Iranian Int. J. Sci. ***4****(2), 2003, p. 223-240*

Significance of VSP Data for Surface Seismic Data; South Ghashu Gas Field, South Iran.

Mokhtari, M.[1] and Pourhossein, H.[2]
[1]*International Institute of Earthquake Engineering and Seismology, email:Mokhtari@dena.iiees.ac.ir*
[2]*Petroleum University of Technology, email: hphossein@toosgeo.com*
(received: 12/6/2003 ; accepted: 9/10/2003)

Abstract
In its traditional and widespread use the seismic reflections from active sources are recorded at the earth's surface and processed to yield an image of the subsurface. The technique has become an indispensable part of the exploration process for oil and gas: few oil wells are drilled today without the use of seismic images. In addition, as an aid to the above, both explorationists and reservoir characterizations specialists have identified the importance of Vertical Seismic Profiling (VSP).

In this study, the key elements of VSP technology will be reviewed very briefly and its practical applications will be illustrated by using the data from South Ghashu gas field in the Bandar Abbas, Southern Iran. As an example, the application of the VSP data from Well No. 4 in planned 3D data surface seismic acquisition design (Bin size, expected frequency content, measured velocity profile, etc.) and rejection of a probable fault in vicinity of the well will be discussed in full length.

Keywords: *VSP Data, Surface Seismic; South Ghashu*

Introduction
The conventional surface seismic method is limited by positioning of the sources and receivers on the surface (or very close to it). This may impose major restrictions on the data. There can be no direct correlation between time and depth, since the geophones are restricted to the surface, only the upgoing wave field can be recorded and imposes limited resolution in time and offset. When the surface sensor restriction is eased, usually by the presence of a well, the receivers

(usually) or sources can be deployed as a subsurface, often vertical, array, allowing most of the restrictions listed above to be eased.

A vertical seismic profiling (VSP) is a technique in which a seismic signal generated at the surface of the earth is recorded by geophones at various depths in a borehole. Because a geophone is located far below the earth's surface when recording VSP data, it responds to both upgoing and downgoing seismic events. As mentioned above, this type of geophone response is important difference between VSP data and surface-recorded reflection data because downward traveling events cannot be identified in data recorded by geophones positioned on the earth's surface (Hardage, 1985).

The data recorded in a vertical seismic profile give some of the fundamental properties of propagating seismic wavelets and assist the understanding of reflection and transmission processes in the earth. These insights, in turn, should improve the structural, stratigraphic, and lithological interpretation of surface seismic recordings. For example, by defining upgoing and downgoing seismic events within the earth, it is possible to determine which events arriving at the surface are primary reflections and which are multiples. Other applications of VSP data include estimation of reflector dip, correlation of S wave reflections with P wave reflections, location of fault planes, studying of the natural and artificial fracturing of rocks, determination of lithological effects on propagating wavelets, looking for reflectors ahead of the drill bit, determining hydrocarbon effects on propagating wavelets, measurement of both P and S wave velocities, salt and volcanic proximity surveys, 4D reservoir characterization and estimation of the conversion of P to S and S to P energy modes within the earth (Hardage,1985).

Vertical Seismic profiling has an advantage over other means of determining reflectivity coefficients (such as by synthetic seismograms derived from sonic logs) because the frequency content is similar to that of surface seismic data (Dobrin and Savit, 1988). Additionally, VSP data usually are not as sensitive to borehole conditions such as washout when compared with other borehole methods (Yilmaz, 1987).

VSP data can provide to the seismic data processor important parameters such as amplitude decay functions and deconvolution operators (Yilmaz, 1987). This is particularly important for more advanced seismic analysis techniques such as Amplitude Variation with Offset (AVO) studies.

Figure 1 shows the underlying relationship between a VSP dataset and the surface seismic CDP or shot gather that might be acquired at the same place (Schlumberger, 2002). The figure shows how reflections, direct arrivals, multiple events and mode conversions are recorded by the geophone array. It demonstrates how the VSP and CDP gather share one common trace, the one with the receiver at surface at the well location. At this receiver location the events (or at least those that propagate to the surface) must show continuity between the two datasets

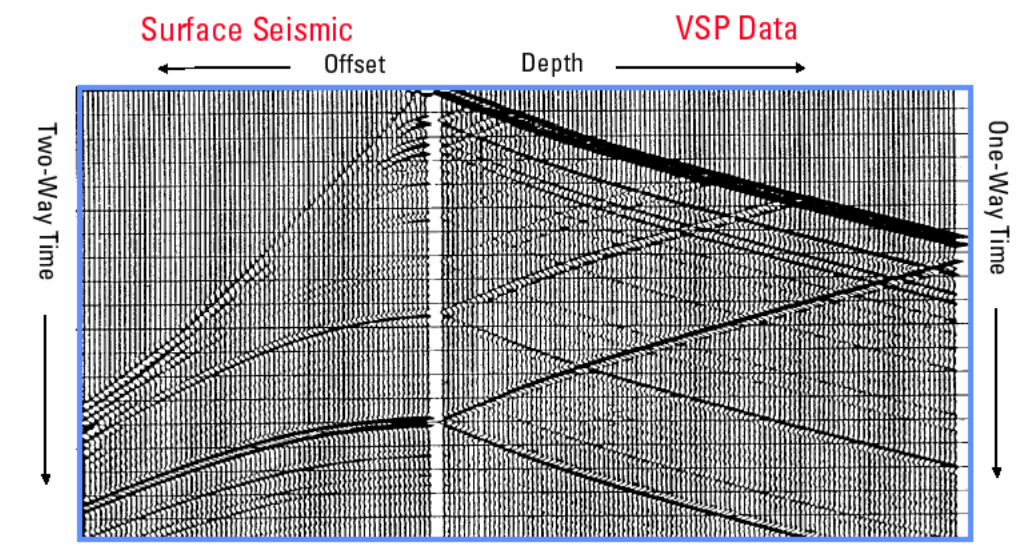


Figure 1 - Comparison of surface and VSP data at a well location (from Schlumberger).

An important additional application of the VSP that has recently gained momentum and becoming a value added to the above mentioned is, it's use in pre-determination of surface seismic design parameters, processing and interpretation. In this study after a short review of the principles of Vertical Seismic Profiling (VSP), its application on planned 3D seismic data in the South-Ghashu gas field will be discussed.

VSP Tools, Equipments and Sources

Main Equipment and physical factors that need to carry out VSP operation, include the well, energy source, downhole geophone, recording cable, surface digital recorder.

Energy Sources

It is preferred that the seismic energy source used in a vertical seismic profile be the same as that used when recording surface seismic data near a VSP well. In many instances this recommendation cannot be followed, and wavelet equivalence between the two sets of data must be achieved by numerical data processing procedures such as deconvolution or frequency and phase shaping of wavelet spectra.

The output strength of a VSP energy source must be carefully chosen at each experimental well site. Many geophysicists have discovered that the attitude, "bigger energy sources are better", is not always a good philosophy when recording surface reflection data, and this caution is perhaps even more important in vertical seismic profiling. Some of the seismic sources that are being applied in borehole seismic operation are Impulsive sources (Airgun, Dynamite) and Controlled Sources (Vibroseis, Marine Vibrator).

Downhole Tools

Recording the seismic wave field within the narrow well that may be 5 Km long, in a fluid that may be hotter than 200^{o}C and at high pressure, the ability to move either up or down, cause some differences in tools. Complicated tools were developed rapidly from the early 1980's to the present. Different companies offer a wide range of tools and equipments (Hardage, 1985).

The Basic VSP Wave types

Figure 2 shows the synthetic wave field for a simple case. The downgoing direct arrival occurs at later times as receiver depth increases and for zero-offset the slope of the direct arrival curve gives the velocity of the medium at that depth. The second event type shown is a downgoing multiple. For the zero-offset case the multiple will always be parallel to the direct arrival.

Multiples that were generated as the wave field progressed downwards to the reflector become part of the signature for the reflection event. Because these events are, after they have been created, part of the downgoing signature, they are only visible for those receivers that 'see' the reflection event. And hence appear to truncate at the reflection interface. This gives a rule to use to discriminate between primary and multiple events, only primary reflection events intersect the direct arrival event.

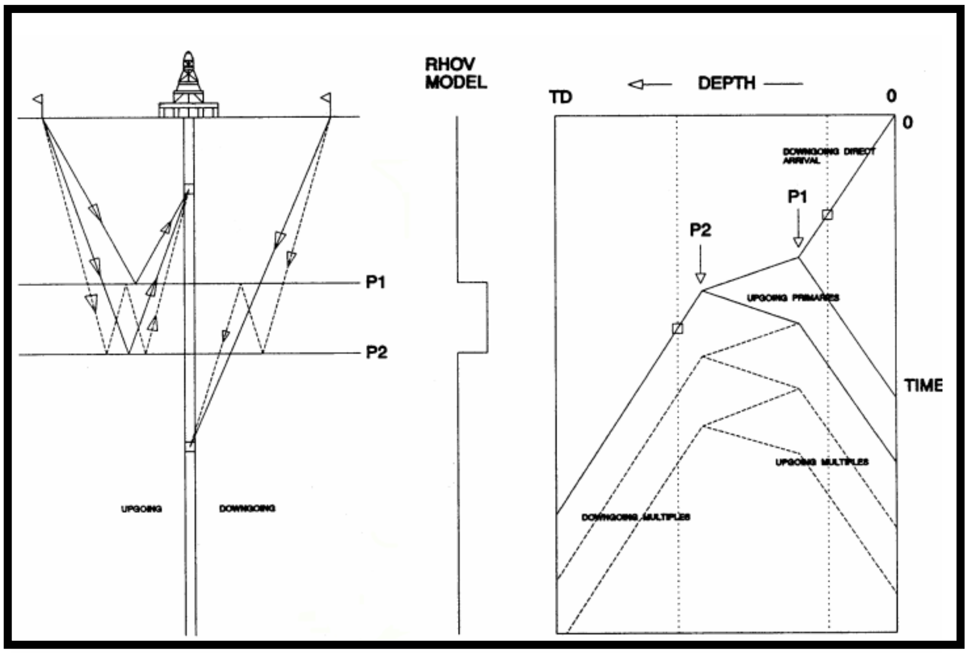


Figure 2 - Seismic events in a zero-offset VSP

Noises in VSP

There are some noises from different sources such as cable waves, geophone clamping, multiple strings of well casing and resonance in multiple casing strings, mechanical and electrical noise, drill site work activities such as welding, stacking pipe and metal goods, and general rig site maintenance and tube waves on VSP data. Other factors, such as field geometry, precise depth control, recording system gain, and correct depth sampling should be considered. In some wells, formation sloughing, fluid movement behind casing, gas bubbles, and borehole mud movement may also create a random noise background if borehole environmental conditions are not stable, but these noises will not be considered. However, it is essential that the sources of these noise modes be identified so that they can be recognized and avoided.

VSP Acquisition Methods

The objective of the acquisition phase is to measure travel times and amplitudes of the seismic waves at borehole/surface, in order to recover the earth's response to a point source at/near the surface or borehole. The 'Borehole seismic survey' covers a variety of different layout of sources and receivers. The basic geometries are described below.

CheckShots

The most basic form of a VSP survey, known as a checkshot, is used to determine interval velocities to geologic marker horizons. Sometimes is called velocity survey.

Zero-Offset VSP

This is the most common type of borehole seismic survey. The energy source is placed close to the wellhead, typically 40-100 meters away. Figure 3A shows the zero-offset VSP in vertical well and Figure 3B shows the same in a deviated well. The geophones are located at depths that are usually evenly spaced in the well, from TD upwards.

Spacing between the geophones is governed by the slowest velocity and highest frequency anticipated within the depth interval of the VSP. Typical depth increments would be 15 to 20 meters.

Offset VSP

This method is the simple extension of Zero-offset (Figure 3C). In this case the large lateral coverage is possible. Lateral coverage of up to one half of the source offset distance can be achieved in the direction of the source. Profiling of a feature (for example to detect faults) can be done by using a fixed offset source position some distance from the well and moving the geophone(s) in the well, or by having the geophone(s) fixed and moving the source.

Walkabove VSP (Normal incident)

The Walkabove VSP is acquired by moving both the source and receiver to keep the path between them vertical. A regular geophone spacing in the well is normally used, and each time the tool is moved, the source on the surface is moved accordingly (Figure 3D). This type of dataset can be very useful because in addition to vertical travel-times that can be measured from it, an image can be generated from the reflections from below the borehole.

Walkaway VSP

This method provides a 2-D seismic picture of the formations on the either side and below a well. In this form, a receiver array of five to seven geophones collects data from multiple surface source locations along a line that extends from the well Figure 3E). Each line typically has hundreds of source positions. These data then can be processed to create an image that usually has higher resolution than from surface seismic surveys.

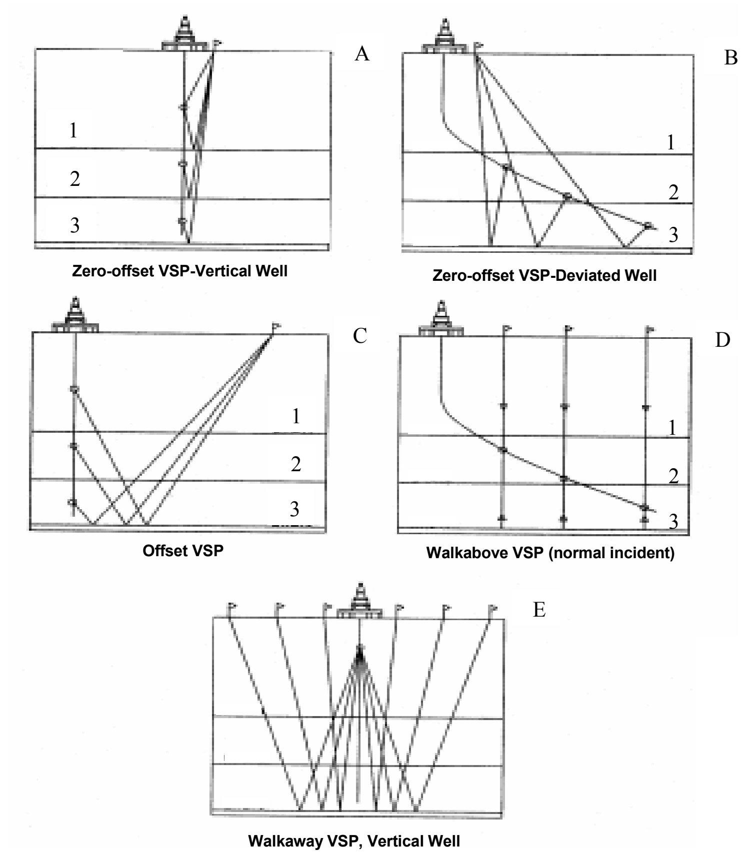


Figure 3 - Different VSP acquisition layouts

VSP Processing

A standard VSP processing produces a VSP stack trace comparable to synthetic seismogram without multiples or a set of seismic traces constituting a high-resolution seismic in the vicinity of the well. VSP processing can be divided into several sequences.

The first processing sequence consists of: Data demultiplexing; Correlation, if the seismic source is a vibrating source; Correlation for the signature fluctuation effect; Correlations for tool rotation and well deviation (Three components borehole geophone are required); Elimination of poor-quality records; Stacking of records made at the same depth; Corrections for spherical divergence and absorption; Component sorting when a three-component tool is used (Mari, *et al.,* 1999).

The second processing sequence consists of the picking of first arrival times, in order to determine the time-depth function and a velocity model at the well location. This function is used to calculate the interval velocity, average velocity and root mean square velocity.

The third processing sequence consist in the separation of waves, such as P waves versus S waves, upgoing waves versus downgoing waves, using velocity filters and sometimes polarization filters, CDP mapping, migration (if there are trace enough traces) and finally displaying the VSP data on surface seismic data.

VSP and the Surface Seismic

Even by using advanced seismic processing, surface seismic is limited by the spherical spreading, adsorption and multiples of the down going and received wave forms. Vertical Seismic Profiling allows a way to correct this surface seismic problem by giving the geophysicist a means of examining the acoustic wave field in situ.

By using VSP it is possible to calculate bin size, reflector dip, migration aperture, velocity profiles, faults with higher accuracy at the vicinity of well and fractures around the well. These parameters can be use in 2D and 3D surface seismic data acquisition design in order to save time and consequently reduce the cost of survey.

In addition VSP has application in data processing, for example using downgoing wave field to design deconvolution operators that attenuate upgoing multiples.

Application of VSP data in design of 3D surface seismic in the South Ghashu Gas Field

The South Ghashu gas field is located in the south of Iran approximately 25 km from the Persian Gulf, 60 km Northwest of Bandar Abbas. Ghashu gas field was discovered a couple of decades ago. The geological structure of the field was delineated by previous exploration and appraisal wells. However, drilling results from Ghashu-04 indicated that the forecast formation depths were significantly different (shallower) from the actual depths. At Ghashu-04 well, the strike of the layers is in the direction of East-West and the dip is toward the North. The layers dip increases with depth.

To be able to evaluate the drilling result and define the above-mentioned discrepancy a VSP data acquisition was planned with modeling before its measurement with the following objectives:

(1) To characterize the seismic responses of the formation at Ghashu field for the design of a 3D surface seismic survey in the near future

(2) To image the subsurface near the wellbore in the up dip direction and validate the drilling interpretation

(3) To record 3-C data for the purpose of shear wave information extraction

South Ghashu VSP survey design

To be able to estimate the acquisition parameters of VSP data before its measurement, based on existing data some models (2D and 3D) have been constructed. The velocity profile was provided by the National Iranian Oil Company-Central. Zero-Offset, Offset and Walkaway VSP were run on the constructed models. Two different dips used to modeling. Each model consisted of 13 dipping subsurface formations. Analyzing and comparing the results of the models, show that the zero-offset VSP will be sufficient in the study area to show the required lateral coverage, therefore the zero-offset VSP was chosen for actual measurement (Figure 4). The source was located at the wellhead and downhole receivers located in the depth range from 1800 m to 4800 m along the wellbore trajectory.

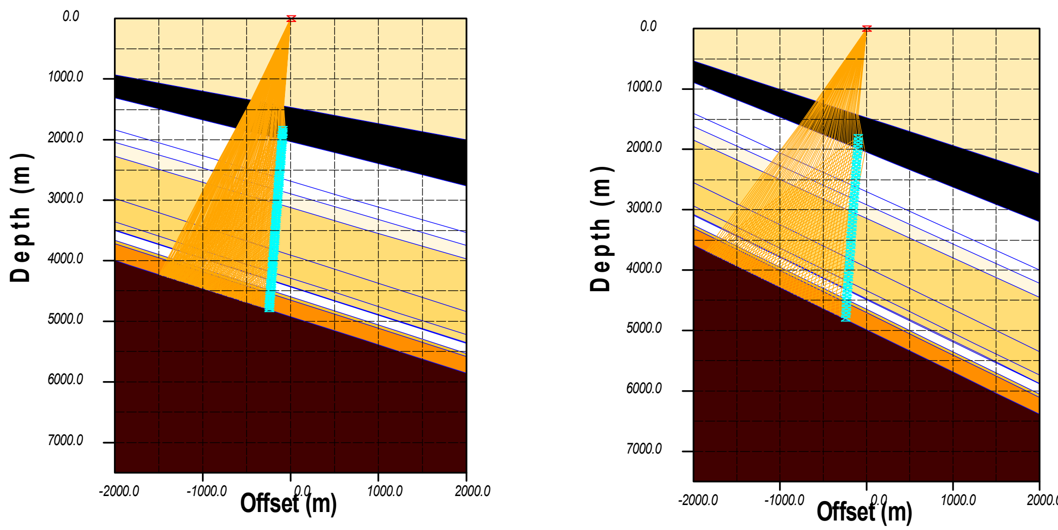


Figure 4 - Ray propagation for zero-offset VSP (two different models)

South Ghashu VSP data acquisition

The VSP survey was conducted in January 2002 (NIOC-Central 2002). It consists of a checkshot survey and a VSP. The VSP levels were recorded from 4880m to 2380m at a vertical level spacing of approximately 20 meters. Checkshots were also recorded from 2380 m to 500 m with a vertical level spacing of 200 meters.

In total 14 control/checkshot levels at/close to formations tops of drilling results were acquired (Esmaeily et all. 2002). As in the check-shot data, only the first arrivals are important for velocity picking and in addition for protection of pit being damaged, low airgun pressure was used. The depth-sampling interval of the VSP was 20 m and the deepest level was at 4860 m MD.

As the purpose of the down log was to estimate the formation interval velocity and the frequency range of the seismic signals, only one shot was acquired at each level at a shallower depth and more shots were acquired as the tool went deeper. All three components were displayed in Figure 5. As can be seen, the signal to noise ratio was poor for the horizontal X and Y components. But it is clear that a shear event can be identified on both horizontal components. For the vertical component, Z, the signal to noise ratio was reasonably good.

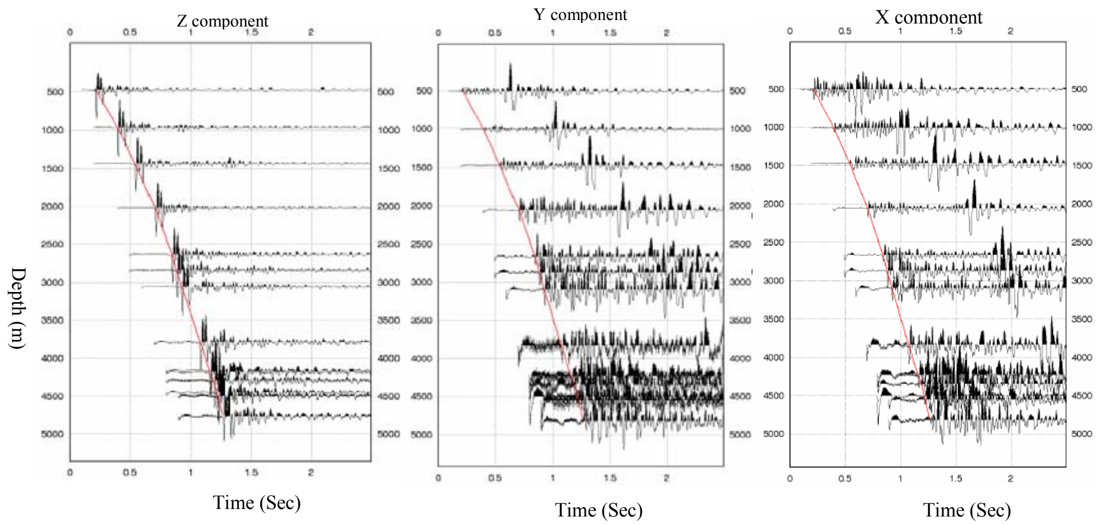


Figure 5 - X, Y, Z components of the checkshot survey during down run in hole

South Ghashu VSP data processing

Each shot of the raw geophone data was evaluated and edited as necessary. The hydrophone data were also evaluated for signature changes and timing shifts. The good shots at each level were stacked, using a median stacking technique, to increase the signal to noise ratio of the data. The transit time of each trace was re-computed after stacking. In addition to the above, the downgoing wave analysis; gain correction and band-pass filter; 3-component rotation; up and downgoing wave field separation; wave shaping deconvolution; ray tracing modeling and Kirchhoff migration were applied to the data.

VSP Wave field Analysis

Figure 6 shows vertical component (Z) power for entire intervals in Ghashu-4 well. Amplitude and frequency analyses show that just above the Asmari Formation (~2400 m MD) the downgoing energy was attenuated and high frequency content drops from more than 90 Hz to less than 50 Hz. A bandpass filter of 5-70 Hz bandwidth was applied after stacking. Figure 7 shows the upgoing P wave field and Figure 8 shows the upgoing P and converted S wave fields.

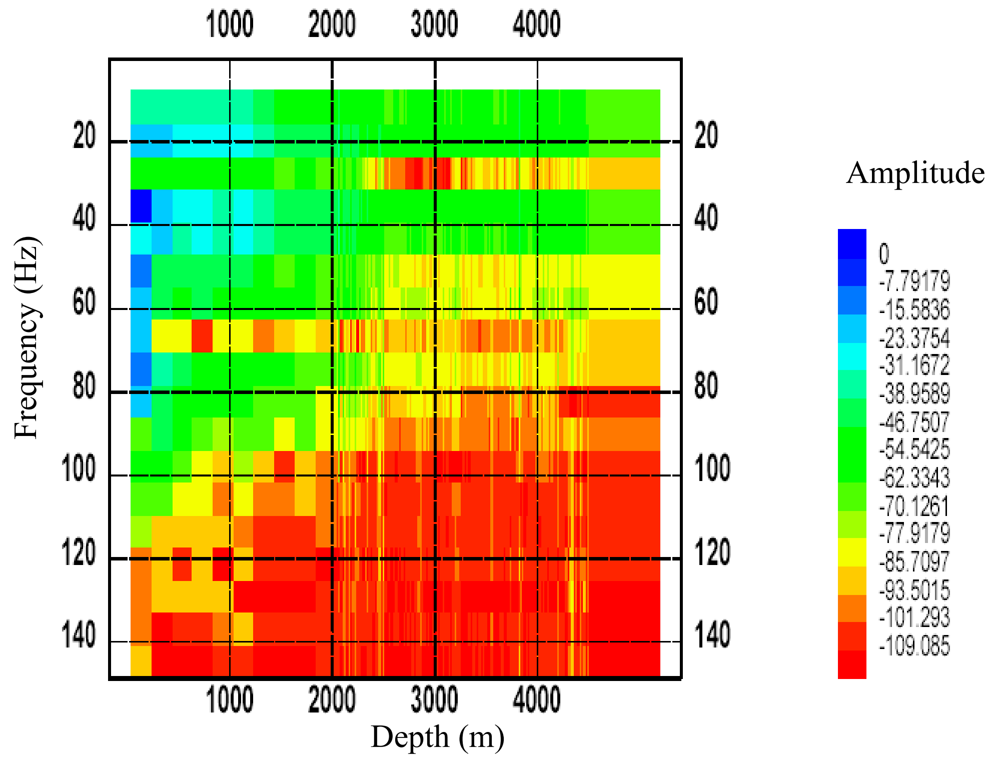


Figure 6 - Power spectrum of Z component in entire Ghashu-4 well

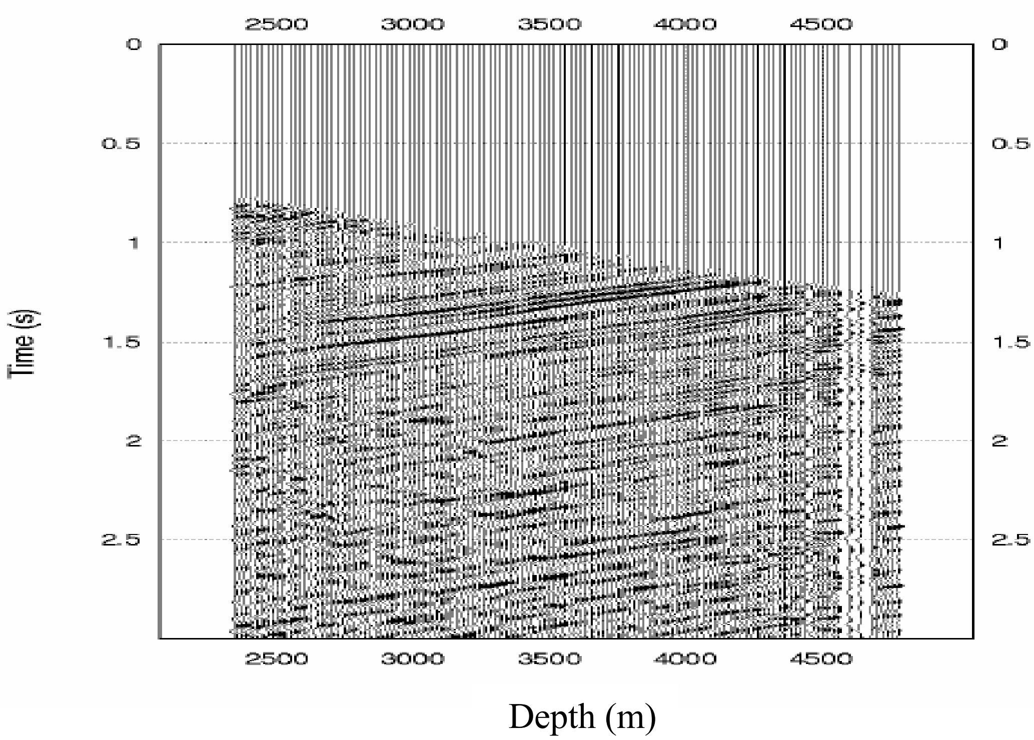
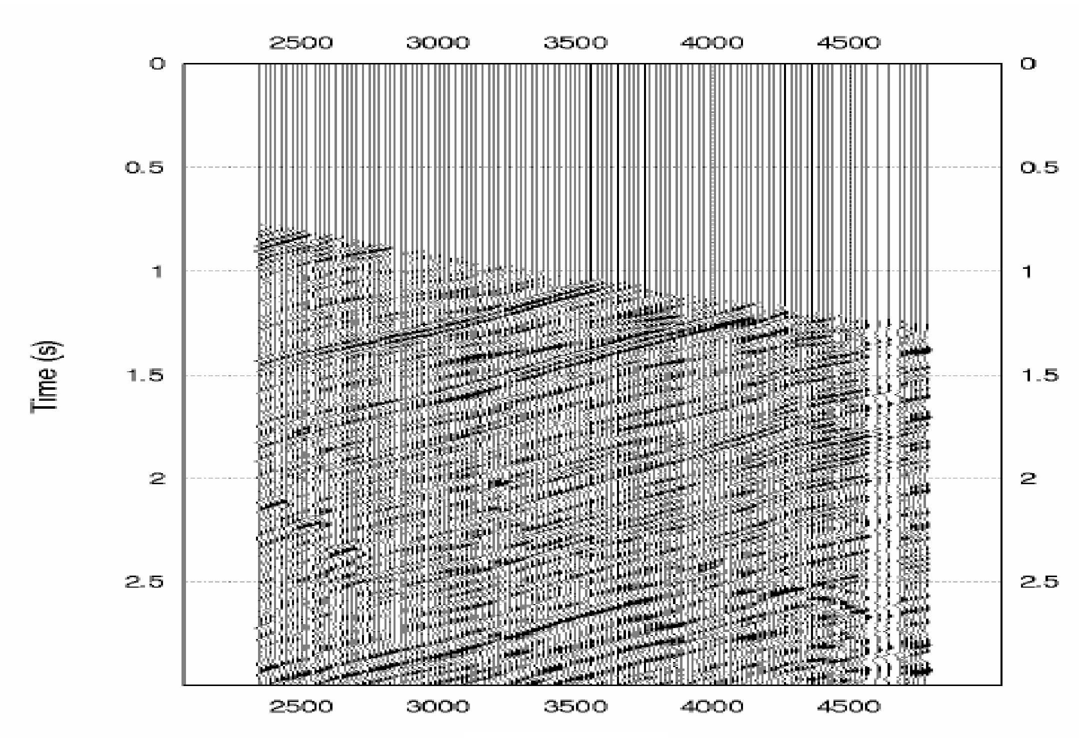


Figure 7 - Upgoing P wave after wave field separation



Depth (m)

Figure 8 - Upgoing P and S waves after wave field separation

Migration

2D Kirchhoff migration method has been applied to enhance upgoing P wave data from parametric wave field separation. Figure 9 shows depth migration results in image format. The migration results of VSP indicated that there is no visible fault within the offset of about 1500 m to the well head location.

Seismic Survey Parameters

As it was discussed before, one other important objective of the VSP acquisition was determination of acquisition parameters for the planned surface 3D seismic in the study area. In the following this will be discussed briefly.

Frequency Analysis

From the VSP data, power spectrum of vertical component for entire interval has been presented in Figure6. The frequency bandwidth changes significantly from 2300 to 2400 m. The frequency reaches more than 90 Hz above 2300 m and it decreases to less than 50 Hz below 2400 m. The power spectrum indicates that the maximum frequency at the target depth is 45 Hz. This maximum frequency can be used for the parameter setting of seismic vibrators and definition of Fresnel zone.

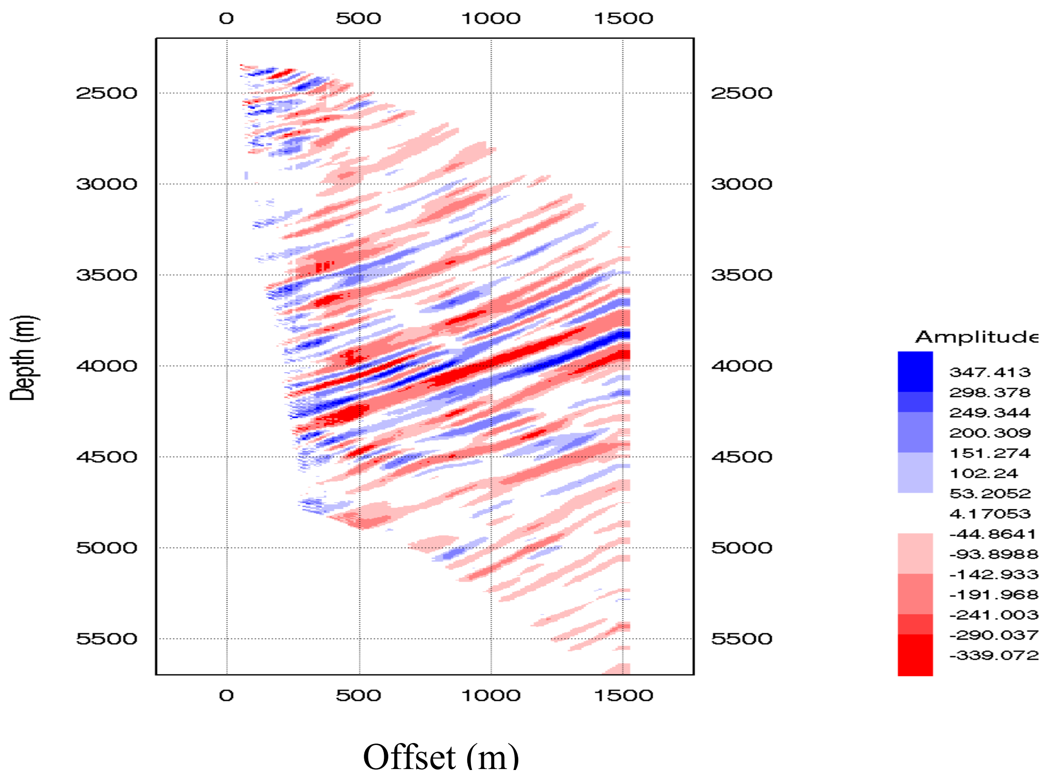


Figure 9 - Depth migration of P wave data.

Velocity Profiles

The formation boundaries were determined by drilling results and the formation dips were determined from the FMI log. The formation interval velocities were determined by a travel-time tomographic inversion. It was found that the interval velocity for each formation layer was greater than which was identified before using drilling data, except for one of the shallower layers. The minimum P wave velocity is at 3515 m/s.

Bin Size

The Bin size is a very important parameter as it will determine the size of structures which can be seen on the seismic as well as determine the effectiveness of the numerical processes used to process the raw seismic data to the 3D volume. The bin size will have a very large effect on the price of a survey. Reducing the bin size by half will increase the trace density in the 3D volume by a factor of four. There are two criteria to determine the bin size to be used in data acquisition – the criteria resulting in the smallest bin size is the overriding one.

Using the VSP data the maximum bin size at the target depth (25-2.7 sec, with a maximum formation dip of 30^0) was calculated to be 45 m × 45 m for the Ghashu field.

Integration of VSP and 2D seismic in Ghashu Field

Figure 10 shows integration of the existing 2D surface seismic section with VSP in Ghashu-04 location. It should be noted that azimuth differences between the 2D section (N7E) and the VSP (N35E) has caused the minor mismatch of the two data set. The results of VSP indicated that major reflection event is continuous across the whole offset range and there is no visible fault within 1500 m of the wellhead location (Figure 10). However, some changes in the reflection characteristic could be related to minor faults or fractures. It also indicates that the formation dip increases with depth.

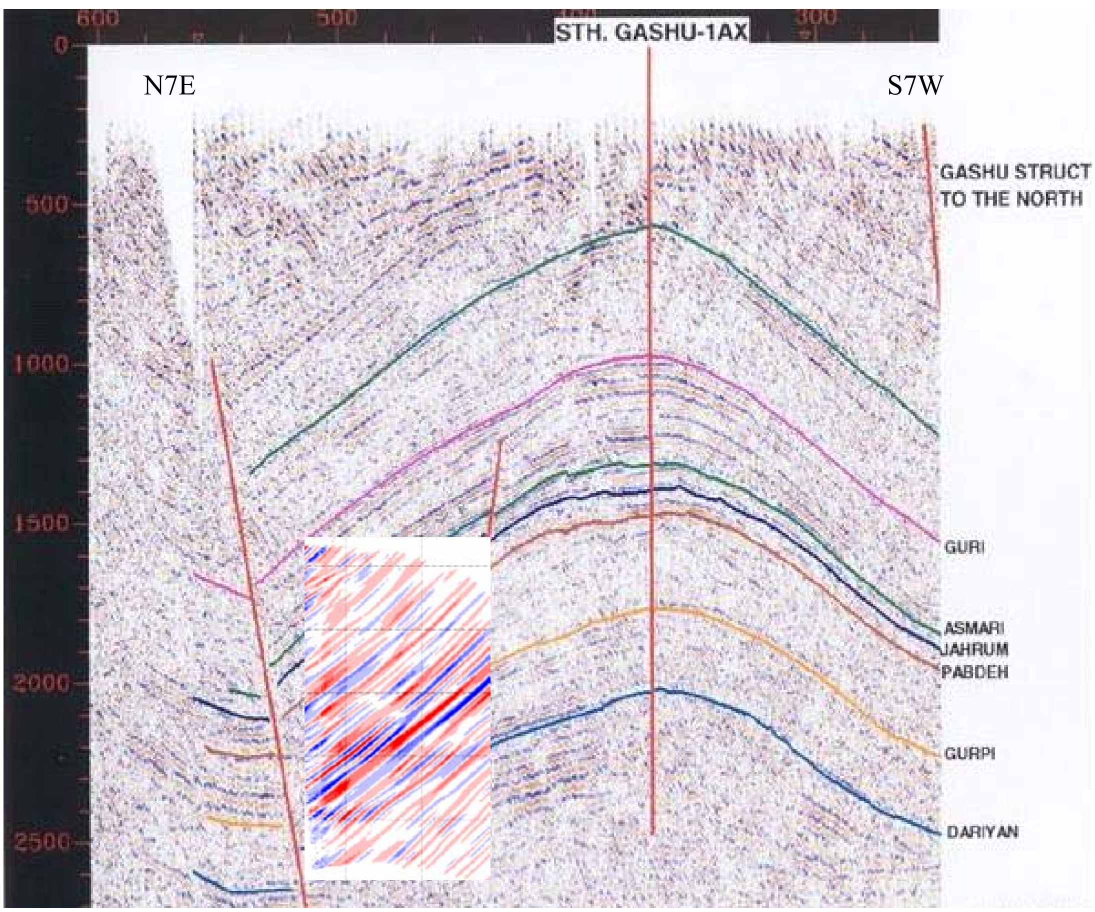


Figure 10 - Integration of VSP and 2D surface seismic in South Ghashu field at the well location.

Conclusions

This study showed the importance of modeling before any seismic data acquisition (surface and borehole). The following is a summary of the results.

As it was stated in the main text, the surface seismic data has not yet been acquired, so we hope to be able to compare the actual results with the predicated in the near future. Using VSP in surface seismic design, the acquisition duration hence the cost can be reduced. In addition defining the correct parameters can result in data resolution and quality increase. Further it can provide most important parameters such as velocity profiles and frequency content, Bin size, Migration aperture, designing of deconvolution operators and multiple identification. It also provides high-resolution section around the well to identify fractures and possible faults and used to increase the accuracy of interpretation of surface seismic.

The results of VSP indicated that major reflection event is continuous across the whole offset range and there is no visible fault within 1500 m of the wellhead location, the layers dip increase with depth and the 3C VSP data provided good opportunity to study shear wave information and rock properties in that area.

Acknowledgements

We wish to express our deepest appreciation to Dr. M. R. Rezaee (University of Tehran) and Dr. Henry Cao (Schlumberger- well services of Iran) for valuable discussion and support. We would like to thank NIOC-Central management, especially Mr. Janahmad for allowing to use South Ghashu VSP data.

References

Dorbin, M.B., and Savit, C.H. (1988) *Introduction to Geophysical Prospecting*, New York, McGraw-Hill book Company 300-303.

Esmaeily, S., Mokhtari M., Janahmad K., and Cao, K. (2003) *The Value of Integrated Borehole Seismic in Iran*, Reservoir Optimization Conference, Tehran.

Hardage, B.A. (1985) *Vertical Seismic Profiling*, Part A: Principles, 14A, Geophysical Press, Amsterdam.

Mari, J.L., Glangeaud , F., Coppens, F. (1999) *Signal Processing for Geologists and Geophysicists*, Editions Technip, Paris.

NIOC-Central (2002) *South Gashu gas field VSP reports*, Internal Publication.

Schlumberger (2002) *Borehole Seismic*, Internal Publication.

Yilmaz, O. (1987) *Seismic Data Processing*, Society of Exploration Geophysicists, Tulsa, USA.