IMAGING WITH REVERSE VERTICAL SEISMIC PROFILES USING A DOWNHOLE, HYDRAULIC, AXIAL VIBRATOR

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ABSTRACT

We present the analysis of a reverse vertical seismic profile (RVSP) acquired over a pinnacle reef in the northern Michigan reef trend. The survey exhibited two features of note: (1) a new, strong, downhole vertical vibrator, and (2) a random distribution of surface receiver locations.

A short sequence of processing steps followed by diffraction summation migration provide a high-resolution image of a portion of the target reef at 4600 feet depth. The high-resolution of the image is due largely to the downhole source, which generated a high-powered signal at frequencies up to several hundred Hz. The source signal was repeatable, allowing our processing scheme to recover these high frequencies.

Due to adverse conditions, a large portion of the surface spread was abandoned. The reduced spatial coverage limits the extent of the migrated image, and therefore precludes an evaluation of the effectiveness of the random receiver spread. However, the partial image agrees with our previous interpretation of the reef. The high-resolution offers new insight into the structure of the reef, although a detailed geological interpretation is not possible due to the limited extent of the image.

INTRODUCTION

Conventional VSP, with seismic sources located on the earths surface and receivers in a borehole, has been available to the petroleum industry for some time. The geometry dictates that VSP should be used only for detailed investigations of known exploration targets. To be worthwhile, such studies should be of high resolution. However, high-resolution VSP sources have not been generally available, and poor data quality combined with high-acquisition expenses have limited the use of VSP techniques.

Until recently, downhole receiver strings have been limited to only a few receivers, requiring several shots to make a VSP gather of adequate aperture. Multi-offset or walk-away VSPs increase subsurface illumination but involve additional expenses, as access to the borehole is required for a longer time. Despite synthetic studies showing the effectiveness of VSP as a 3D imaging tool (e.g., Chen and McMechan, 1992), 3D VSP field surveys are almost unheard of. Published VSP case studies over the past ten years do not show the drastic improvement in quality which has been seen in surface seismics.

Reverse VSP (RVSP) has the potential to be less expensive and to provide better subsurface illumination than conventional VSP (Payne, 1994). With downhole shots, and by using surface receiver spreads similar to surface seismics, RVSP can produce a 3D data set in days or even hours once the receivers are in place. This possibility has not been realized before because of the lack of a powerful downhole source that does not damage the wellbore. The use of noise from the working drill bit as a source suffers from an extremely noisy environment, and from the difficulty of measuring the seismic signature of the drill bit. Thus, this limits the quality and resolution of images currently obtainable with the drill bit as a seismic source (e.g., Haldorsen *et al.,* 1995).

In 1998, the Earth Resources Laboratory (ERL) at MIT, supported by the ERL Reservoir Delineation Consortium, set out to test a new downhole source developed by Paulsson Geophysical Services, Inc. (P/GSI). MIT owns two boreholes in the productive northern Michigan reef trend. The test site is an ideal place to test new technologies, and MIT has a store of knowledge of the area built from several research programs over the past 20 years. The target, shown in Figure 1, is a Silurian pinnacle reef at 4600 to 5000 ft depth. The stratigraphy overlying the reef is pancake flat, as mapped by well logs and VSP studies.

One difficulty with the test site is the thick layer of glacial till. Besides static and multiple problems, the till attenuates high frequencies. Surface seismics here rarely contain frequencies greater than 40 to 50 Hertz, and previous VSPs average 60 Hertz.

DATA PROCESSING

The data set consists of 50 levels shot at a 25 ft spacing from 3000 to 4000 ft depth and a 50 ft spacing from 4000 to 4500 ft. We eliminated the shot depth of 4300 ft was due to casing concerns. The source was swept from 10 to 360 Hz in 10 s, and 10 sweeps were stacked at each level.

Before migrating the data, we applied the basic processing steps of amplitude balancing, deconvolution, and statics corrections. Briefly, these steps involve:

1. **Source-consistent amplitude balancing:** The receiver gain was changed after the first five shots. To correct for this variation, the individual recorded traces are normalized by dividing each by the power averaged for all receivers in the corresponding common-source gather, measured in a window around the first-break time.

2. **Receiver-consistent deconvolution:** We apply a deconvolution process described by Haldorsen *et al.* (1994). This method aligns the direct field using first-break time picks, estimates the coherent signal over a window of traces, and uses the signal to spike the direct and reflected wavefields and minimize random noise. The deconvolution process was applied in the receiver domain for a better separation of direct and reflected energy.

3. **Elevation and residual statics:** Elevation statics are applied using a constant near-surface velocity, assuming vertical ray paths near the surface. The residual static involves a receiver-consistent time shift to match the first-break times from the data to those derived from ray tracing through the velocity model used in the migration. The goal of the residual static is to reduce errors due to inaccuracies in the migration velocity model.

Figure 2 shows the amplitude-balanced traces and the same traces after deconvolution. In the latter plot, the direct arrival and its reverberations were collapsed into one event, and the reflected wavefield can be seen clearly.

Figure 3 is an estimation of the source spectrum. We use a median filter to isolate the direct wavefield in the deconvolved traces in Figure 2. The spectrum of each trace is found by a Fourier transform, then the spectra are averaged and smoothed. Analysis of the data in the frequency-wavenumber domain confirms that the coherent signal is strong to 200 Hz, and weak but visible to 300 Hz. Frequencies this high are extremely unusual in this region.

For imaging, we use an unlimited-aperture diffraction stack after correction for spherical spreading. Because of the simple symmetry of the flat-layered earth model used, we need only trace rays once for each depth of the image grid. The entire data set of roughly 13000 traces can be migrated in a few hours on a Sun workstation.

IMAGING RESULTS AND DISCUSSION

The north-south slices of the migration result are shown in Figure 4. Because of the crescent shape of the receiver spread, the east-west slices have only a very narrow region of illumination and are therefore not shown. The image is of the edge of the reef, with the reef to the left (south), from 4600 to 5000 ft depth. The reflector just below 4500 ft is a carbonate draped over the reef, and its step down off the reef is clearly visible. The reflector at about 4700 ft is another carbonate layer deposited between eras of reef growth. According to this image, this layer may extend into the reef. This structural detail has been hypothesized based on well log data, but has not been directly seen before in seismic data.

The geometry of the RVSP source array inherently results in uneven fold coverage on the target, especially when the sources extend to the target depth. We use ray tracing in a flat-layered earth model to estimate the illumination of the reef and apply an amplitude correction. The result of the amplitude adjustment, shown in Figure 5, works well for the flat layers at shallower depths. However, a 3D ray tracing scheme is needed to better estimate the illumination of the dipping layers near the reef, and to account for the uneven illumination of the underlying flat layers. Such a scheme is currently being developed.

Figure 5 compares the image made from the RVSP data to a VSP image made by Keho and Beydoun (1988). The VSP data used to make the image on the left was collected in 1983, with a signal spectrum of around 50 Hz. The improved detail and sharpness of the RVSP image is evident.

CONCLUSIONS

The downhole, hydraulic, axial vibrator from PGSI has placed the reverse VSP method back into the geophysicists portfolio of techniques. The observed signals are strong and broadband, especially considering the 600 feet of glacial till at the Michigan test site. Semblance deconvolution and diffraction stack depth migration has provided us with an unusually detailed 3-D image of a portion of the reservoir. The correctness of the

RVSP image can be judged from its comparison with other images we have obtained at the test site.

ACKNOWLEDGEMENTS

We thank Paulsson Geophysical Services, Schlumberger, and the members of the Earth Resources Laboratory "Michigan Consortium" (Comprehensive Test of the New Downhole, Hydraulic, Axial Vibrator), who made the 1998 research program possible.

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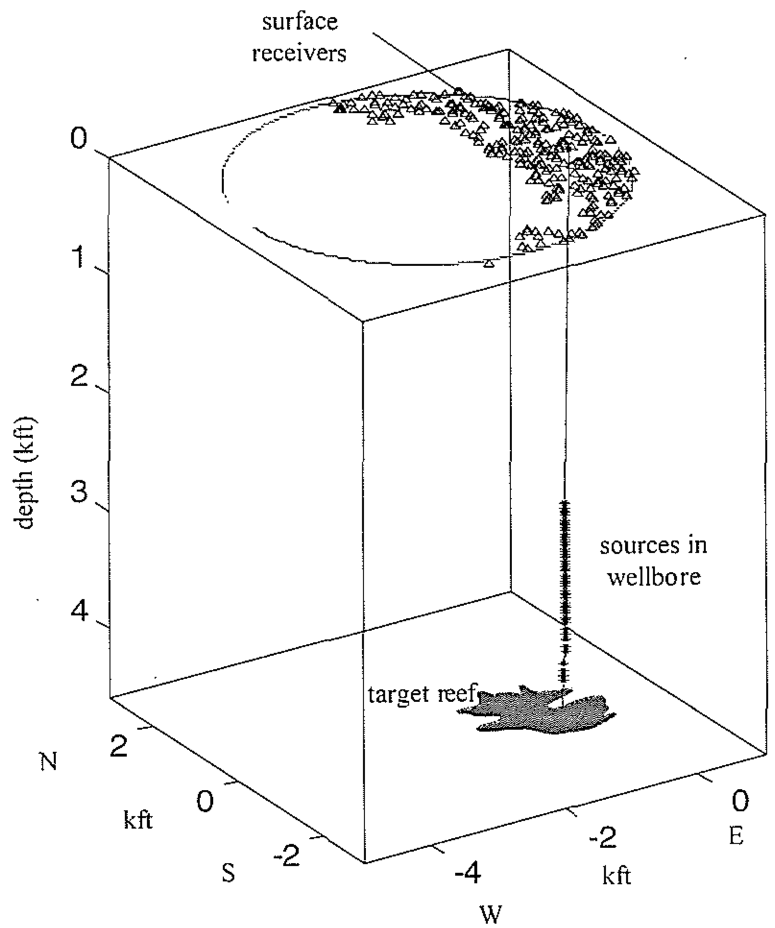

Figure 1: RVSP survey geometry. The circle on the surface represents the intended receiver spread.

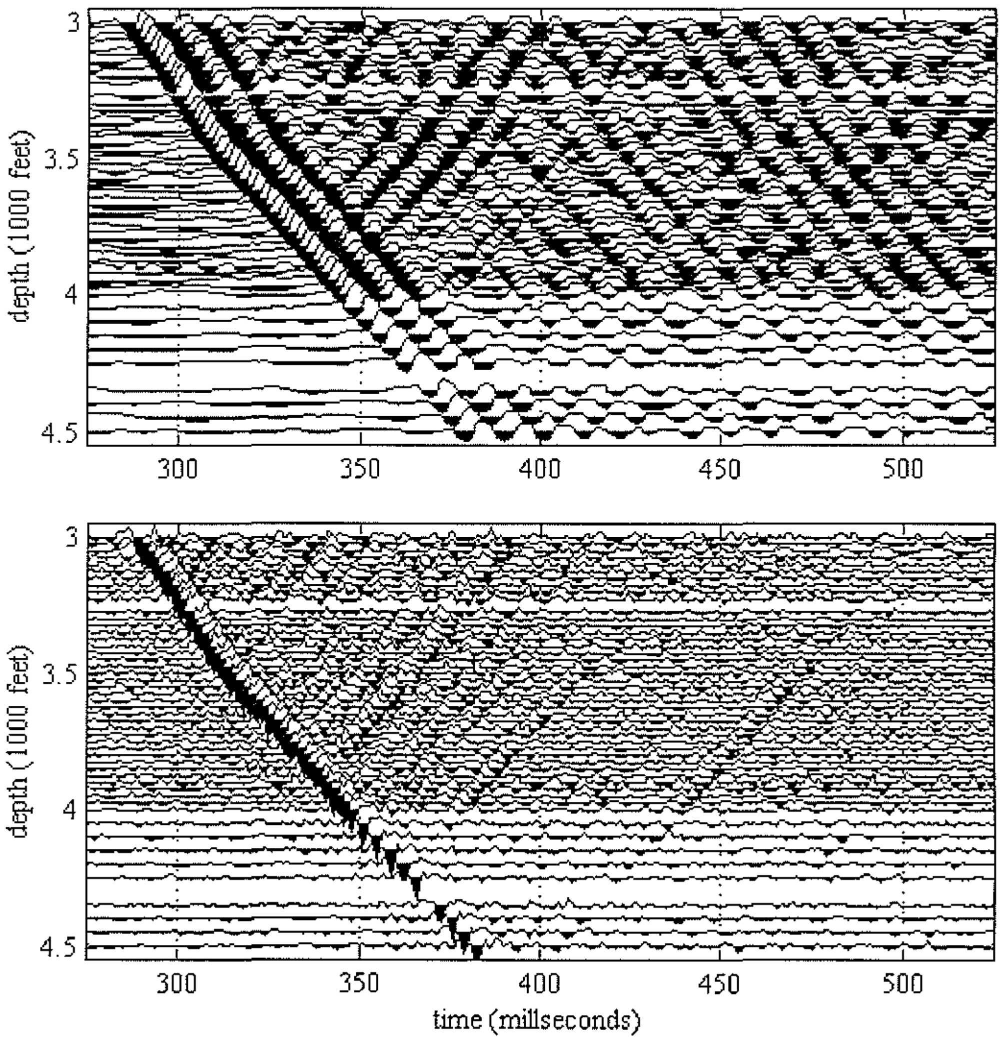

Figure 2: Common receiver gather of the RVSP data. The receiver is 869 ft from the wellhead. The top plot has the receiver power corrected traces, the bottom plot is the same gather after deconvolution.

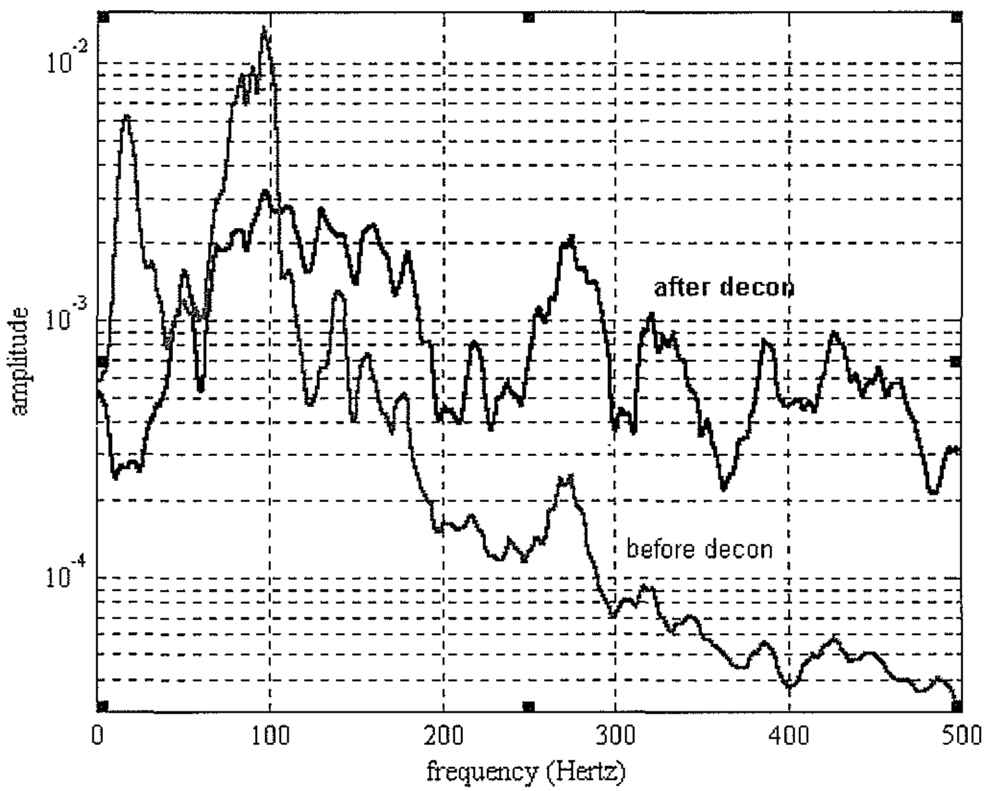

Figure 3: Estimate of the source spectrum. This is the average spectrum of the direct field only from the deconvolved traces shown in Figure 2.

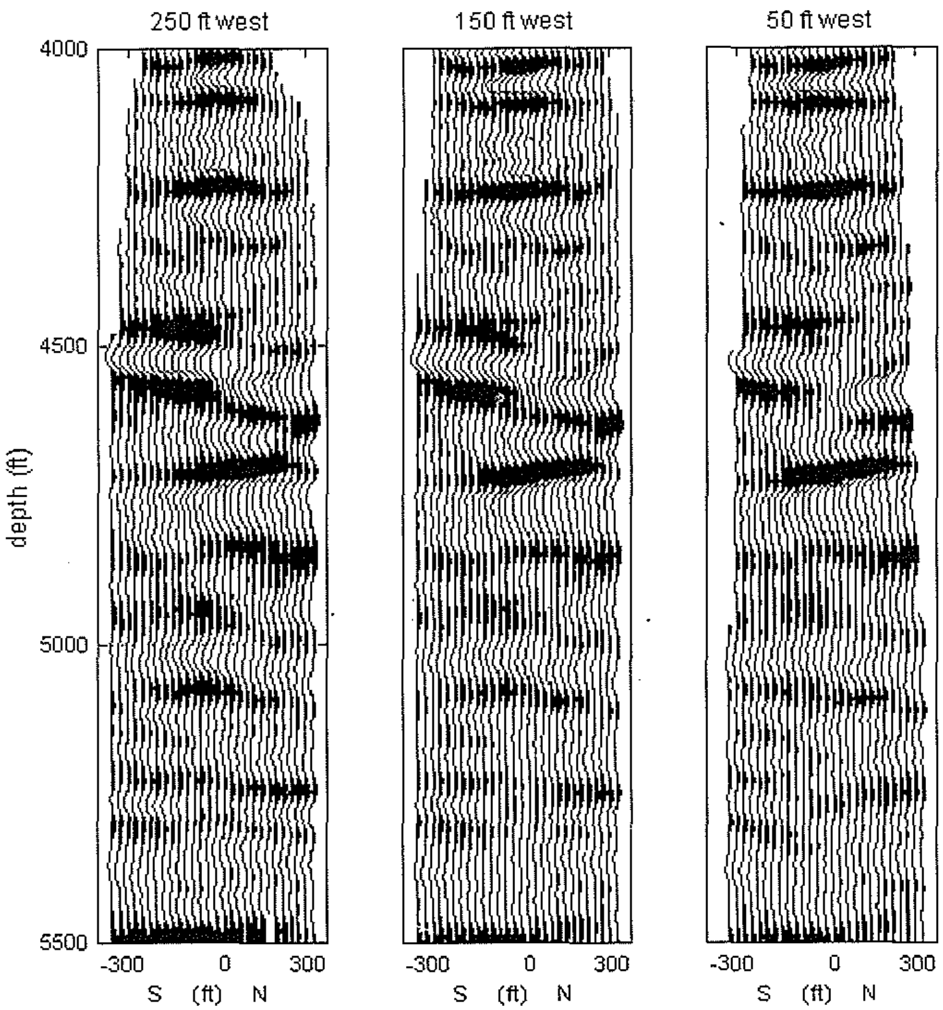

Figure 4: Slices of the migrated image. Left is on-reef, to the south. All distances are relative to the wellhead of the source borehole. See text for discussion.

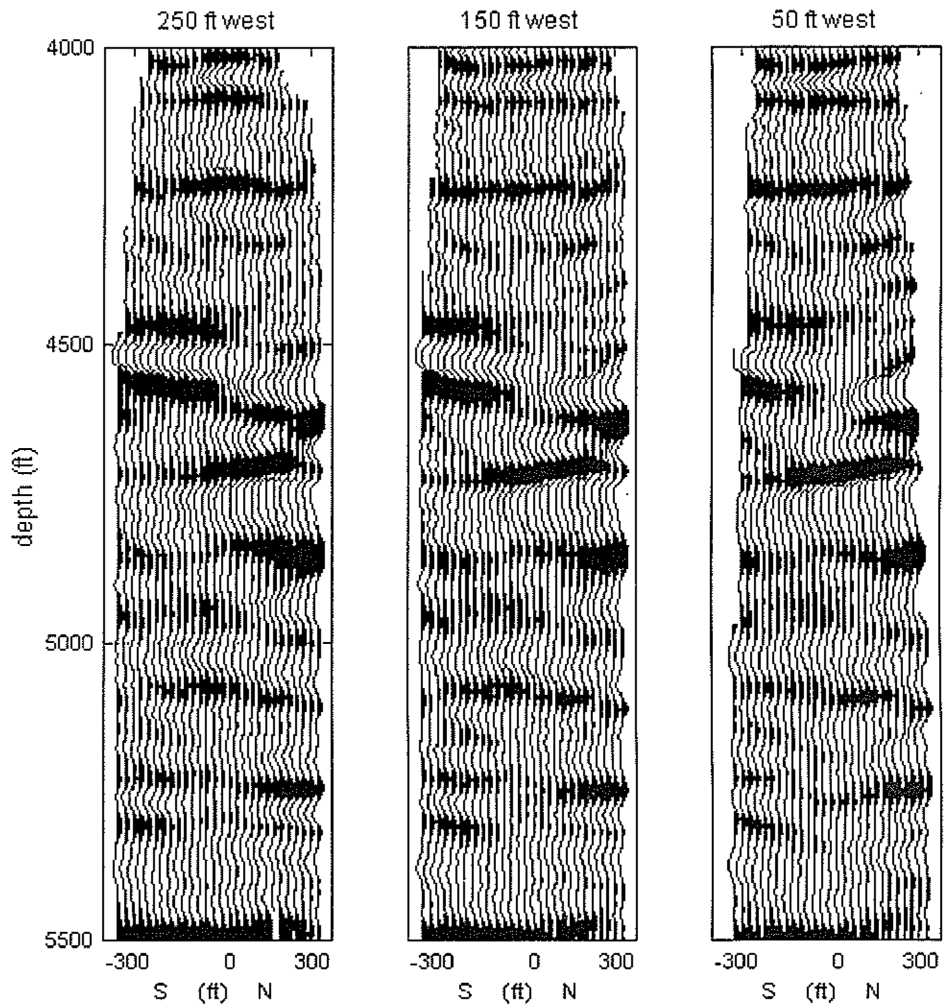

Figure 5: Same image slices as in Figure 4, corrected for array illumination.

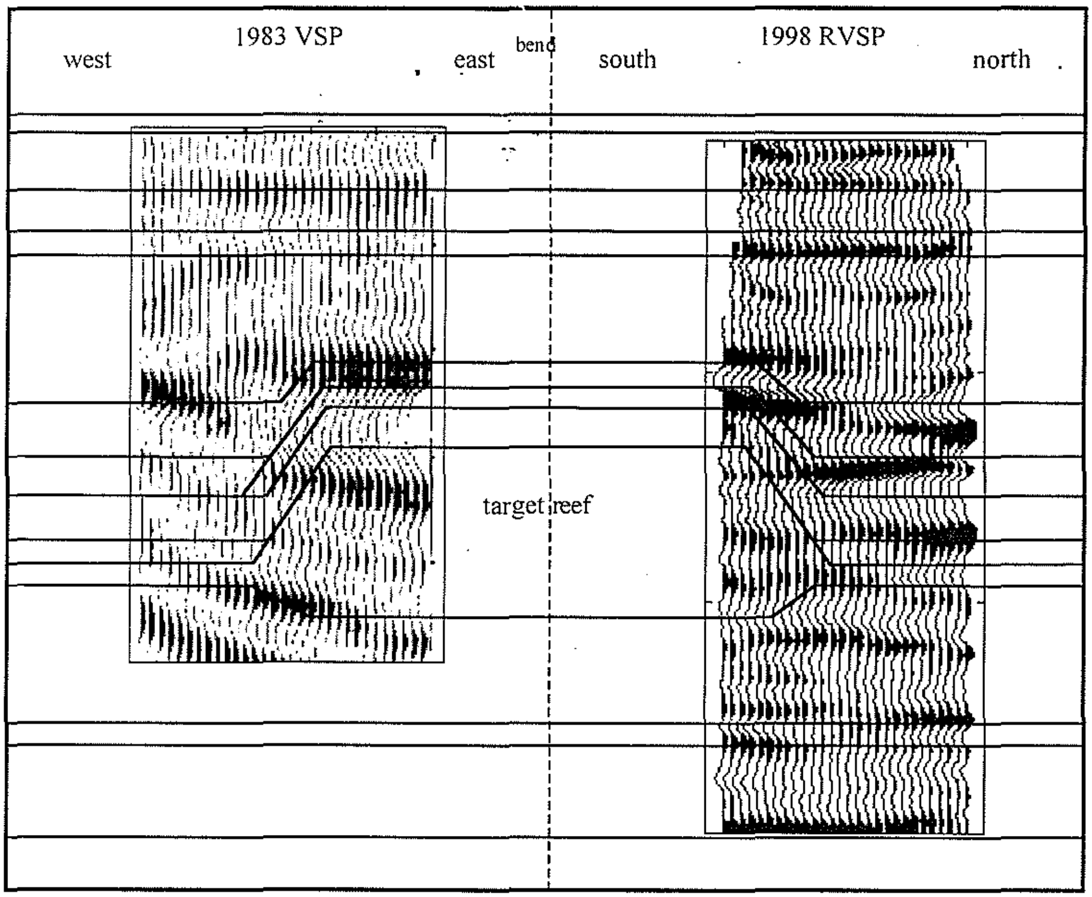

Figure 6: Comparison of test site images. On the left is a depth migrated image (Keho and Beydoun, 1988) from surface vibrator VSP data (single source, offset 4000 ft) acquired in the MIT Burch borehole in 1983. On the right is a depth migrated image from the 1998 RVSP data with the downhole source in the MIT Stech well. The earth model is shown.