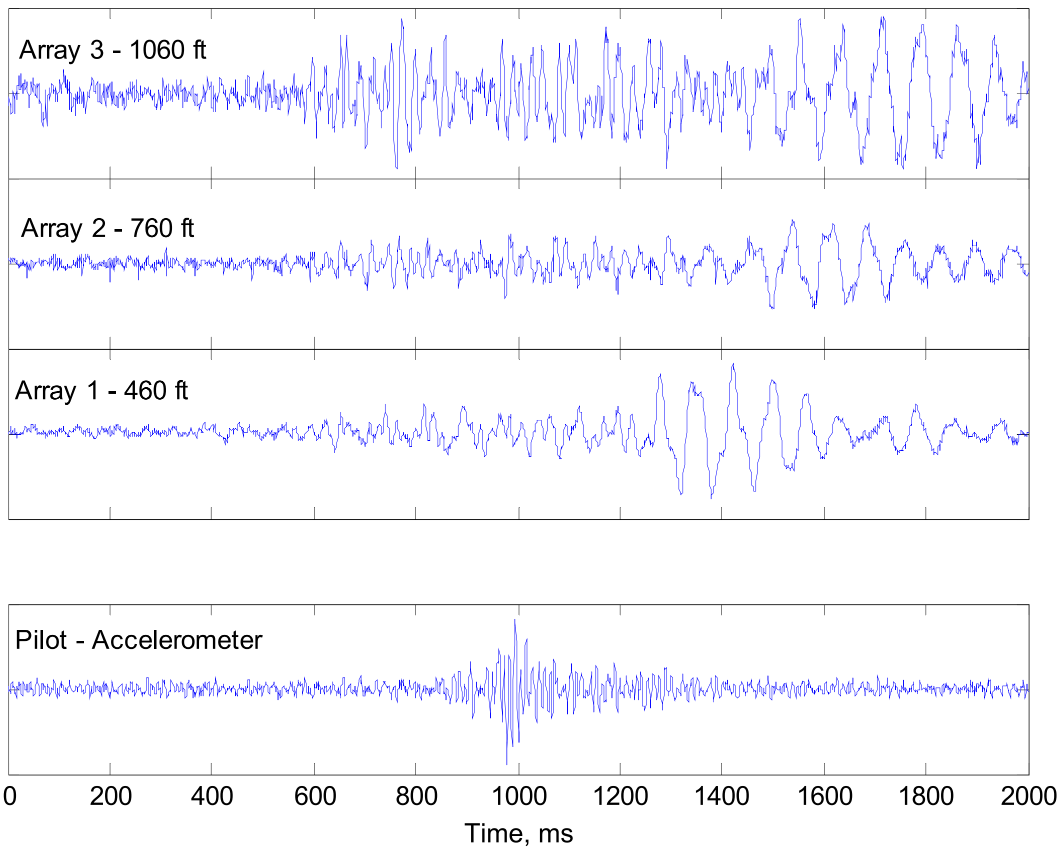

Figure 19. Surface seismic correlation with MWD impulse. On-bottom, no rotation.

MWD Seismic with No Sweep

An example of a seismic correlation without the sweep mechanism is shown in Figure 20. The tool is cycling at a constant rate of 22Hz. The P-wave arrival on the furthest array occurs around 350 ms before the pipe wave but there is a 46 ms ambiguity in the arrival time corresponding to the tool cycle period. This signal could still be used to detect local P-wave velocity since the two signals will shift as depth increases.

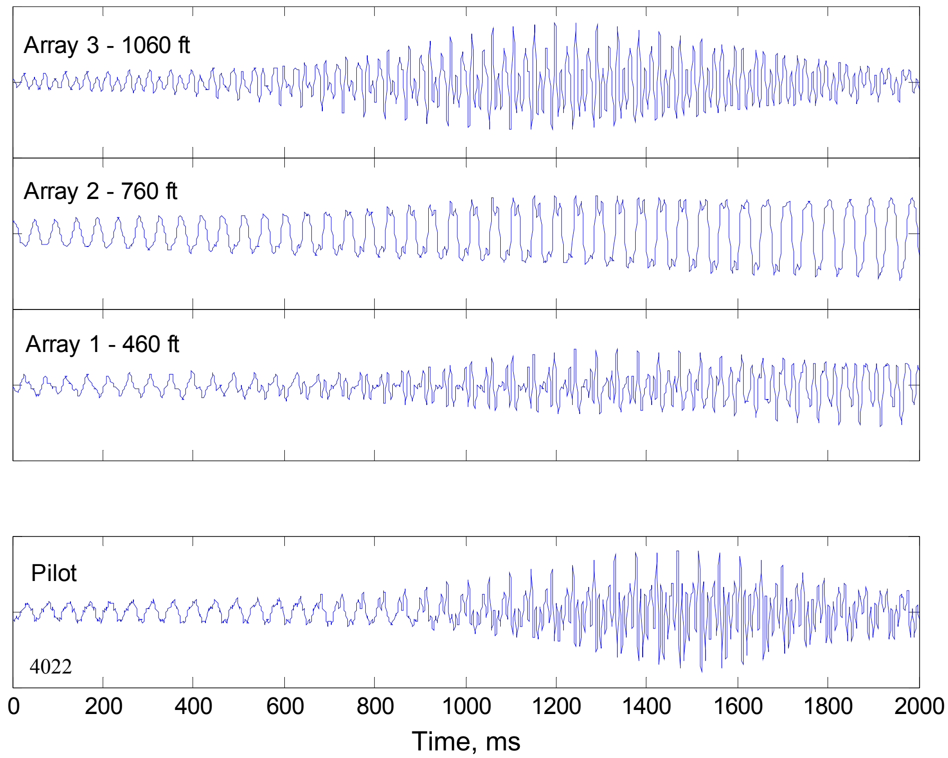

Figure 20. Correlation with MWD system PDC drilling with HydroPulse™ tool, no sweep. , TVD = 2294 .

Surface Seismic Profiling

Seismic records were also generated by correlating the pilot signal received on surface with the geophone records. This requires extraction of the impulse function from the pilot signal. In practice, this was only possible with the standpipe pressure signal. The quality of the signal was further reduced by the AC coupler cutoff frequency. Figure 21 shows an example of the recovered impulse cycle rate function. The tool is cycling from 10 to 20 Hz. A substantial fraction of the pulses are observed. In some cases the apparent cycle rate doubles and in some cases the rate is halved.

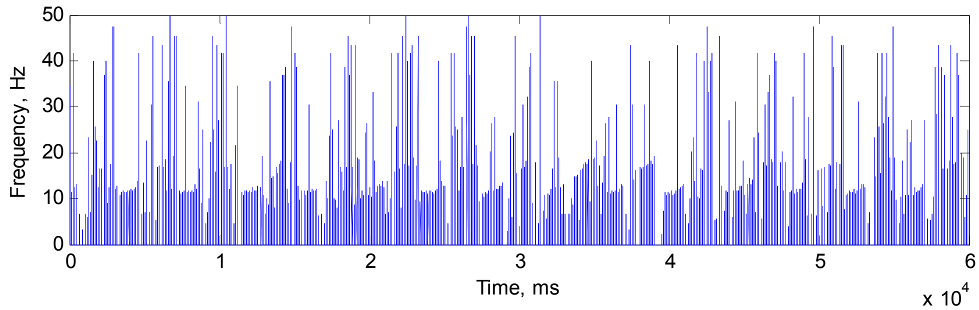

Figure 21. Impulse function times cycle rate recovered from pressure pilot signal. Record 4066.

A seismic-while-drilling record obtained from cross correlation of the pilot impulse function is shown in Figure 22. (This record corresponds to Figure 17) Clear P-wave arrivals are seen on the outer arrays. Corresponding records obtained with the HydroSeis™ 2' and 30' off-bottom are shown in Figure 23 and Figure 24. The P-wave amplitude is lower relative to the ground roll but still apparent.

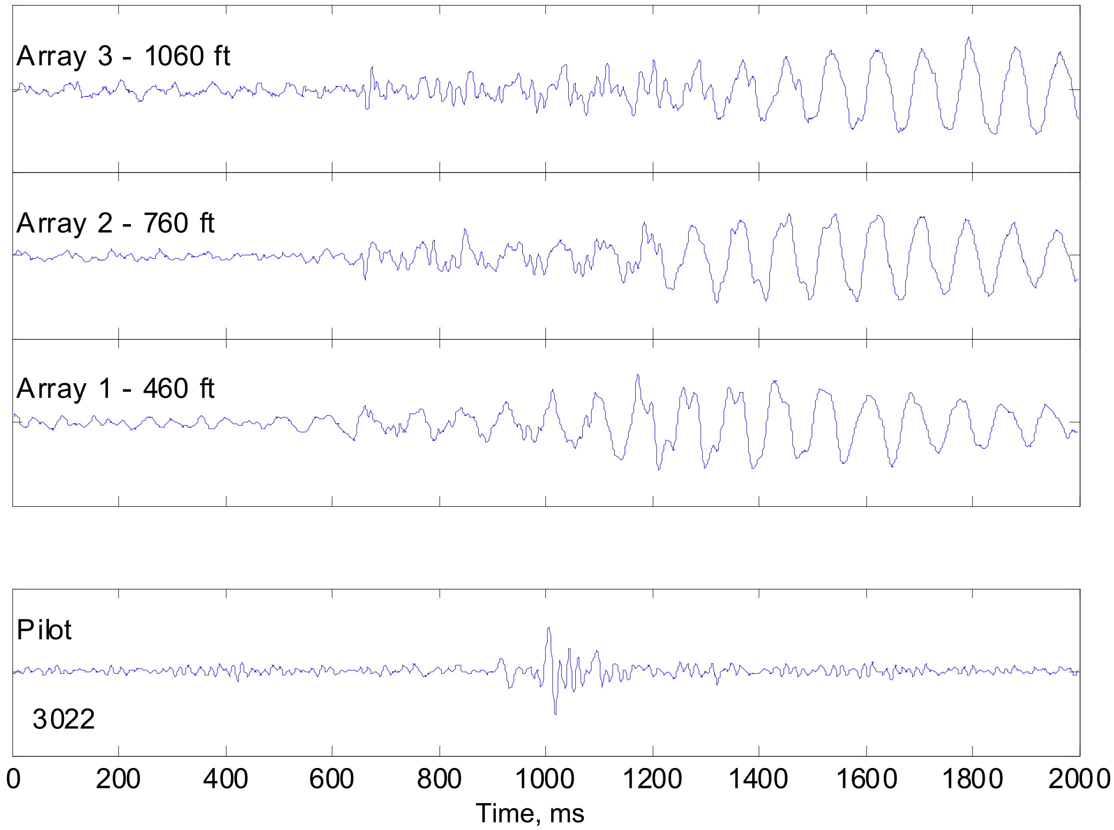

Figure 22. Seismic while drilling example with pressure pilot.

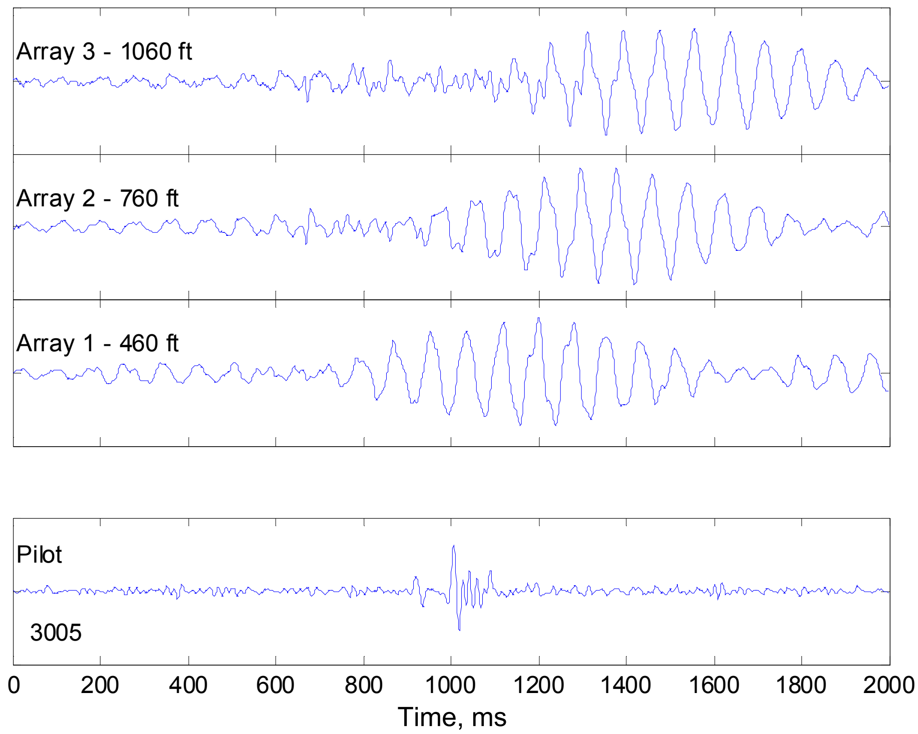

Figure 23. Correlated seismic records – 2' off-bottom, MD=2412'.

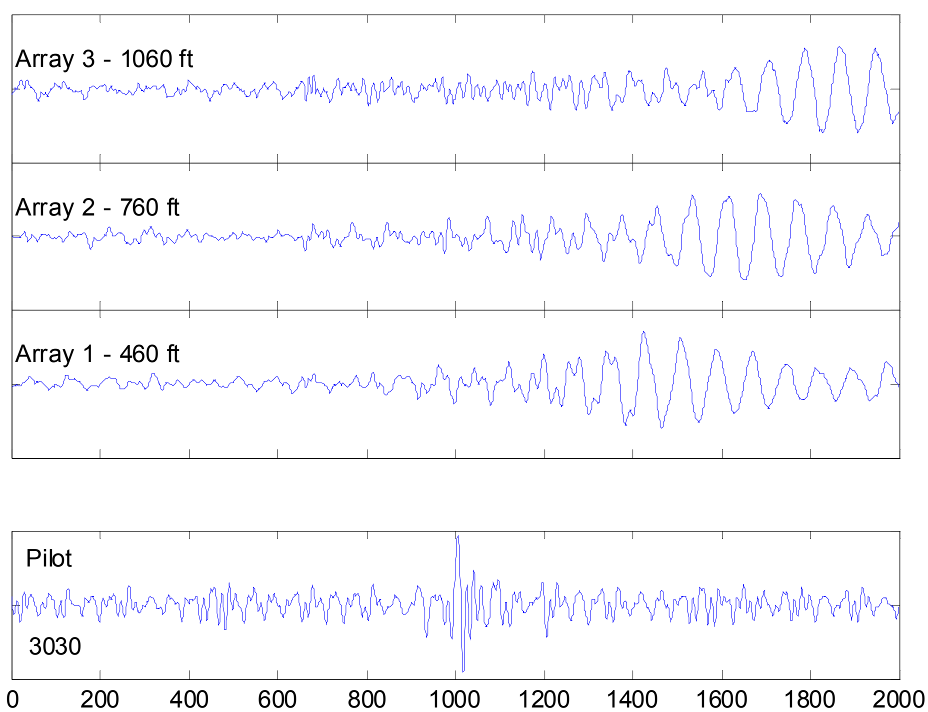

Figure 24. Correlated seismic records 30' off-bottom.

Signal Stacking

The surface seismic data record length was limited to 60 seconds by the seismograph memory. Multiple records may be stacked to enhance signal to noise. Figure 25 shows a stack of three seismic records. The signal is also high-pass filtered at 20 Hz to reduce ground roll. The P-wave arrivals become clearer on all geophone arrays. Since the HydroSeis™ tool operates continuously, signals may be stacked until the tool moves further than the seismic depth resolution. This is a feature of the swept impulse seismic technique in common with Vibroseis methods.

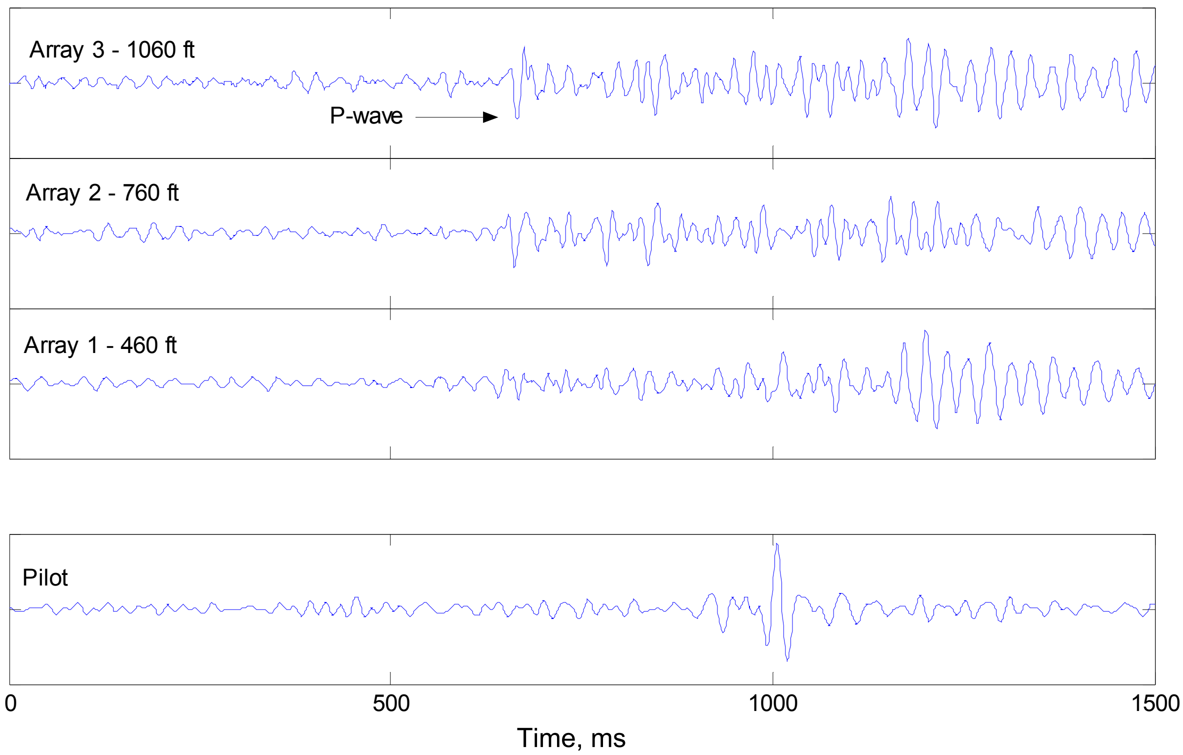

Figure 25. Three stacked correlograms with 20 Hz high-pass filter to reduce ground roll.

Timing Resolution

A detail of a first arrival is shown in Figure 26. The signals received on the two outer arrays are shown. The difference in ray path to these arrays is 15' corresponding to a travel time delay of 1.5 ms, which is clearly seen on the first arrival. A similar detail from three arrivals is shown in Figure 27. Differences in the ray path correspond to arrival time differences of 2 ms or less.

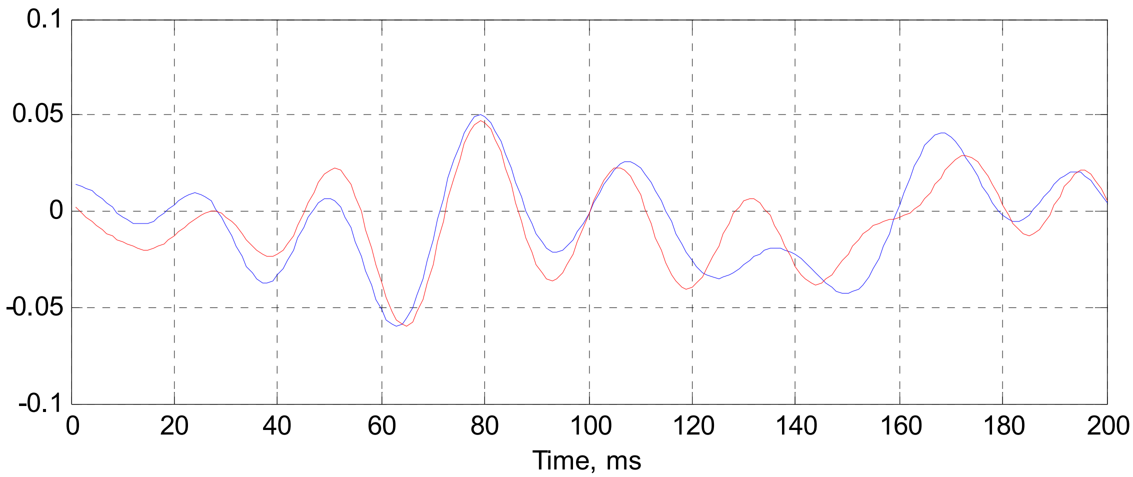

Figure 26. First arrival at 60 ms from array 2 and array 3 with 15' difference in ray length corresponding to 1.5 ms time delay. Stack of three records at 2253' TVD.

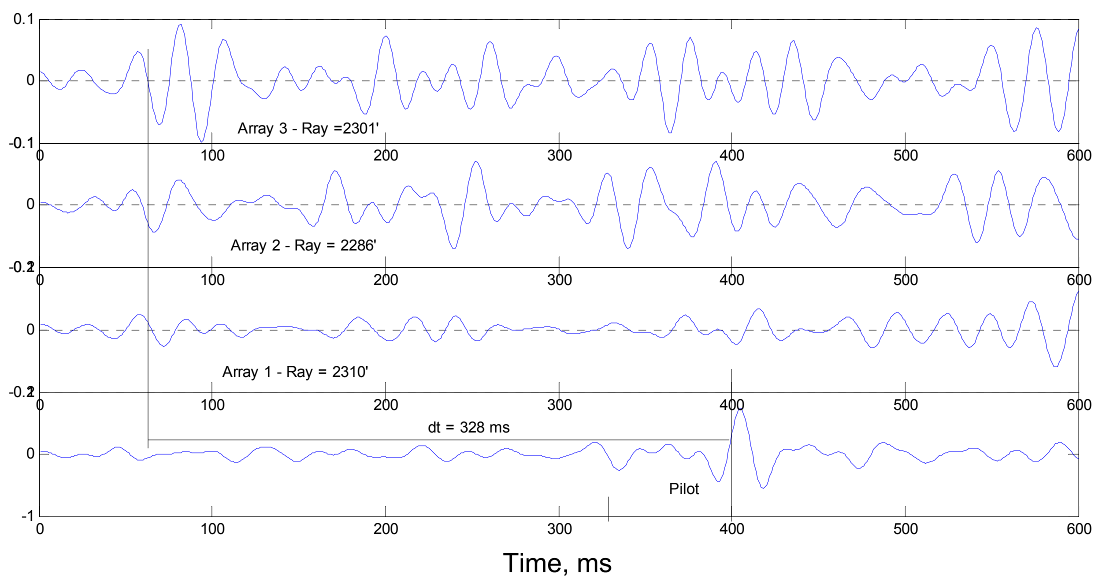

Figure 27. Three arrivals at TVD of 2261' showing resolution of ±1ms.

Look-Ahead Seismic Imaging

A seismogram constructed from three sets of stacked surface data is shown in Figure 28. (The records have been inverted as a consequence of plotting versus depth.) A number of coherent reflections are observed following the first arrival. The reflections correspond to strong reflectors in the formation at 2700' and 3000'. This data represents the first demonstration of look-ahead seismic-while-drilling with a PDC bit. The first arrival of the P-wave varies by about ±5 ms in these records.

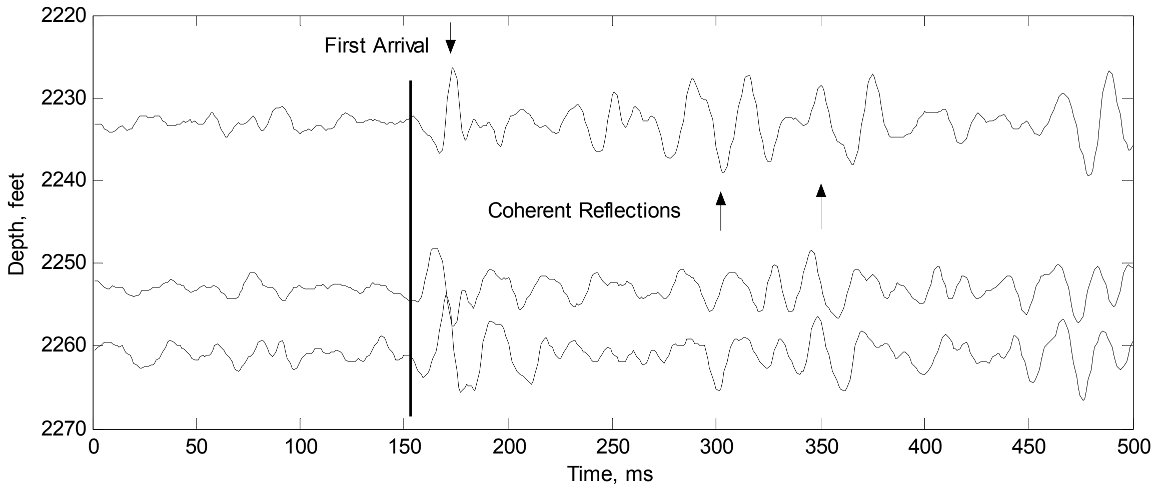

Figure 28. Seismogram from three sets of stacked data array.

Look-Ahead Seismic Imaging with CoPilot

Look-ahead seismic imaging while drilling using the CoPilot as a receiver is illustrated in Figure 29. The WOB and axial acceleration sensors on the CoPilot act as seismic receivers. Processing involves generating an impulse function from the internal pressure signal and cross-correlating this function with the received signals.

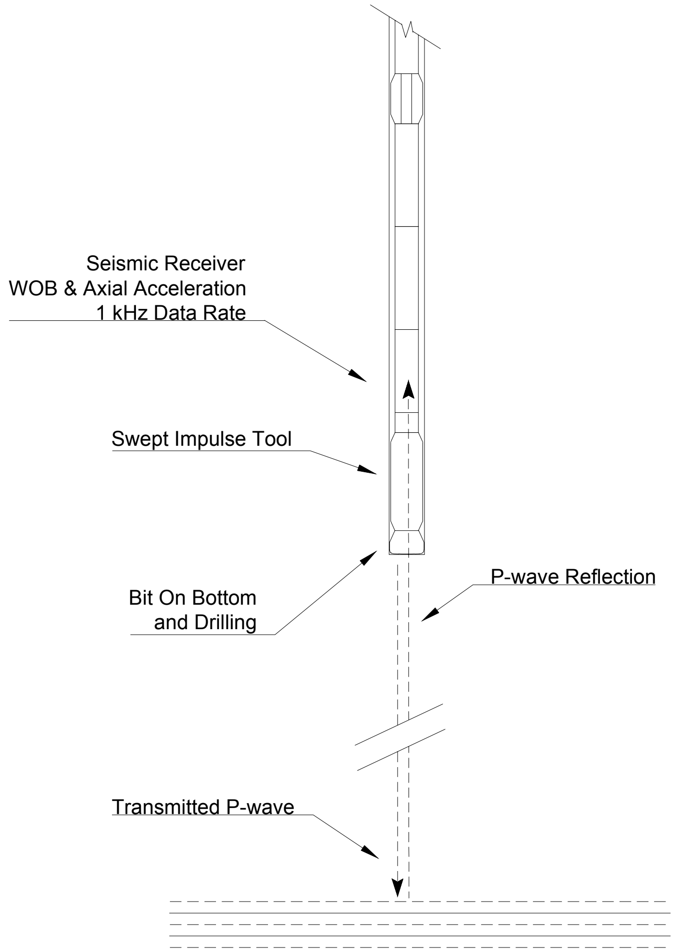

Figure 29. Look-ahead seismic-while drilling using CoPilot as receiver.

The cross-correlated internal pressure signal is shown in Figure 30. The pressure signal shows a strong reflection from the swivel located 2850’ from the source at 1238 ms. The calculated pipe wave velocity is 4608 ft/s overall which is consistent with a calculation of pipe wave velocity (Table 4). The axial accelerometer signal, Figure 31, shows the reflection of a P-wave in the drill collars (670’) at 78 ms corresponding to a velocity of 17,180 ft/s in the pipe, which is also reasonable.

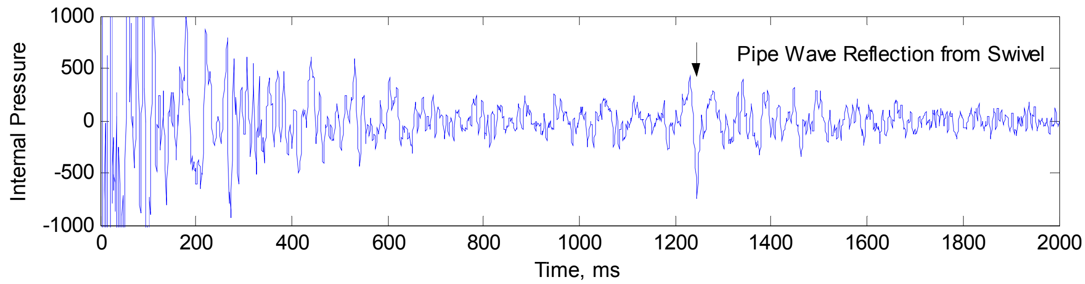

Figure 30. CoPilot data internal pressure correlation - drilling.

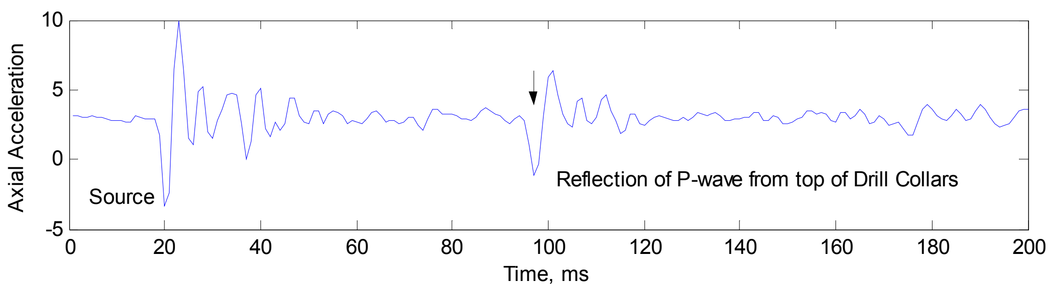

Figure 31. CoPilot axial acceleration cross correlation. Source time = 20 ms.

The effect of the source location on the cross correlation is shown in Figure 32. The drill collar reflection is highly attenuated when the tool is on bottom indicating that the impulsive load is coupled into the formation. The on-bottom plot shows a strong impulse at 1 ms corresponding to the BHA impacting the hole bottom and a reflection 20 ms later, neither of which are seen on the off-bottom signals.

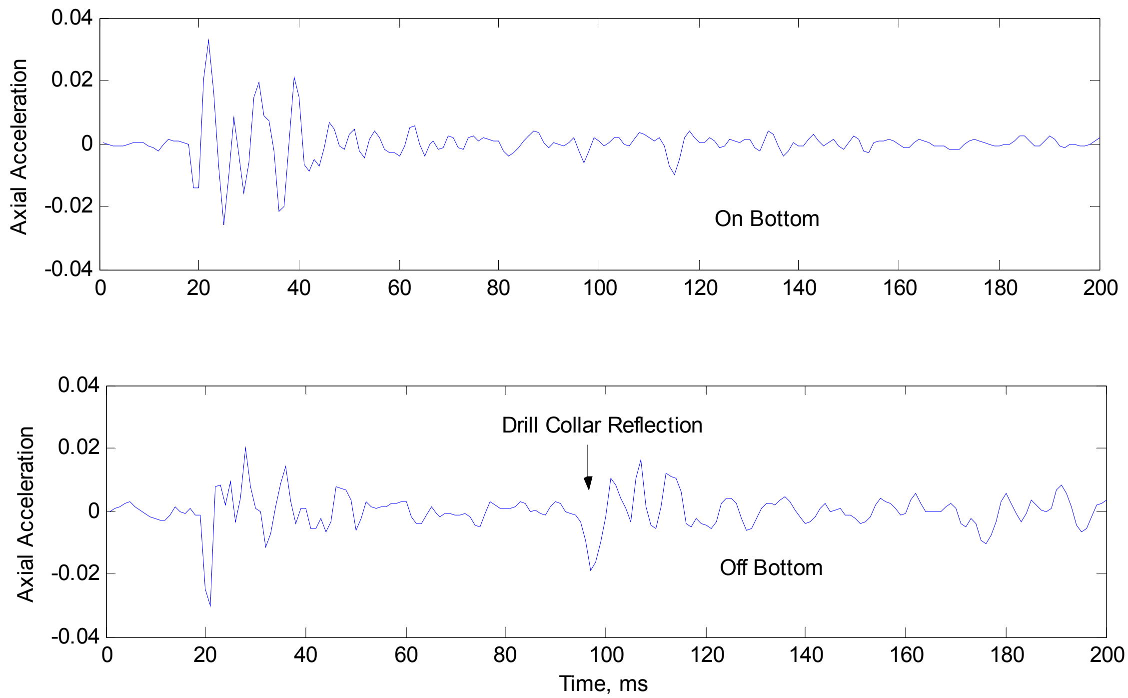

Figure 32. Axial acceleration correlation on- and off-bottom, no rotation. TVD=2522'.

A comparison of on-bottom records with the local formation velocity as determined by VSP is shown in Figure 33. There are suggestions of seismic reflections at 500, 530, 545 and 595 ms, corresponding to strong gradients on the velocity profile. Data obtained while drilling includes a strong reflection from the drill collars. This reflection is attenuated substantially when the tool was run on-bottom without rotation. Two seismograms from the surface seismic correlations are shown in Figure 34 for comparison. The surface seismic has substantially lower resolution but appears to indicate major reflections at similar times – 545 and 595 ms.

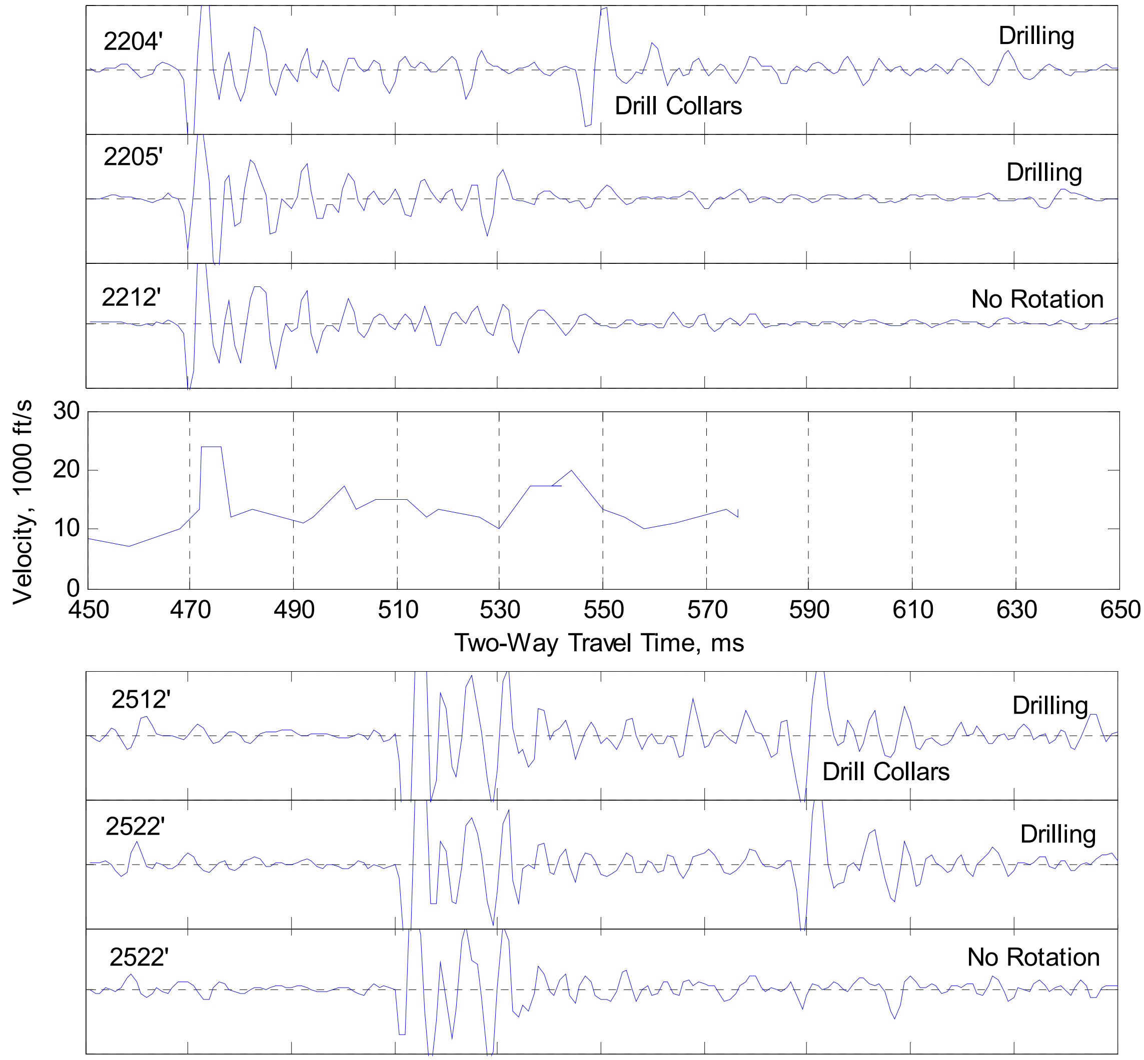

Figure 33. CoPilot axial acceleration correlations. Formation velocity is shown for reference.

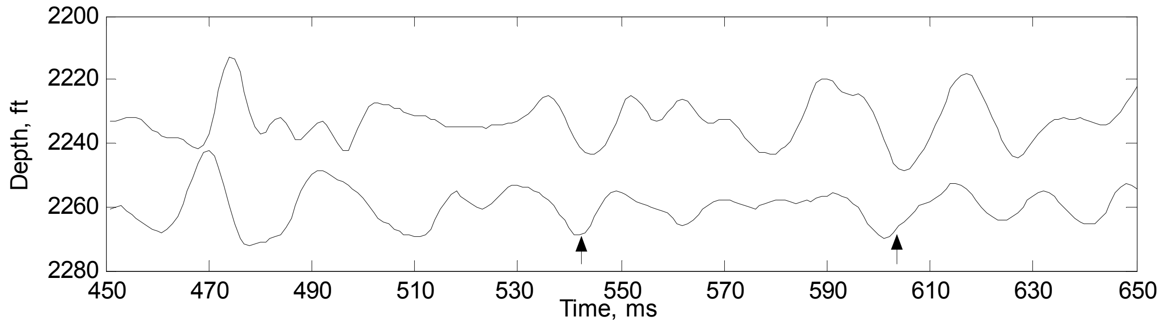

Figure 34. Surface seismic records.

Seismic Radiation Pattern

Figure 35 shows the geophone signal when the tool is on-bottom and slightly off bottom. The source time is set to zero based on the pilot signal and pip-wave travel time. A P-wave first arrival appears at around 200 ms in both traces. A shear wave arrival is expected when the tool is drilling but not when off bottom. If the shear wave velocilty is half theP-wave velocity the shear wave arrival should appear at 400 ms. The on-bottom signal shows an apparent arrival at this time while the off-bottom signal is relatively quiet.

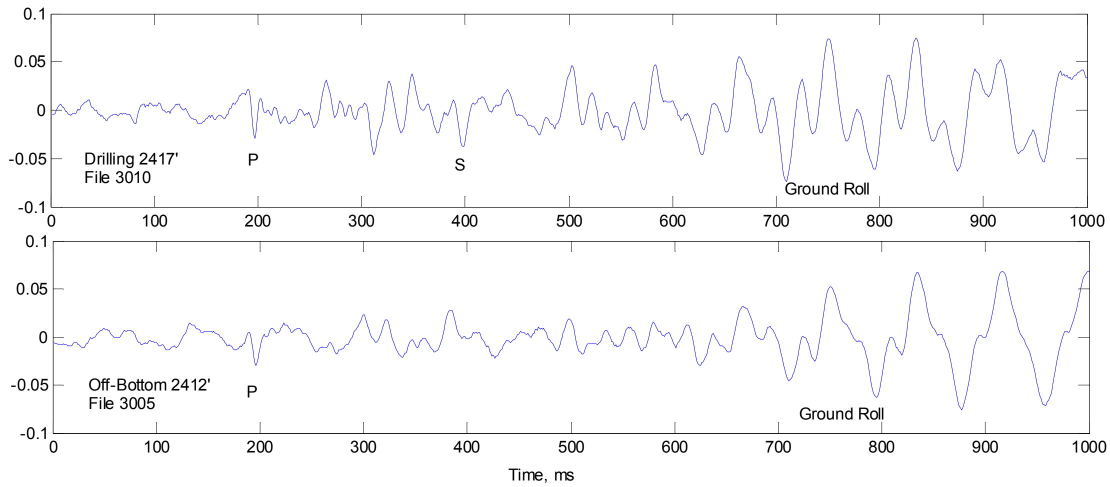

Figure 35. Geophone signals tool on-bottom and 2' off bottom. Source origin is at t=0 ms.

Conclusions

The seismic data collected during this test represent the first instance of seismic-while drilling with a PDC bit and the first in an inclined well with a drill bit source. The HydroSeis™ generates a strong impulsive signal that can be used for high resolution reverse vertical seismic profiling while drilling. The source generated 35 discrete cycle rates as opposed to the 60 possible positions of the sweep mechanism. This caused the tool to cycle at a constant rate at the beginning and end of the sweep. Modifications to the sweep mechanism can increase the number of cycle frequencies to improve bandwidth.

Near simultaneous arrivals were observed at all three arrays indicating P-wave transmission through the earth. Velocity estimates obtained from the first arrivals are consistent with velocity estimates from a previous VSP survey of the site. The VSP first arrival timing resolution ± 1 ms corresponding to a resolution of ± 10 ft in these formations which is well within the project obbjectives. Enhanced resolution can be obtained by stacking records or taking data over longer time periods. The timing accuracy appears to be about ± 5 ms, which appears to be limited by the accuracy of the pressure pilot signal timing.

Useful pilot signals for the surface seismic work were obtained from the standpipe pressure but not the top-drive acceleration. It was not possible to obtain a direct measurement of pipe wave speed, which would be required for accurate profiling. Variations in pipe wave speed due to changes in mud composition and temperature could be responsible for the variation in the apparent pipe-wave velocity. A pipe-mounted accelerometer, such as is used with the Baker-Atlas Tomex system should provide a cleaner pilot signal. Further pilot signal development is needed for accurate profiling.

The first arrival is a downwards pulse consistent with the suction pulse character of the source. The signal is strongest at the array furthest from the rig and at an angle of almost 45 degrees from the inclination of the tool The strong signal is consistent with an impulsive suction pulse that radiates symmetrically from the bit as opposed to drill bit seismic signals, which radiate along the bit axis. The pulse is attenuated as the distance from the bit to the hole bottom increases.

The seismic bservations confirm the seismic radiation pattern of the HydroSeis™ source illustrated in Figure 36. The suction pulse generates a tensile wave in the formation that propagates to the surface as a P-wave. The suction pulse character is confirmed by the downward motion of the first arrival. The pressure wave radiation pattern is confirmed by the improved strength of the signal as the receivers move away from the drill rig. The BETA test site is relatively shallow, which causes the ground roll to arrive just before the P-wave arrivals. In deeper wells, the ground roll delay will be more pronounced and will interfere less with the profiling.

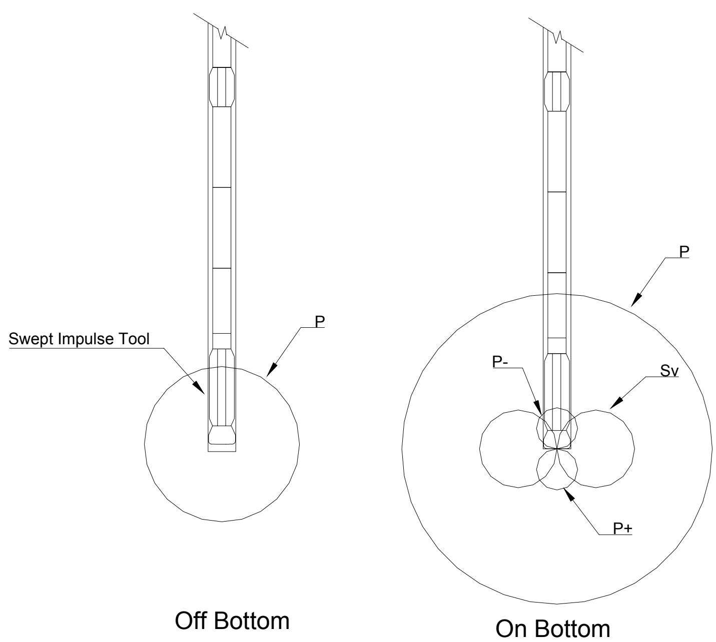

Figure 36. HydroSeis™ seismic radiation characteristics.

The tests showed that a stronger surface seismic signal is obtained while drilling than when on-bottom and not rotating. This may be due to reduced multipath signal transmission from the rotating drillstring to formations above the bit.

Seismic data was also obtained using the CoPilot tool for the pilot signal. Surface seismic correlation with CoPilot signal are consistent with the surface seismic.

The surface seismic signal appears to include reflections from formations up to 1000 feet ahead of the bit. There was not sufficient data collected to confirm moveout of the signals but the signal strength and resolution should be sufficient to allow look-ahead imaging. The CoPilot was also used as a receiver for look-ahead seismic imaging. These results show that the CoPilot couples into formation better when not rotating. The evidence for look-ahead is incomplete but timing resolution of signal is ±1ms based on drill collar reflections. The CoPilot look-ahead and surface seismic look ahead signals are consistent with higher resolution available from the CoPilot data.

Figure 37 shows the HydroSeis™ seismic while drilling system configuration for look-ahead pore-pressure prediction. This is a straightforward adaptation of the *Tomex* and *DBSeis* SWD analysis approach for VSP and reflection imaging ahead of the bit[6]. Ocean-bottom cables containing multi-component geophones and hydrophones are placed in an array on the seafloor to detect direct and reflected arrivals generated by the HydroSeis™ tool. An accelerometer or strain gauge at the top of the drillstring provides a reference signal. The source impulse time reference is obtained by examining the delay and moveout of drillstring multiples in the pilot signal autocorrelation function[7]. A drillstring deconvolution filter is also obtained through prediction error filtering of the pilot signal autocorrelation. To obtain a VSP-like section, the corrected pilot signal is cross-correlated with the geophone signals, and then multichannel filters are applied to attenuate signals radiated by the drill rig and by the drillstring[8]. Alternatively, the pilot signal compensation can be applied after cross-correlation.

Once the VSP section is created, conventional VSP processing[9] can be used to generate a velocity versus depth profile above the current bit position (a real time checkshot survey), and a reflection image ahead and to the side of the drill bit using VSP-CDP mapping and/or VSP migration[10].

VSP and SWD surveys have been successfully used to predict overpressure in many areas through the use of traveltime profiles and reflectivity ahead of the bit. The key requirement for the success of this approach is a drop in the P-wave velocity within the overpressured interval (which frequently occurs). The drop in velocity creates an acoustic impedance contrast and a reflected arrival with a phase reversal. Seismic trace inversion

[6] Meehan, R.J., L.Nutt, N. Dutta and J. Menzies (1998) "Drill bit seismic: a drilling optimization tool," *IADC/SPE 39312*, Society of Petroleum Engineers, Richardson Texas.

[7] Rector, J.W. and Marion, B. P. (1991) "The use of drill-bit energy as a downhole seismic source," *Geophysics*,56,5,628-635.

[8] Rector, J.W. and Hardage, B. A. (1992) Radiation pattern and seismic wave modes generated by a working roller-cone drill bit, *Geophysics*, **57,10**, 1319-1333.

[9] Hardage, B.A. (1985) *Vertical Seismic Profiling, Part A: Principles,* Pergammon Press.

[10] Van der Poel, N. J. and Cassell, B. R. (1989) "Borehole seismic surveys for fault delineation in the Dutch North Sea,"*Geophysics*, **54, 09**, 1091-1100.

can be used to convert the reflectivity profile into an acoustic impedance profile. The HydroSeis™ technique, through its creation of stronger energy above 100 Hz, should enable automated processing and display of overpressure initiation depth.

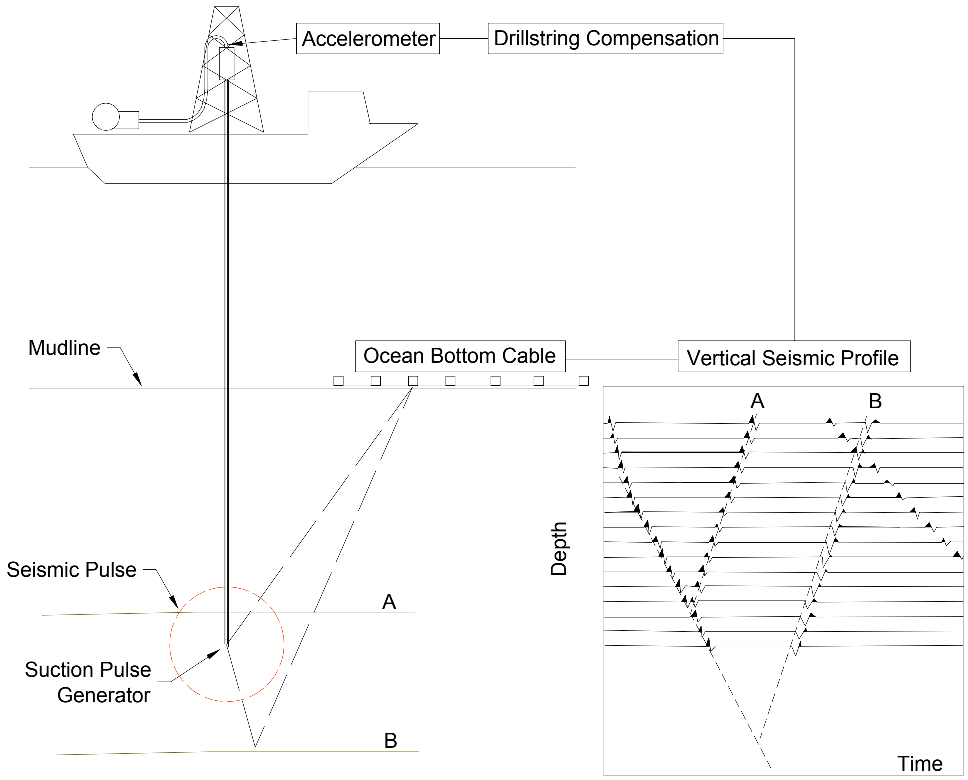

Figure 37. Vertical seismic profiling using the HydroSeis™ source with an ocean bottom geophone cable and drillstring pilot sensor.

Raw VSP data can often be used to identify reflectors ahead of the bit and to indicate range. Upgoing primary reflections (A and B) from horizontal formations ahead of the bit are symmetric in time with the first break The intersection of a line through these reflections with the first break line indicates the depth of the formation. Drops in formation impedance related to high pore pressure would be characterized by a negative reflection coefficient that could be highlighted on a real time display. Further processing including vertical stacking would reduce non-coherent noise and reduce the amplitude of tube waves, cone waves and first break signals to highlight reflections.