# Hydrophone cable acquisition and imaging

Jitendra S. Gulati, Robert R. Stewart, and Brian H. Hoffe


## ABSTRACT

This paper investigates the feasibility of using hydrophone detectors to acquire VSP data. The interest in hydrophones stems from the fact that they offer a rapid and efficient way for acquiring VSP data.

With this objective, CREWES acquired seismic data using hydrophone detectors in a 100m cased and water-filled hole over the Blackfoot field in Alberta, Canada. The data was simultaneously acquired with several 2-D seismic surveys over the field.

Events on raw hydrophone data correlate with corresponding geophone receiver gather. Tube waves are observed to be the primary source of noise on the hydrophone data. They are effectively suppressed using a combination of predictive deconvolution and velocity filters. VSPCDP stacking and migration are then used to obtain the final section from the hydrophone data. Correlation and interpretation of the hydrophone image with those from previously interpreted 2-D and 3-D surface seismic surveys reveal the anomaly associated with the channel structure in the Blackfoot field. In this survey, hydrophones in boreholes resulted in efficient acquisition of VSP data and interpretable images.


## INTRODUCTION

The widespread use of vertical seismic profile (VSP) data in imaging the earth is partially hindered by its cost. Apart from a well being required, the VSP is expensive in its present form also due to the speed at which the data are acquired. VSP data are conventionally acquired using downhole seismic tools containing three-component geophones clamped to the borehole wall. Coupling the geophone to the borehole wall is critical to recording true earth motion (Van Sandt and Levin, 1963; Wuenschel, 1976; Gaiser et. al., 1988; Wuenschel, 1988) and is a complicated and time-consuming process in the borehole. Another factor adding to the acquisition time is that most tools have a maximum of five geophone levels, so the tool is usually moved over the borehole length and shot points repeated to obtain adequate fold and offset coverage per bin location. Recently, Omnes and Clough (1998) demonstrate the implementation of a twelve-level tool which significantly reduced the acquisition time of the VSP surveys they conducted. This is a welcome advance.

A less expensive alternative for the rapid and efficient acquisition of VSP data is the use of multi-level vertical hydrophone array. Hydrophones are pressure sensitive receivers and not required to be clamped to the borehole wall. They are, therefore, easy to deploy in a borehole and a large number of them can be simultaneously used in the borehole. Early experiments using hydrophone detectors in borehole were those conducted by White and Sengbush (1953) and Riggs (1955). Recent experiments to evaluate the capabilities of using a vertical array of hydrophones for VSP on land were carried out by Marzetta et. al. (1988) and Krohn and Chen (1992). Findlay et al. (1991) and Sheline (1998) showed the successful implementation of an offshore crosswell reflection imaging program that used an array of hydrophone receivers. Milligan et. al. (1997) demonstrated the viability of using a vertical hydrophone array in a walkaway VSP to image shallow structures on land. Most authors note that a major impediment to the use of vertical hydrophone array in a borehole has been the presence of strong coherent noise on the VSP data in the form of tube waves. Tube waves are guided waves confined to the borehole fluid and hydrophones are more sensitive to the tube waves compared to properly clamped geophones (Wuenschel, 1988; Krohn and Chen, 1992).

Both field and processing methods to attenuate tube wave noise on VSP data have been investigated by several authors. Riggs (1955) and Gal'perin (1974) observed that moving the surface source away from the borehole significantly reduced the intensity of tube waves. Hardage (1981) made similar observations and also found surface ground roll sweeping across the well head to be the principal source of tube waves. Krohn and Chen (1992) used dipole hydrophones to attenuate tube waves in field. Pham et al. (1993) and Milligan et al. (1997) used closed-cell-foam baffles between hydrophone elements to suppress tube waves in borehole surveys. Velocity filtering has been very effective in isolating tube waves in the processing centre (Hardage, 1981; DiSiena et. al., 1984; Marzetta et. al., 1988; Milligan et. al., 1997). Median and wavelet filtering can also be used to remove tube waves from VSP data (Schuster and Sun, 1993). Marzetta (1992) developed an inverse borehole coupling theory to derive a tube-wave free quantity which he called as “squeeze strain” from data recorded using hydrophones in a borehole.

While these field experiments are very important to the study of vertical hydrophone cable on land, the source-offset range in these surveys was severely limited. The use of hydrophones in VSP surveys depends on the ability to obtain reliable offset sections or seismic volumes of size of current VSP surveys. It was to fill in some of these gaps that the CREWES Project at the University of Calgary acquired a shallow vertical hydrophone cable data on land in November 1997 at the Blackfoot oil field located in Alberta, Canada. The objectives of the hydrophone VSP survey were 1) to compare hydrophone data with nearby three-component geophone records and determine the validity of the raw hydrophone records and 2) to see if the hydrophone cable can be used to obtain reliable stand-alone images. The following sections give details of the Blackfoot survey from the acquisition to the data analysis and interpretation stage.

## FIELD DESCRIPTION AND DATA ACQUISITION

On November 1-2, 1997 the CREWES Project at the University of Calgary with assistance from Boyd PetroSearch Consultants Ltd. and PanCanadian Petroleum Ltd. recorded a high-resolution 3C-2D seismic survey at the PanCanadian-owned Blackfoot field. The Blackfoot field is located some 50-55km east of Calgary in Alberta, Canada (Figure 1). The producing formation within the Blackfoot area is a Lower Cretaceous, cemented glauconitic sand (Wood and Hopkins, 1992).

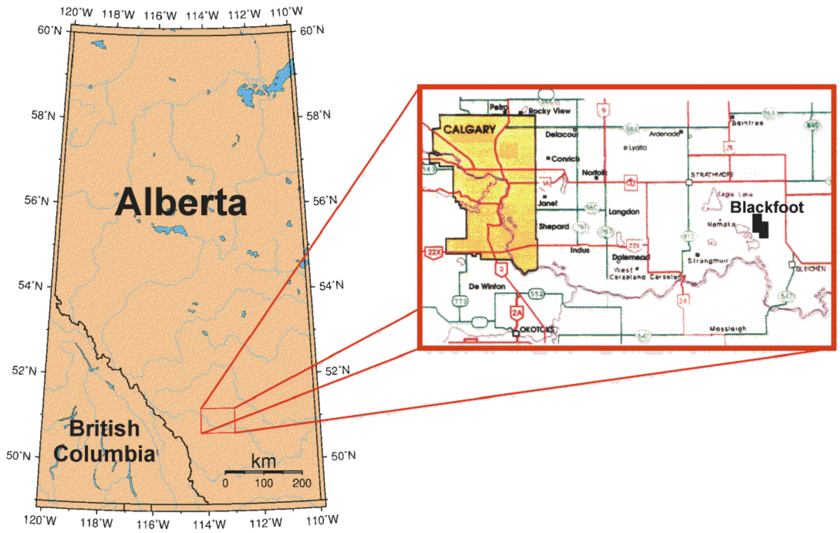



Fig.1. Map showing the location of the PanCanadian Blackfoot field.

The 3C-2D survey (Figure 2) involved the acquisition of a 3km reflection profile which consisted of a combination of “normal-resolution” 20m and “high-resolution” 2m receiver intervals. The shot interval employed for the entire 2D profile was 20m and shot on the half-station. The survey also involved the simultaneous recording into 21×3 buried 3-C geophones situated in 6, 12 and 18m holes drilled every 50m along the central km of the profile. In addition to these buried geophones, a 48-channel vertical hydrophone cable with a 2 m receiver interval was deployed in a 100m cased hole located in the centre of the profile. A walk-away AVO VSP was also recorded in a well located near the centre of the spread at the same time the surface shots were being taken.

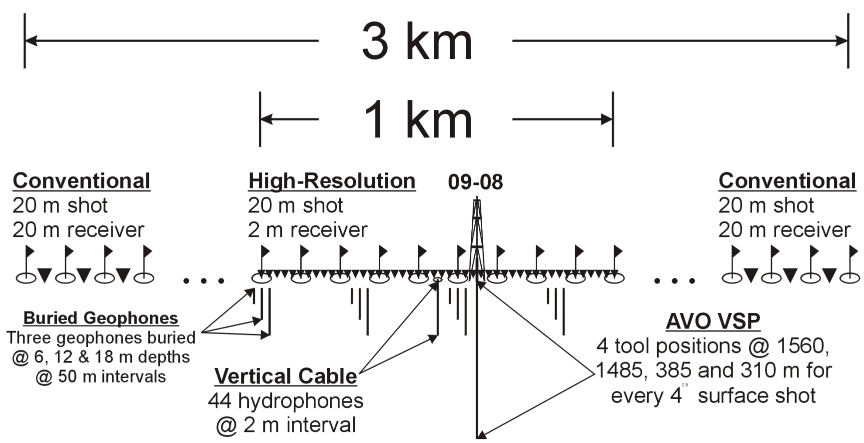



Fig.2. A schematic diagram of the Blackfoot 3C-2D survey (not to scale).

The 48-channel hydrophone cable consisted of Benthos AQ-4 hydrophones at 2m separation with AQ-302 preamps molded into the cable which is terminated by an Amphib-122 connector. Adapter plugs were constructed to tie these channels into the surface recording spread and the preamps were powered via a 12V battery during recording. Acquisition parameters for the hydrophone data were the same as that for the entire survey. Data were recorded with a 6s record length at a sampling rate of 1ms. The preamp gain used for recording was 24dB with low and high cut filters set at 3Hz (12dB slope) and 413Hz (293dB slope) respectively. A total of 151 shot points with each consisting of a 4kg charge size loaded in a single hole at 18m depth were used for the survey.

The objectives and results of the entire survey are discussed in Hoffe et al. (1998). In this paper, results from the hydrophone data are presented.

## VERTICAL HYDROPHONE CABLE DATA VERSUS GEOPHONE DATA

Hydrophones and geophones not only measure different physical quantities but also record data in different physical environments. One is suspended in a fluid medium in a borehole or in a marine environment whereas the other is clamped to a borehole-solid interface or an air-ground interface. Properly clamped geophones are believed to portray the true earth motion. Therefore the use of hydrophones in borehole surveys is justified if it is known that the pressure waveform in the borehole fluid is directly related to the stress waveform in the solid when an elastic wave passes the borehole. White (1953) developed a "borehole coupling" theory which quantified borehole fluid pressure and motion due to the passage of low frequency elastic waves past the hole. He observed that the "formation break" [*White (1953) defines "formation break" as the pressure signal that has the same velocity as of that of the wave cutting the borehole, and which was also called as "squeeze strain" by Marzetta (1992)*] due to a compressional wave was in phase with the disturbance in the surrounding solid. This is true when the velocity of the wave in the solid is larger than that in the borehole fluid. Blair (1984) and Schoenberg (1986) also made similar observations for low frequency or which is the same as long wavelength seismic waves.

The borehole radius in which the vertical hydrophone cable was deployed was around 14cm. Using frequency filter panels, the smallest possible wavelength of the seismic data was calculated to be 20m. The borehole geometry, therefore, satisfied the long wavelength criterion given by Blair (1984) and the hydrophones should represent the earth motion similar to a geophone in the surrounding solid. Thus, in theory, we expect the P-wave signal on the pressure and velocity phones to be in phase assuming similar detector transduction for both phones.

To test the validity of this hypothesis, a hydrophone receiver gather at 18m depth is compared with a three-component geophone gather at the same depth located about 8m away from the hydrophone. Field tests showed that an upcoming compressive stress would record as a negative pulse on the geophone and a pressure increase would record as a positive pulse on the hydrophone. We analyzed the field data considering the above report. The first break refraction arrivals on the geophone and the hydrophone appeared opposite polarity. On reversing the polarity of the hydrophone data, the first break arrivals on the two phones appeared to be in phase with each other. This is in direct agreement with White's borehole coupling theory and increased our confidence about the hydrophone data.

Figures 3-5 show the hydrophone data at 18m depth, the vertical and the inline horizontal component of the geophone at the same depth respectively. One can observe that although the hydrophone is noisy compared to the geophone gather it mimics the refraction and reflection arrivals of the geophone data. The hydrophone data has the character of both the vertical and inline horizontal components of the geophone. This is because the hydrophone is sensitive to pressure generated by both the compressional and shear wavefields. Notice also that reflections on the hydrophone data are more prominent for shots at intermediate-to-far offsets as the ground roll arrives later in time. This conforms well with Hardage's (1981) observation that ground roll is the major source of tube waves.

Figure 6 is a comparison of the amplitude spectrum of the stack of the hydrophone and vertical component geophone gather at 18m depth. The hydrophone is seen to be lower frequency compared to the geophone stack. Also, severe notches on the spectrum of the hydrophone stack are representative of the tube wave interference with body wave reflections on the hydrophone gather.

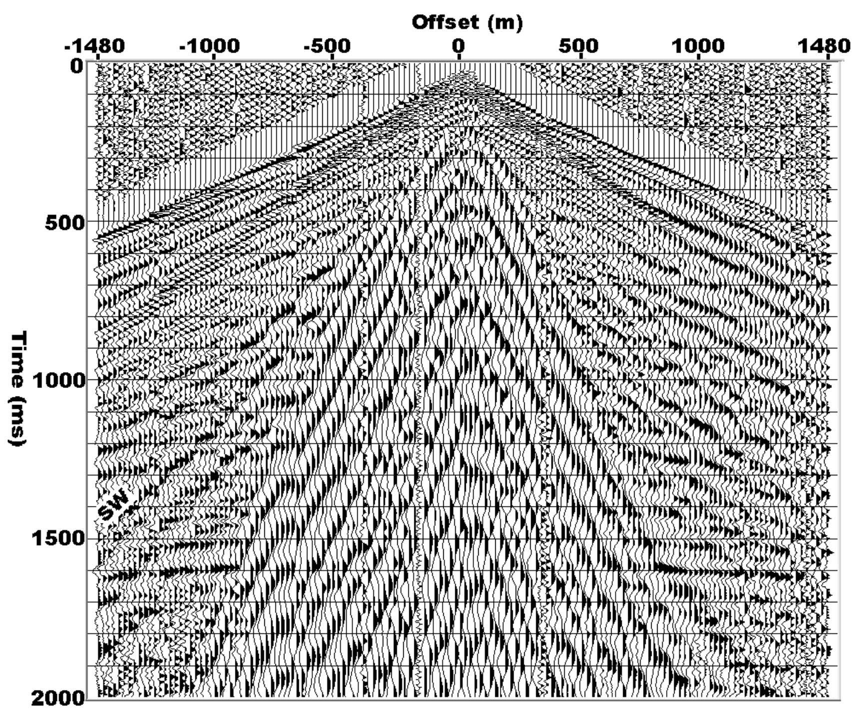



Fig.3. Receiver gather for hydrophone at 18m depth displayed with reversed polarity and 250ms AGC window. SW is the zone of shear-wave refraction arrivals.

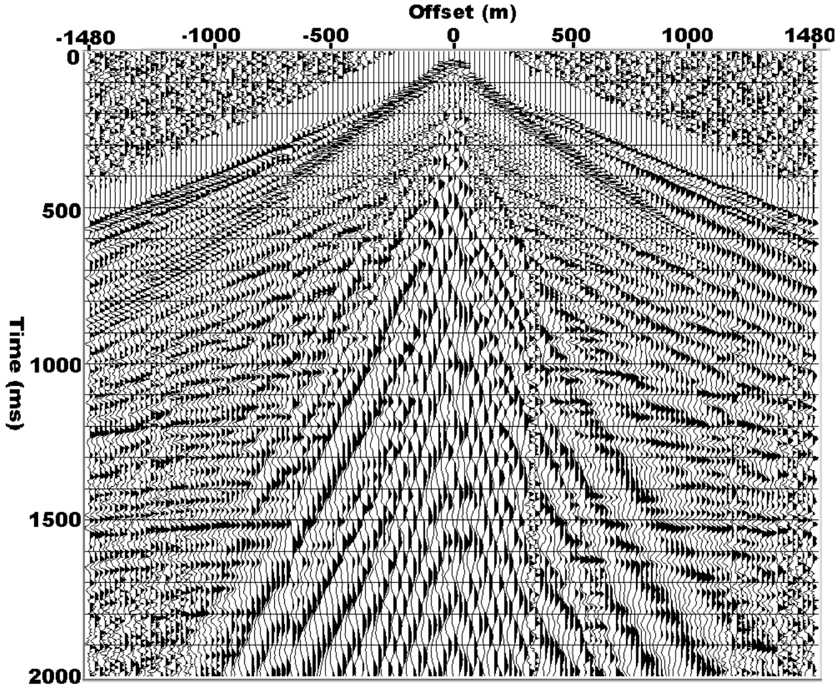



Fig.4. Receiver gather for vertical component geophone at 18m depth displayed with normal polarity and 250ms AGC window.

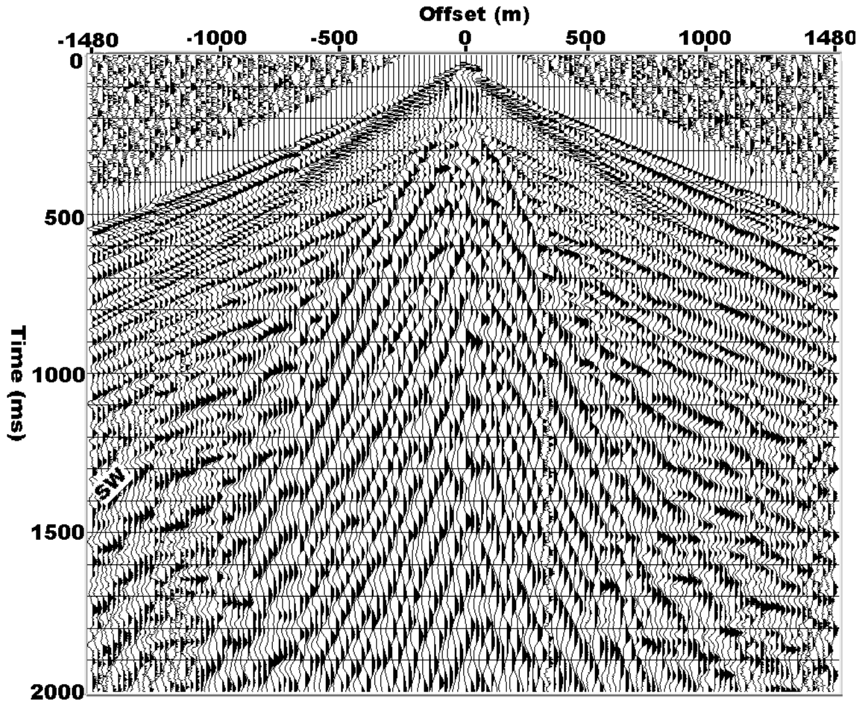
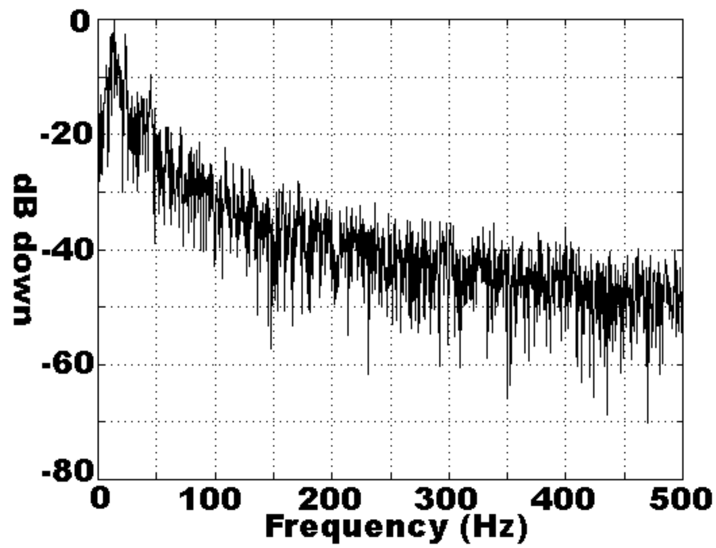
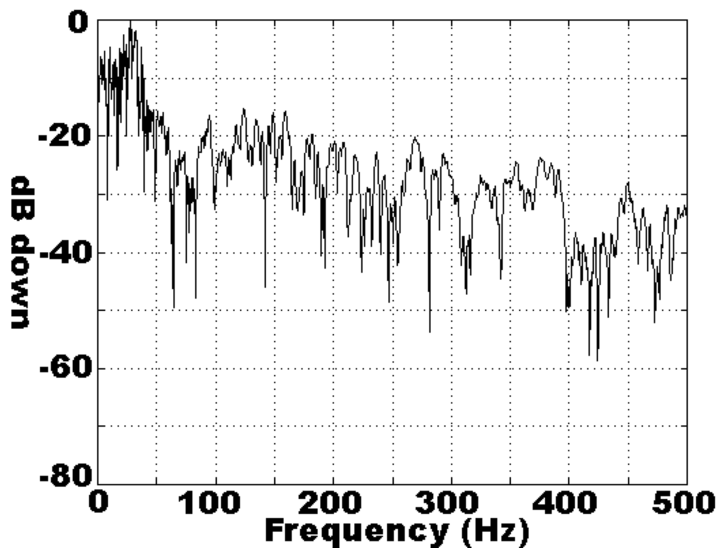



Fig.5. Receiver gather for inline horizontal component geophone at 18m depth displayed with normal polarity and 250ms AGC window. SW is the zone of shear-wave refraction arrivals.




(a)




(b)

Fig.8. Amplitude spectrum of stacked receiver gather for (a) hydrophone at 18m depth and (b) vertical component geophone at 18m depth.

## PROCESSING THE HYDROPHONE CABLE DATA

Tube waves are the primary source of noise present on hydrophone data acquired in boreholes. This is true when the objective is to generate an image of the earth. The main objective of processing the hydrophone data was, therefore, to suppress tube waves and at the same time obtain an image that could be reliably interpreted. However, tube waves can also be used to determine valuable information about the rigidity of the solid surrounding the borehole as shown in White and Sengbush (1953) and Riggs (1955).

The steps involved in processing the hydrophone data (Figure 7) follow. After trace edits and mutes, shot statics computed during processing of the “normal-resolution” 20m surface seismic survey were applied to the hydrophone data. Shot statics were small and therefore application of shot statics only marginally changed the moveout of events in the hydrophone receiver gathers (Figure 8). A spherical spreading gain correction using a preliminary RMS velocity function was then applied to the data.

In the simplest case, we can assume that tube waves bounce back and forth only from the top and bottom of the borehole. In other words, tube waves are predictable in time. The time taken for the tube wave to travel from the top to the bottom of the borehole and back was calculated to be around 150ms. Although an oversimplified assumption, it nevertheless forms a basis to use predictive deconvolution. It was observed that a predictive deconvolution operator with a 12ms prediction distance significantly suppressed tube waves. Several reflection events that were either not visible or feebly visible on the raw data can now be observed on the processed data (compare Figures 9 and 10). The low-frequency and low-velocity tube waves were further reduced by *f-k* filtering of shot gathers of the data (Figure 11). Several events at times less than 1000ms are now visible on the data. Figures 12-14 show the results of the above processing steps for three different shot gathers. Upgoing reflection events are evident on the data in Figures 14 than in Figures 12. Notice a change in character in Figure 12 at a depth of about 44m due to the reflection and transmission of tube waves at that depth. Change in borehole rugosity at that depth is a likely reason for the reflection and transmission of tube waves at that depth. This change in character is notably absent on the processed shot gathers in Figures 13 and 14.

Velocity analysis of receiver gathers was then performed after trace equalization of the traces. The data were then VSPCDP stacked using the procedure described in Gulati et al. (1997). Several coherent reflections typical for the Blackfoot area are seen on the stacked section (Figure 15). Note that a cable every 750m or so would adequately image the reservoir at around 1000ms. Reflections on the stacked data away from the borehole show a better continuity compared to those closer to the borehole. This is because the tube wave contamination was stronger for shots closer to the borehole compared to shots at intermediate-to-far offsets from the borehole. The dead traces in the section represent missing shot locations along the profile. Time-variant spectral whitening was applied to the stacked data which was then passed through either an f-x deconvolution or a post-stack migration operator to give the final interpretable section.

F-x deconvolution of the whitened data resulted in a better continuity of events (Figure 4.16). The whitened VSPCDP stacked data was also migrated, under the assumptions discussed in Chapter 2, using migration velocities equal to the stacking velocities for the hydrophone gather in the centre of the vertical array (Figure 4.17). Events on the migrated section are more representative of the horizontal, flat-layered geology of the area than the f-x deconvolved section. This shows that post-stack migration, under certain limitations, can be applied to stacked VSP data.

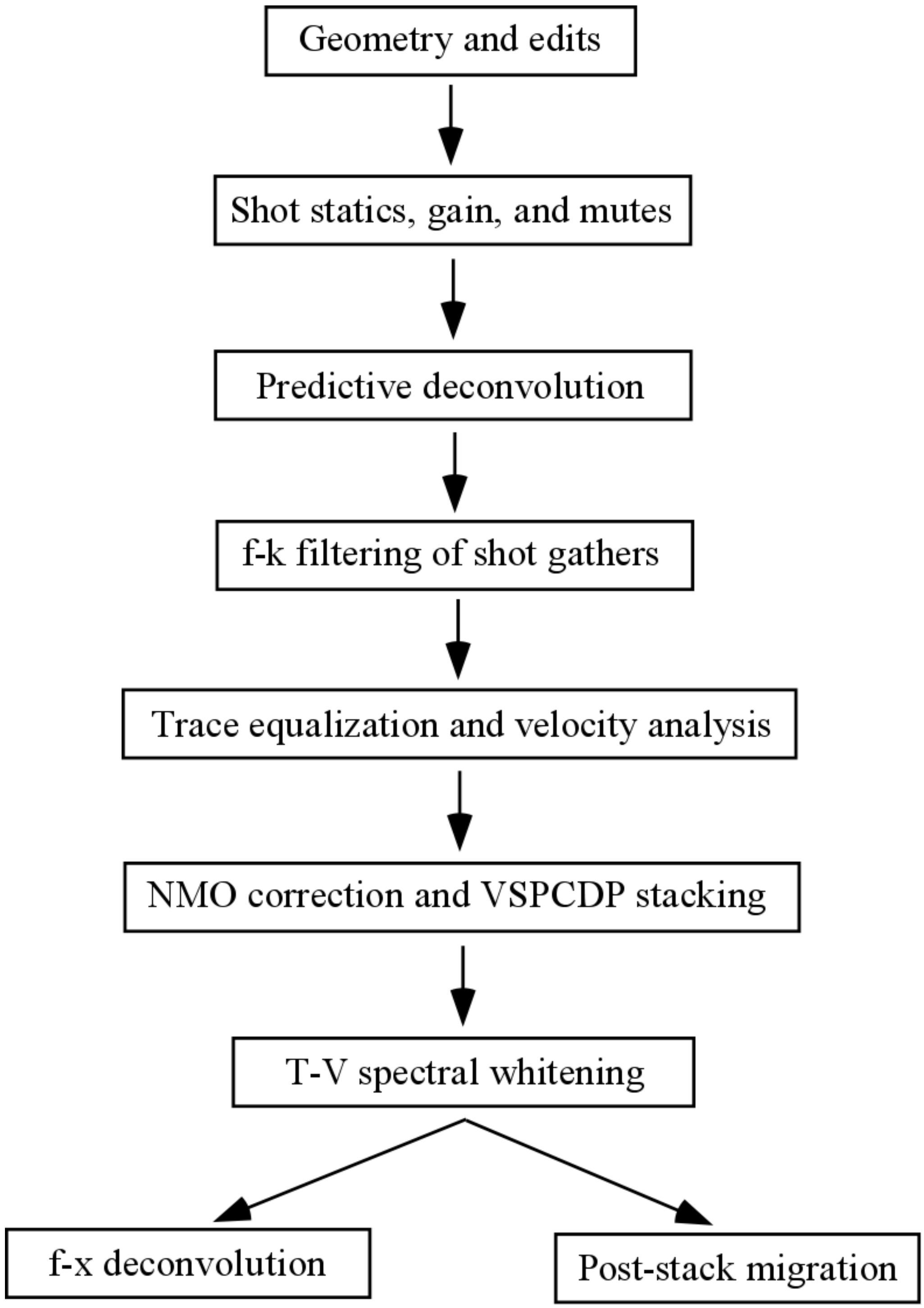
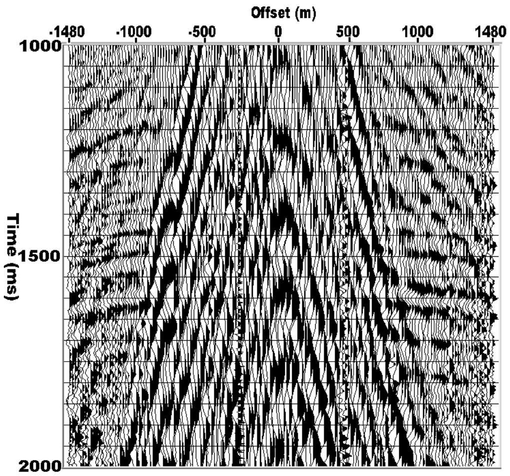
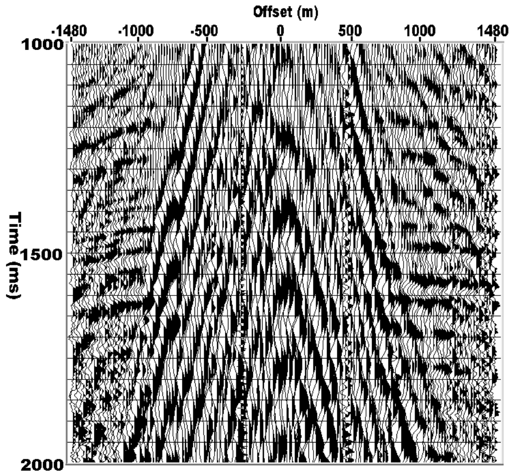



Fig.7. Hydrophone vertical cable processing flow.




(a) with no statics




(b) with statics applied

Fig.8. Receiver gather for hydrophone at 98m depth.

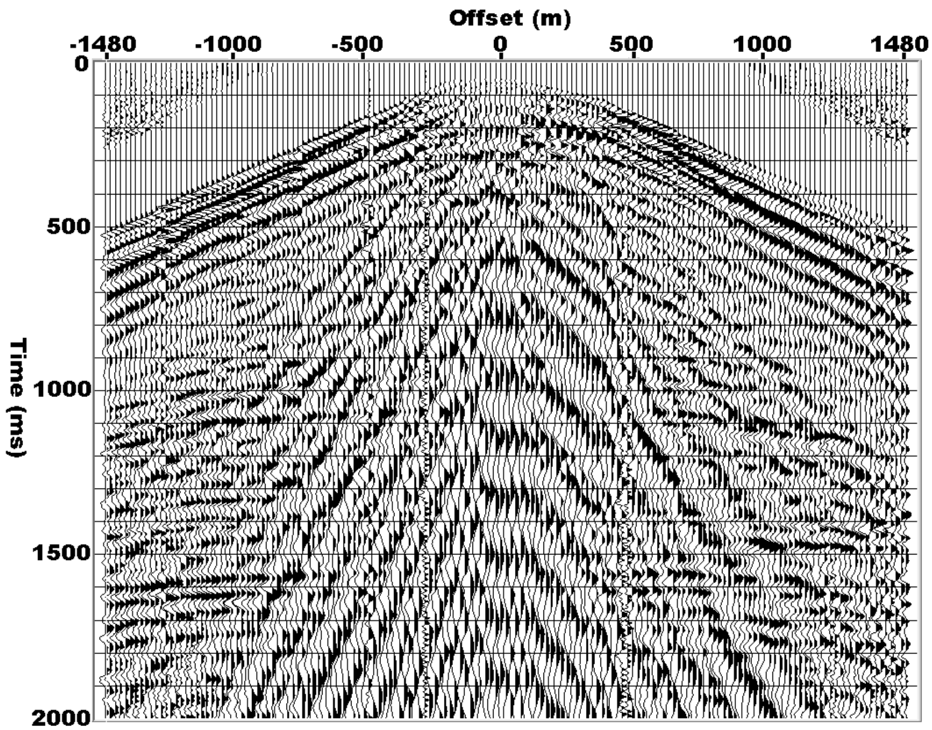



Fig.9. Raw receiver gather for hydrophone at 98m depth after application of shot statics. AGC is used for display purpose.

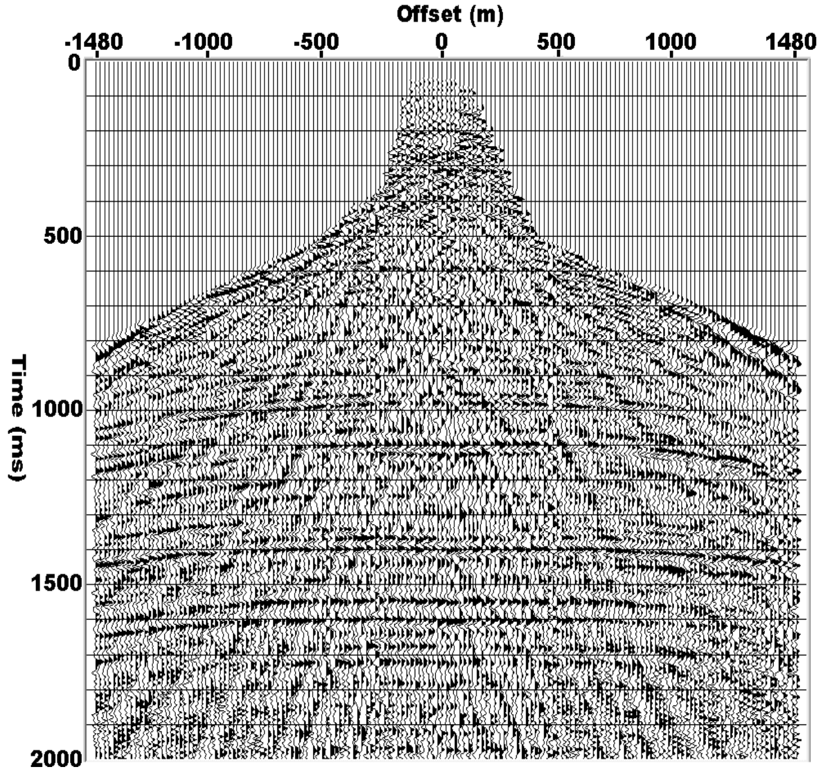



Fig.10. Same receiver gather as in Fig.9 but after top mute and predictive deconvolution, with AGC for display.

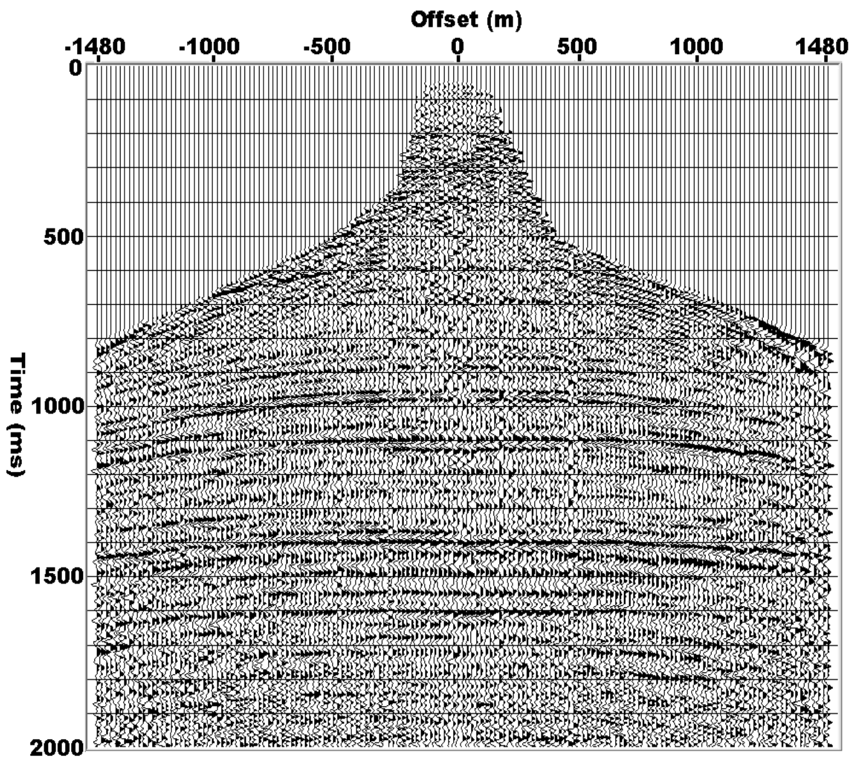
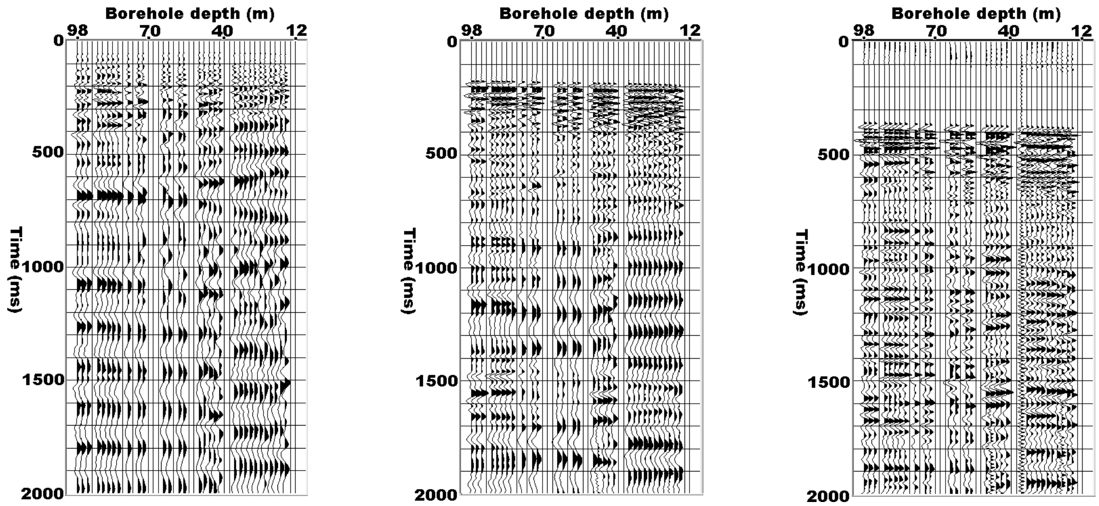
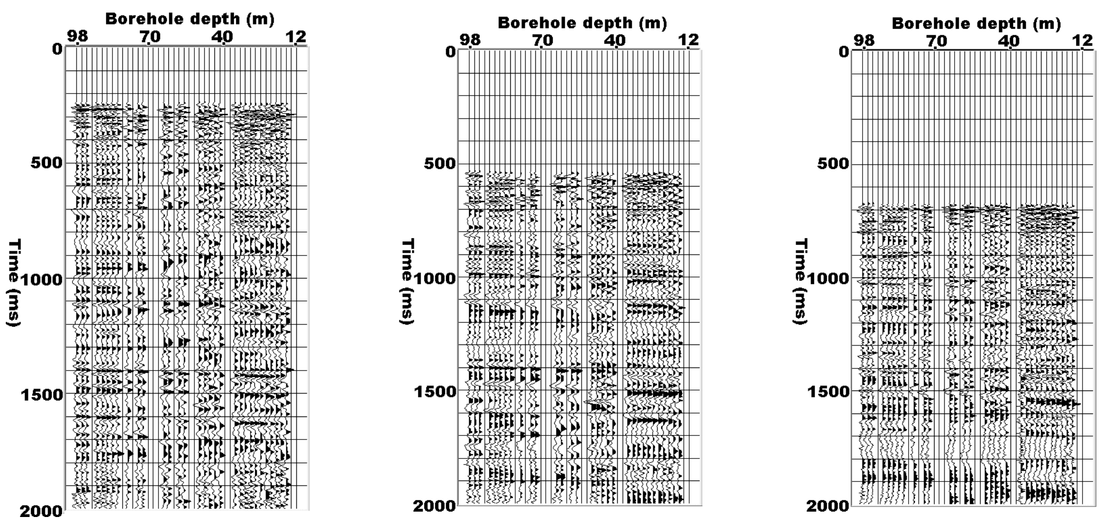



Fig.11. Same receiver gather as in Fig.10 but after *f-k* filtering of shot gathers, with AGC for display.




(a) (b) (c)

Fig.12. Shot gathers after application of gain. Shot offsets are (a)112m, (b)450m, and (c)1000m. AGC used for display.




(a) (b) (c)

Fig.13. Shot gathers in Fig.12 after application of mute and predictive deconvolution. Shot offsets are (a)112m, (b)450m, and (c)1000m. AGC used for display.

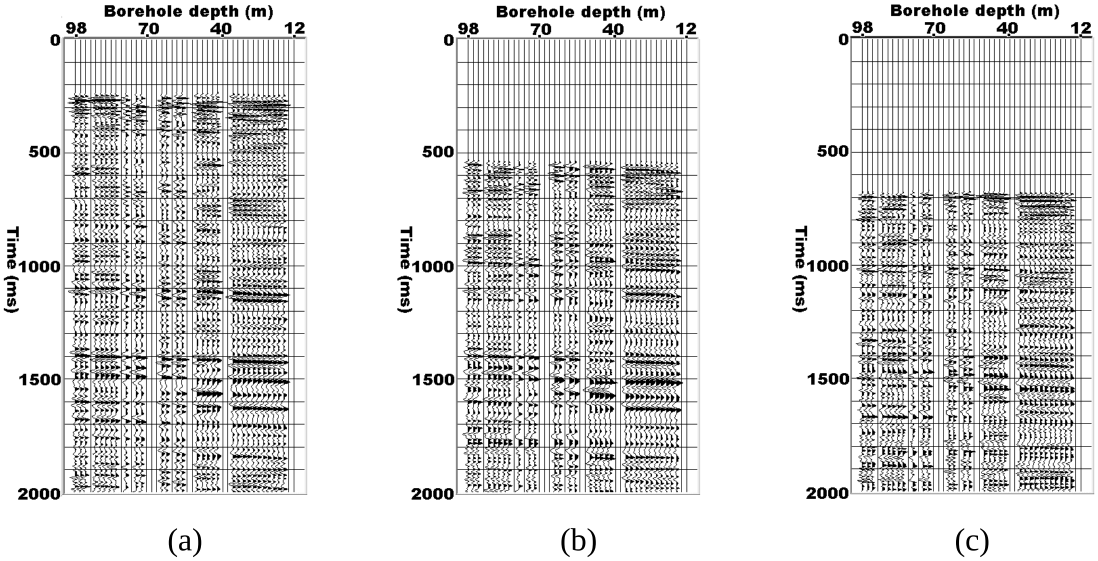



Fig.14. Shot gathers in Fig.13 after *f-k* filtering. Shot offsets are (a)112m, (b)450m, and (c)1000m. AGC used for display.

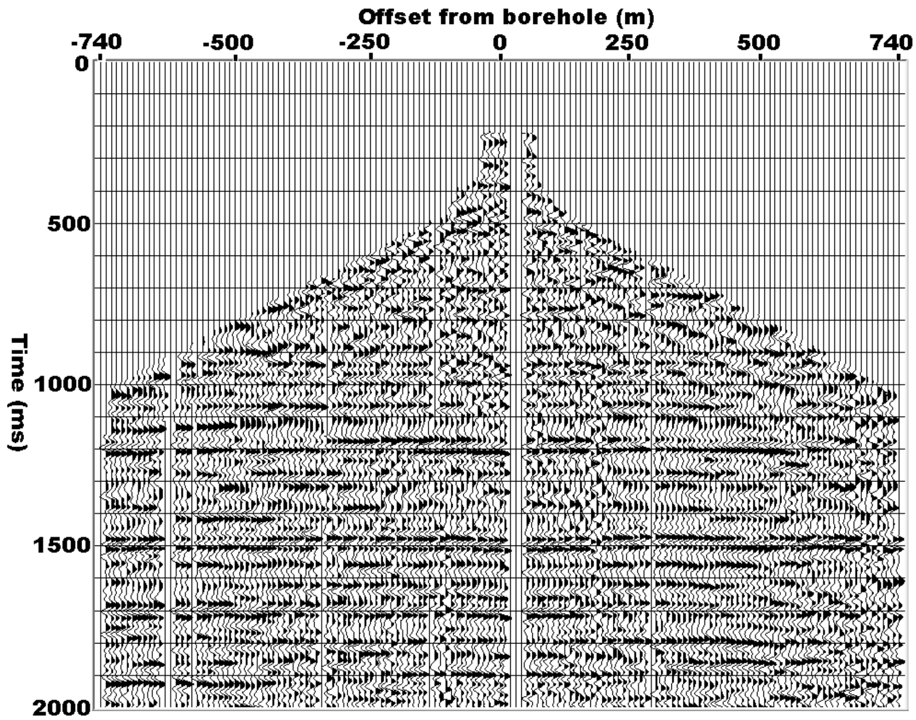



Fig.15. VSPCDP stacked section of the hydrophone data. Trace normalization used for display.

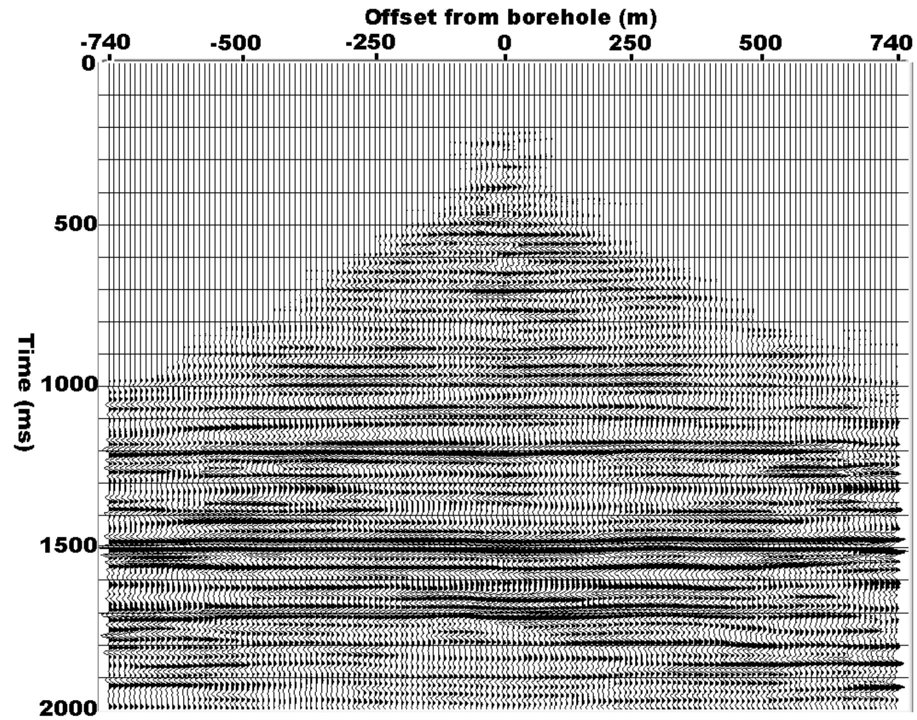



Fig.16. f-x deconvolution of the whitened VSPCDP stack in Figure 15.

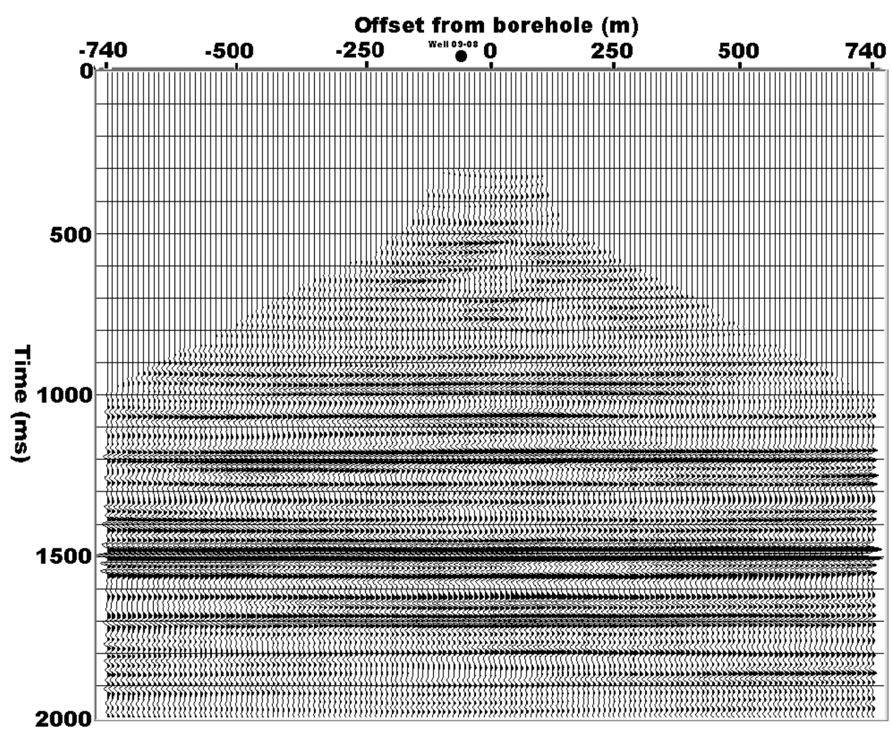



Fig.17. Post-stack migration of whitened VSPCDP stack in Figure 15.

## CORRELATION AND INTERPRETATION OF THE HYDROPHONE DATA

The migrated hydrophone data (Figure 17) was then correlated with the final migrated section from the 20m surface seismic survey. The hydrophone data correlates well with the surface seismic data although it is lower frequency (Figure 18). Interpretation of the Blackfoot area has been performed by several people (eg. Miller, 1996 and Margrave et al., 1998). The purpose of the present exercise is not a complete interpretation of the area but to show that hydrophone data can be reliably interpreted. Events were identified on the hydrophone data by correlating it with a previously interpreted crossline from a 3C-3D survey over the area (Figure 19). Figure 20 shows events identified above and below the channel interval. In fact, the channel play is interpretable on the hydrophone section.

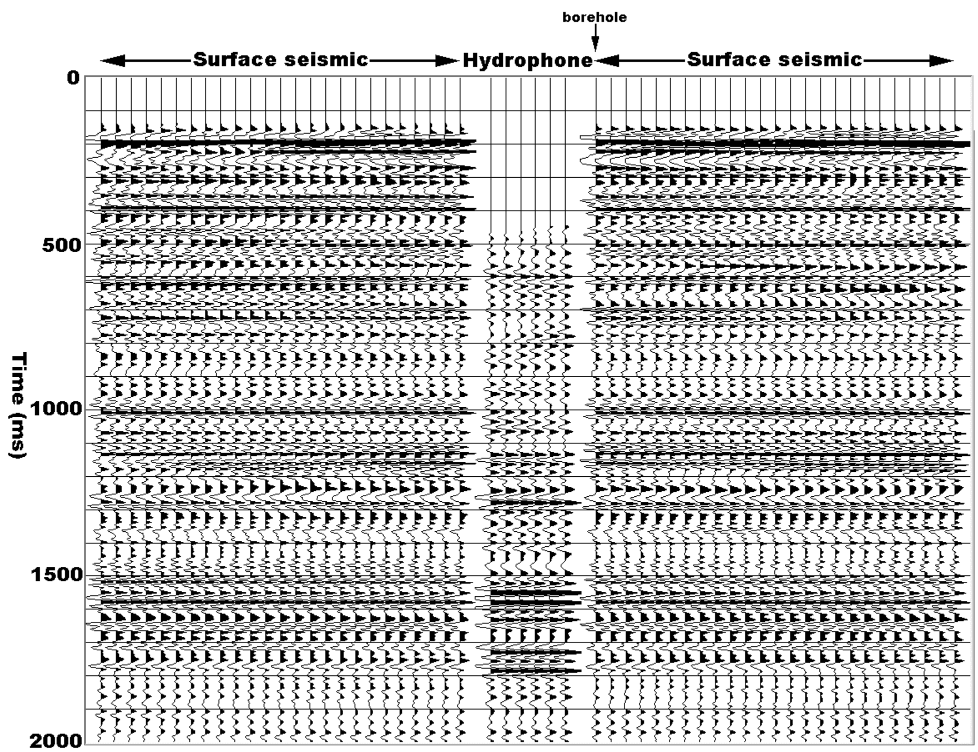



Fig.18. Migrated hydrophone traces near the borehole spliced into a section of the final migrated 20m surface seismic data.

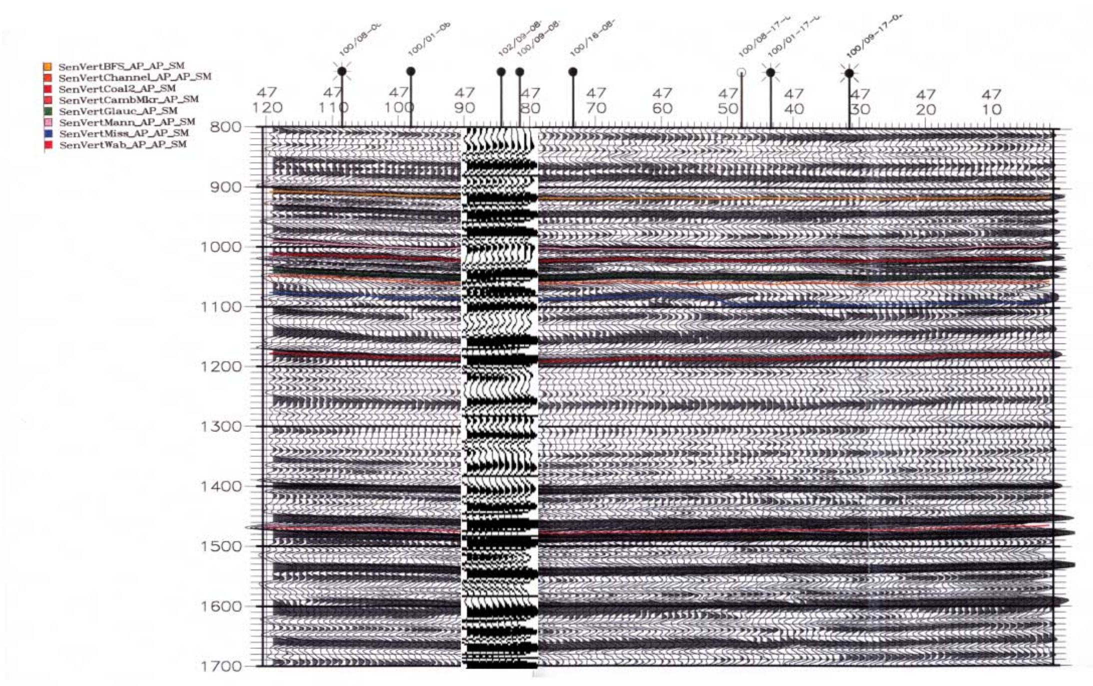



Fig.19. Migrated hydrophone traces inserted into a previously interpreted crossline from a 3C-3D survey in the area.

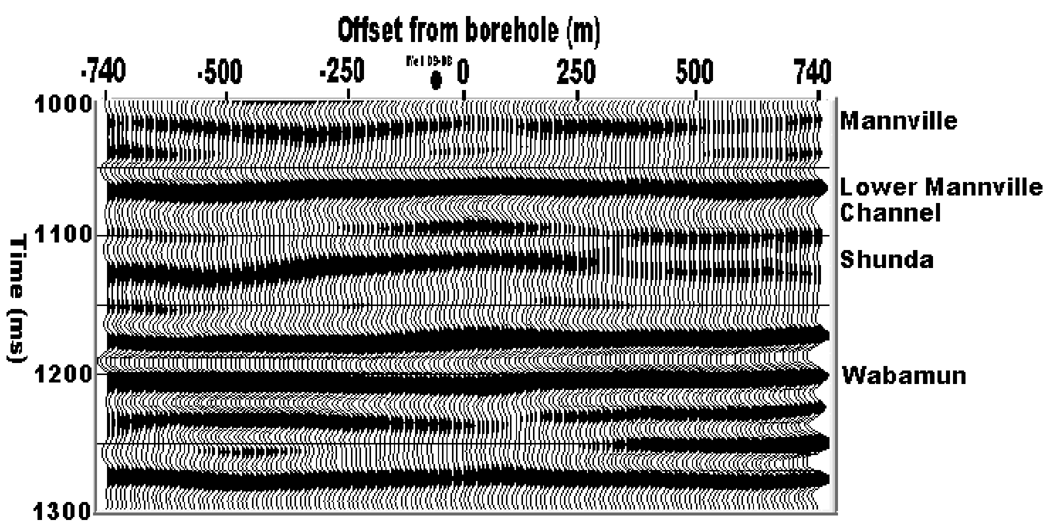



Fig.20. Interpreted hydrophone data. The anomaly associated with the channel at around 1100ms is visible in the centre of the profile.



Contents

## DISCUSSION

Apart from resulting in rapid acquisition of VSP surveys, the vertical hydrophone cable may have advantages in other applications. In areas such as those covered by carbonates or basalts on the surface, the reflection signal is weak due to the strong impedance contrast among layers. In such areas, the problem could be minimized by the use of hydrophone cables in several areally distributed shallow boreholes. In coal exploration projects, boreholes usually have diameters of 7.6 cm or less and VSP in such boreholes is done using slimline wall-locking tools (Gochioco, 1998). Alternately, the vertical hydrophone cable due to the small size of hydrophones could easily be deployed in such boreholes and result in efficient acquisition. Since hydrophones in borehole are sensitive to both compressional and shear stresses, the hydrophone cable could also be used for full waveform inversion or imaging purposes.

## CONCLUSIONS

Comparison of vertical hydrophone cable data with geophone data shows that in the long wavelength case, as predicted by theory, hydrophones in borehole represent the true earth motion. Tube wave contamination of hydrophone records is severe at short offsets and decreases with increasing offset. This property of increasing signal-to-noise ratio with increasing offset is very similar to that observed so commonly on ground roll affected geophone data.

In the simplest case, tube waves can be assumed to be predictable in time assuming that they bounce back and forth only from the top and bottom of the borehole. A predictive deconvolution operator used to suppress tube wave contamination on the hydrophone data was found to be very effective.

Processing of the vertical hydrophone cable data resulted in an image that correlated well with that from the 20m surface seismic survey and a previous 3-D sesimic survey over the area. Events present on the surface geophone data were identifiable on the hydrophone data as well. In fact, the channel structure was very much interpretable on the hydrophone image. These correlations and interpretations indicate that hydrophones in boreholes would not only result in efficient acquisition of VSP data but also result in images that can be interpreted.

## REFERENCES

Blair, D.P., 1984, Rise times of attenuated seismic pulses detected in both empty and fluid-filled cylindrical boreholes: Geophysics, 49, 398-410.

DiSiena, J.P., Byun, B.S., Fix, J.E., and Gaiser, J.E., 1984, F-K analysis and tube wave filtering, in Eds. Toksoz, N.M. and Stewart, R.R., *Vertical Seismic Profiling, Part B-Advanced Concepts*, Geophys. Press.

Findlay, M.J., Goulty, N.R., and Kragh, J.E., 1991, The crosshole seismic reflection method in opencast coal exploration: First Break, 9, 509-514.

Gaiser, J.E., Fulp, T.J., Petermann, S.G., and Karner, G.M., 1988, Vertical seismic profile sonde coupling: Geophysics, 53, 206-214.

Gal'perin, 1974, Vertical seismic profiling, Ed. White, J.E., SEG.

Gochioco, L.M., 1998, Shallow VSP work in the U.S. Appalachian coal basin: Geophysics, 63, 795-799.

Gulati, J.S., Stewart, R.R., Peron, J.F., and Parkin, J.M., 1997, 3C-3D VSP: Normal moveout correction and VSPCDP transformation: CREWES Research Report, Chpt. 9.

Hardage, B.A., 1981, An examination of tube wave noise in vertical seismic profiling data: Geophysics, 46, 892-903.

Hoffe, B.H., Stewart, R.R., Bland, H.C., Gallant, E.V., and Bertram, M.B., 1998, The Blackfoot high-resolution 3-C seismic survey: design and initial results, Presented at 68th Ann. Intl. SEG Mtg., Expand. Abst., 103-106.

Krohn, C.E., and Chen, S.T., 1992, Comparisons of downhole geophones and hydrophones: Geophysics, 57, 841-847.

Margrave, G.F., Lawton, D.C., and Stewart, R.R., 1998, Interpreting channel sands with 3C-3D seismic data: The Leading Edge, 4, 509-513.

Marzetta, T.L., Orton, M., Krampe, A., Johnston, L.K., and Wuenschel, P.C., 1988, A hydrophone vertical seismic profiling experiment: Geophysics, 53, 1437-1444.

Marzetta, T.L., 1992, Inverse borehole coupling theory and its application to hydrophone vertical seismic profiling: 62nd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 145-147.

Miller, S.L.M., 1996, Multicomponent seismic data interpretation: M.Sc. thesis, University of Calgary.

Milligan, P.A., Rector III, J.W., and Bainer, R.W., 1997, Hydrophone VSP imaging at a shallow site: Geophysics, 62, 842-852.

Omnes, G., and Clough, P., 1998, Data acquisition with a 12-level 48-channel borehole seismic system: The Leading Edge, 17, 955-959.

Pham, L.D., Krohn, C.E., Murray, T.J., and Chen, S.T., 1993, A tube wave suppression device for cross-well applications: 63rd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 17-20.

Riggs, E.D., 1955, Seismic wave types in a borehole: Geophysics, 20, 53-67.

Schuster, G.T., and Sun, Y., 1993, Wavelet filtering of tube and surface waves: 63rd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 25-28.

Schoenberg, M., 1986, Fluid and solid motion in the neighbourhood of a fluid-filled borehole due to the passage of a low-frequency elastic plane wave: Geophysics, 51, 1191-1205.

Sheline, H.E., 1998, Crosswell seismic interpretation and reservoir characterization: An offshore case study: The Leading Edge, 17, 935-939.

Van Sandt, D.R., and Levin, F.K., 1963, A study of cased and open holes for deep-hole seismic detection: Geophysics, 28, 8-13.

White, J.E., 1953, Signals in a borehole due to plane waves in the solid: J. Acoust. Soc. Am., 25, 906-915.

White, J.E., and Sengbush, R.L., 1953, Velocity measurements in near-surface formations: Geophysics, 18, 54-69.

Wuenschel, P.C., 1976, The vertical array in reflection seismology – Some experimental studies: Geophysics, 41, 219-232.

Wuenschel, P.C., 1988, Removal of detector-ground coupling effect in the vertical seismic profiling environment: Geophysics, 53, 359-364.

Wood, J.M., and Hopkins, J.C., 1992, Traps associated with paleovalleys and interfluves in uncorfomity bounded sequence: Lower Cretaceous Glauconitic Member, Southern Alberta, Canada: AAPG Bull., 76(6), 904-926.