3-D VSP: Recent history and future promise

Robert R. Stewart and Jitendra S. Gulati

ABSTRACT

This paper provides an overview of the current state of 3-D VSP and its promise. The measurement and its analysis has grown out of conventional VSP and walkaway surveys. A number of examples from the marine environment and land demonstrate the utility of the measurement.

INTRODUCTION

Borehole seismic surveys have a long history of providing rock properties (e.g., interval velocity, impedance, attenuation) near the borehole. These surveys have also assisted surface seismic interpretation through time-to-depth values and the extraction of a zero-phase, largely multiple-free reflectivity. These results were basically one-dimensional (within a Fresnel zone) near the borehole. Typically, a Fresnel zone might be about 100m for a 1500m target and VSP measurement.

With the advent of offset source positions, techniques were developed to make a section or offset image. Regularly placed source positions extending away from the well (the walkaway geometry) allowed higher fold in each bin or image point location. This produced a credible 2-D section. While valuable, this 2-D VSP image still had limitations, suffering from restricted angular coverage per bin, limited total bin fold, difficulty tying various shot statics and moveout, etc.

The fundamental geometric limitation, and indeed many of the other previously mentioned problems, in VSP can be overcome by using an areal distribution of shot points (or in the reverse VSP case, an areal distribution of receivers). This is allowing a 3-D image to be reconstructed.

Early 3-D VSP surveys included those by AGIP/Schlumberger in 1986 and the Brent field profile shot in 1993 (van der Pal et. al., 1995). The fault patterns mapped using the Brent 3-D VSP were more complex and resolved compared to those from the surface seismic (van der Pal et. al., 1995). Fairborn and Harding, Jr. (1996) show a case in Louisiana of using a downhole vibratory source and a surface spread of receivers to reconstruct a 3-D image of a sinkhole. A Chalk reservoir that was obscured by gas on the surface seismic in the Ekofisk field (Dangerfield, 1992) was the site of a 3-D VSP. In this case, 58 shot lines were recorded by the downhole receivers. Farmer et al. (1997) indicate that processing of the 3-D VSP survey resulted in a vastly improved image of the Ekofisk reservoir. Recently, READ Well Services completed a 3-D VSP survey in the UK Continental Shelf on BP's Magnus field. The survey with more than 14,000 shots along a 540 km spiral shooting line is believed to be the largest 3-D VSP survey to date.

Shekhtman et al. (1993) outlined a method of land VSP where they used a surface area of vibrators and a 3-level VSP tool to reconstruct a 3-D image. Mittet et al.

(1997) used a 3-D elastic reverse time migration scheme and applied it to synthetic and the Oseberg 3-D VSP circular shoot (Figure 1). To override memory problems in implementation of their method, they redatum the data to a depth level approximately 200m above the receiver. They noted that they rarely see a P-S-S event in their measurements, almost always the P-S primary conversion. Clochard et. al. (1997) show the feasibility of imaging complex structures using a 3-D VSP survey. Zhang et al. (1997) developed rapid moveout correction and VSPCDP mapping methods to process the Blackfoot 3C-3D VSP survey and correlated their results with those from a surface 3-D survey. Farmer et al. (1997) used a 3-D tomographic inversion scheme for determining velocities in the depth migration of a 3-D VSP survey over the Ekofisk field. Gulati et al. (1997) developed efficient methods for VSPCDP transformation of 3-D VSP surveys. Several authors (e.g., Leaney et al. 1997) have discussed using the 3-D VSP to investigate the azimuthal dependence of velocity. In their case, they shoot around the borehole with fixed receivers and search for anomalous arrival times and amplitudes as a function of azimuth (and angle). They show results consistent with azimuthal aniosotropy.

A recent (and first, to our knowledge) conference on 3-D VSP was held in Stavanger, Norway on October 9-10, 1997. This meeting gave an overview of previous cases, limitations, opportunities of the measurement.

Blackfoot 3C-3D VSP

The Blackfoot survey included the simultaneous monitoring of a 3-D set of surface shots by a downhole receiver. The shots were 4.0 kg of dynamite emplaced at an18 m depth. The receiver used was the Western Atlas 5-level three-component tool. Initial results were presented by Zhang et al. (1996) and Stewart and Zhang (1996). Their results were very promising considering that this was, to their knowledge, the first simultaneous 3-D VSP and surface seismic survey conducted. New sections are shown in Figure 2 and compared with final migrated traces from the surface 3-D seismic over the same area. There is a reasonable correlation between the VSP and surface seismic, nonetheless the VSP is lower frequency. We attribute this to compromised receiver coupling at some depths, only five-level recording, low fold, and a processing flow in its infancy.

Ekofisk 3-D VSP survey

The Chalk reservoir in the Ekofisk field is obscured by gas leaking to the surrounding formations (Dangerfield, 1992). The gas cloud over the reservoir leads to a severe loss of data over the crestal area of the field on surface seismic surveys (Figure 3). Borehole profiles over the field resulted in improved images of the reservoir (Figure 4). A full 3-D VSP survey with 58 shot lines was recently performed over the same field to improve the resolution of the seismic response at the reservoir (Farmer et al., 1997). Farmer et al. (1997) used a 3-D tomographic inversion scheme to determine velocities in a depth migration of the 3-D VSP data. The result was apparently the best image ever obtained of the Ekofisk reservoir (Figure 5).

The future

There are a number of acquistion, as well as processing, advancements that will greatly improve 3-D VSP results. A receiving sonde with 9 or more levels would reduce recording (and rig) time and allow greater survey coverage. It would also allow very effective separation of direct, reflected, and various mode wave-types. The increased measurement would improve noise reduction, deconvolution, statics estimates, and Q analysis. The processing of 3-D VSP data is still in its infancy. Better statics analysis, velocity determination, noise reduction, and imaging methods are required. Integrating the VSP images as sections, horizons, and slices can be made more straightforward.

What is the promise of 3-D VSP? With simultaneous borehole and surface measurements, we are looking for better source estimation and deconvolution, additional velocity values, a zero-phase, multiple-free high resolution section. This should all be only of nominal additional cost. There may be operational advantages – a well is available but full 3-D surface measurement is not. The surface seismic image may be inadequate due to compromising surface conditions (e.g. topography, complexity, busy marine region) or geologic complication. We also know that P-S images from the 2-D VSP can give higher spatial resolution than their P-P counterparts. The 3-D measurement may open up a new realm of P-S imaging.

Conclusions

Results of some of the 3-D VSP surveys indicate the tremendous potential of the technique in obtaining high-resolution 3-D images around the well. The 3-D VSP with a wider areal coverage could be used to get real-time 3-D images (both pure P- and shear-wave) in the appraisal of lithology and in determining future well locations. Methods to rapidly acquire and process the 3-D VSP data need to be developed.

References

Clochard, V., Compte, P., Nicoletis, L., Lucas-Svay, J. and Dillon, P.B., 1997, 3D walk-away imaging in the overthrust model. . Presented at the 57th Ann. EAGE Mtg., E047.

Fairborn, J.W. and Harding, R.S., Jr., 1996, 3D seismic velocity tomography at SPR sinkhole site, Weeks Island, Louisiana: Presented at 59th Ann. Intl. SEG Mtg., Expand. Abst., 896-898.

Farmer, P., Chapman, C., Fryer, A., Paul, A. and Sandvin, O., 1997, 3-D tomographic inversion and depth migration of VSP data. Presented at 60th Ann. Intl. SEG Mtg., Expand. Abst.

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

Mittet, R., Landro, M., Hokstad, K. and Ostmo, S., 1997, A methodology for 3D elastic depth imaging of marine 3D walkaway data. Presented at the 57th Ann. EAGE Mtg., E046.

Shekhtman, G.A. Zernov, A.E., Potapov, O.A., Lebedeva, I.I., Sokolova, K.B., 1993, Areal modification of the VSP method: Presented at the 55th Ann. EAGE. Mtg., P090.

Stewart, R.R. and Zhang, Q., 1996, 2-D and 3-D VSP interpretation: Blackfoot field, Alberta, The CREWES Research Report, Chpt. 41.

van der Pal, R.C., Bacon, M. and Pronk, D.W., 1995, Enhancing seismic resolution in the Brent field by a 3D VSP. Presented at the 57th Ann. EAGE Mtg., B017.

Zhang, Q., Stewart R.R. and Sun, Z., 1997, 3D borehole seismic imaging and correlation – a field experiment. Presented at the 59th Ann. EAGE Mtg., E048.

Zhang, Q., Stewart R.R., Parkin,, J.M. and Sun, Z., 1996, Analysis of the Blackfoot 3C-3D VSP survey, The CREWES Project Research Report, Chpt. 40.

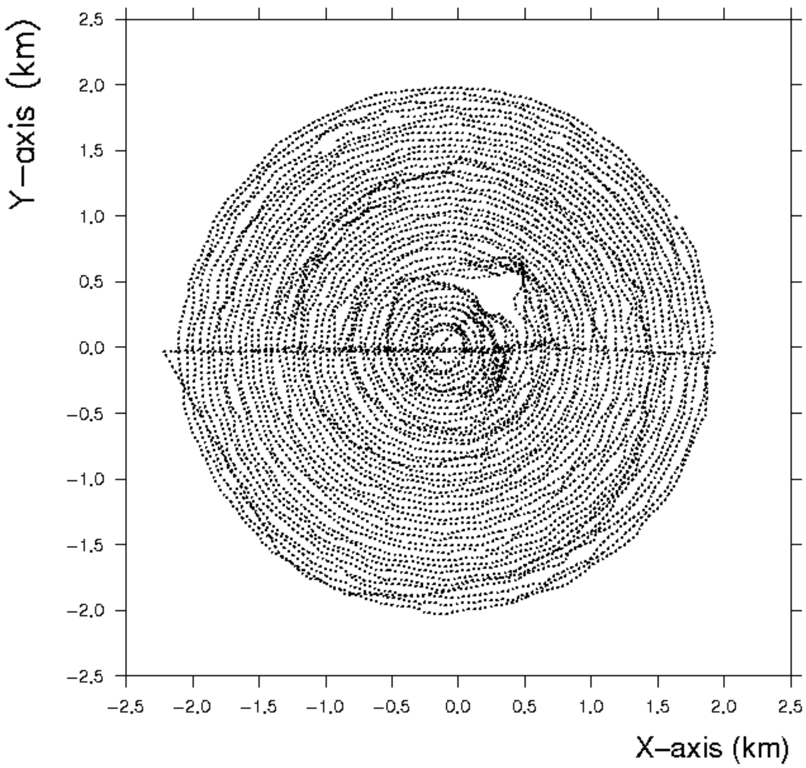

Fig. 1. The Oseberg circular-shoot with 5 geophone levels and approximately 10,000 shots (downloaded from [http://www.iku.sintef.no/Seismikk/vsp/vsp.html)](http://www.iku.sintef.no/Seismikk/vsp/vsp.html).

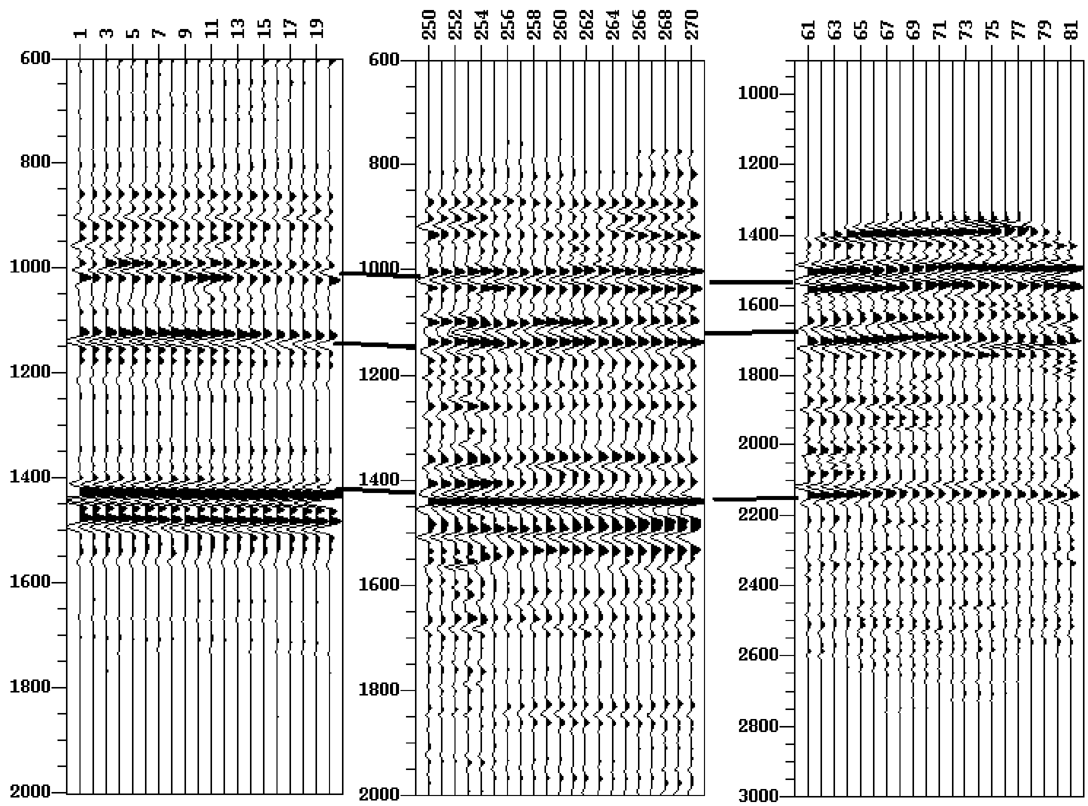

Fig. 2.(a)Section of migrated traces from the surface 3-D survey over the Blackfoot area and (b) Section of VSPCDP transformed traces from the Blackfoot 3C-3D VSP survey and (c) Section of the VSPCCP transformed radial component traces from the Blackfoot 3C-3D VSP survey in P-S time (plotted at 2/3 scale of corresponding vertical component data).

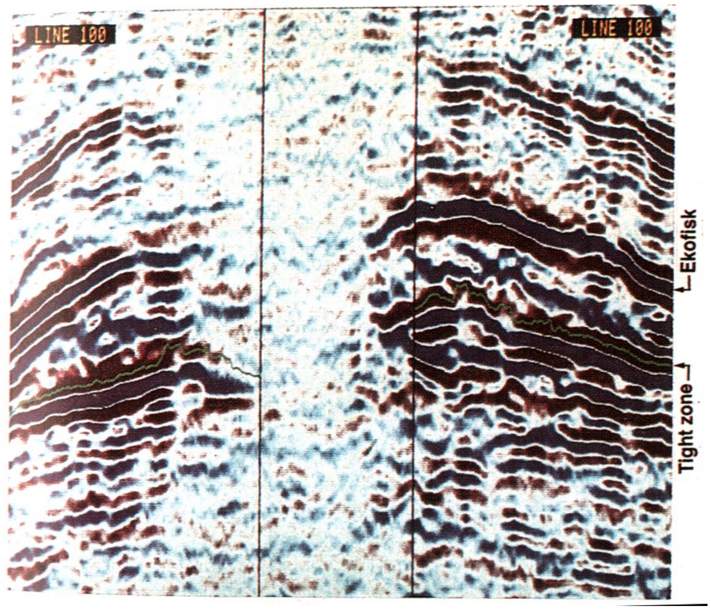

Fig. 3.Portion of surface seismic line showing loss of data over structural crest of the Ekofisk reservoir (from Dangerfield, 1992).

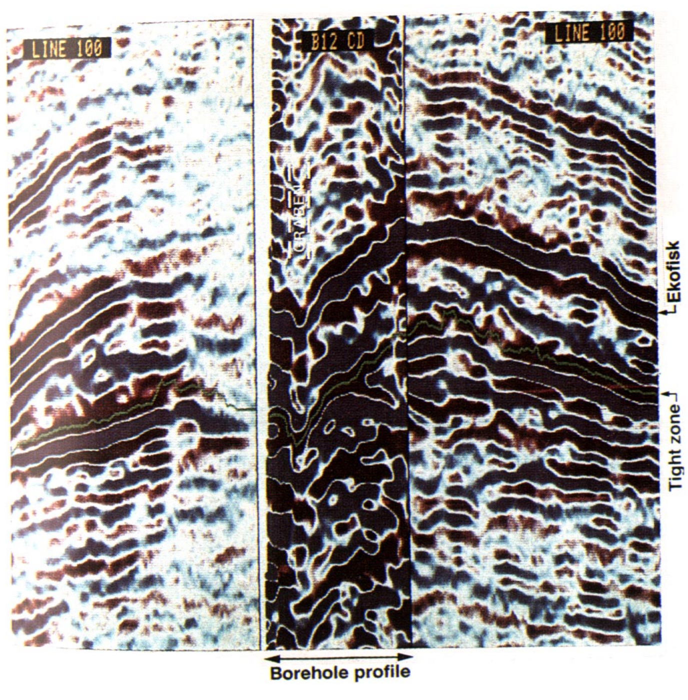

Fig. 4.Same surface line as in Figure 3 with walkaway profile inserted (from Dangerfield, 1992).

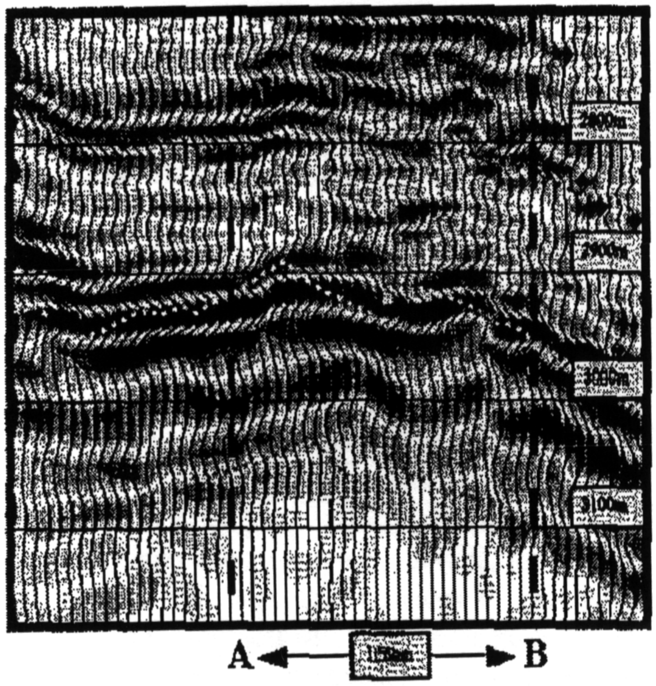

Fig. 5.Reservoir image obtained from the 3-D VSP survey over the Ekofisk field. A-B represent the gas affected zone (from Farmer et. al., 1997).