Introduction

Modern processing of vertical seismic profiles (VSP) has remained static for many years. Wave field separation is applied to estimate upward and downward traveling waves (Hardage (1983); Yilmaz (1987)). Each such wave field is then processed independently to obtain a subsurface image could be correlated with more traditional surface measurements. After processing several VSPs using standard techniques, we concluded that the traditional methodology provided neither the image quality we desired nor the ability to directly extract both reservoir and local model parameters. Consequently, we developed an approach that opened up the possibility to achieve both of these goals simultaneously. Hopefully the examples below will show that our approach can, indeed, produce high quality images and that the technology can be used to perform high quality inversions.

We discuss a robust reverse-time-migration approach for imaging, angle gather analysis, and full waveform inversion of vertical seismic profiles (VSP). We show that our method significantly improves the ability to produce high quality images and near-borehole model parameters. We demonstrate that, even when sampling is not optimal, our method can still provide higher quality subsurface images then more traditional methods. Through a densely sampled 2D walkaway synthetic, we show that full waveform inversion is a viable process for extraction of near-borehole model properties. We anticipate being able to apply prestack inversion (LMR) methods to enhance extraction of reservoir properties.

Method

As described, the traditional approach to VSP processing begins by separating up- and down-going wavefield components at the borehole. This of course does not take into account that the wavefields change direction away from the borehole, but also that “up” and “down” are not the only two directions of interest; any correlation between two different components of the wavefields is of interest. Thus, any separation must be continuously applied as the fields propagate.

We originally developed our RTM imaging condition motivated by the desire to improve amplitude response and to avoid the well-known RTM imaging artifacts present in cross-correlation imaging (Baysal et al. (1983)). Such artifacts are usually attenuated during post processing with a low-wavelength filter, but can be better handled with a realization that the problem is caused by an increasing difficulty in distinguishing actual reflections from copropagating source and receiver wavefields at high opening angles. The solution then depends at least partly on estimating the opening angle for each piece of the image. Of course, creating true angle gathers from an RTM can be much more costly than the modeling and imaging, so our technique accomplishes this without the intermediate creation of angle gathers. The problem is more urgent and more complex with VSP geometry, but we found that our approach adapted well. The first verification of the validity of the approach was an improved response in full waveform inversion. In imaging VSPs, high-angle responses are much more prevalent. Sometimes, as in the examples in this paper, large features such as water bottoms, tops of salt, and others, are entirely imaged in the high angle domain, so it is crucial to handle the amplitudes correctly. We consider our success with VSP imaging to be another proof of the validity of our approach.

Figure 1 Borehole receiver gather from a densely sampled synthetic VSP.
Examples

Imaging

Of course, fundamental to all of this is an imaging technique that at least matches existing algorithms for surface data. We show one live-data example with rather poor borehole acquisition as an example of how our approach can exceed traditional VSP processing, and in some ways provides a better image than that achieved with surface data. In Fig. 3, we can see that the VSP image shows a very good match to the surface data near the water bottom, and is a great improvement over the traditionally processed VSP. It is worth noting that much of the detail evident in the comparison shown in Fig. 3 in our VSP and the surface image is not present in the model. Further examples will be shown of good matches to occlusions in the salt, etc.

Figure 2 (Spiral acquisition with location of 40 borehole receivers at bottom of salt.

Figure 3 Comparison of Panorama VSP, Surface image, Traditional VSP, and imaging $V_p$ model
Amplitude-compliant Angle Gathers

Although in complex geometries, it can be difficult to use angle gathers for vertical updating, for example, properly behaving angle gathers are a further indication of the correctness of the approach, and can of course be used in verification of model improvements, traditional tomography, etc. We have used the Hess-VTI model to synthesize a walkaway VSP and to generate angle gathers demonstrating the same AVA behavior as exists in the surface acquisition; there is a strong AVA effect present at the top of the central reflector, due to the density contrast there. Imaging with an isotropic model causes a deviation in the wide-angle response which mostly eliminates the reflection in the migrated image, just as it does in the surface acquisition.

![Image of Hess-VTI model with well and angle gathers](image_url)

**Figure 4** Hess-VTI model, with well. The “turtle” at the center of the model is difficult to image without anisotropy due to a strong AVA response.

![Image of walkaway VSP shot over Hess-VTI model and isotropic model](image_url)

**Figure 5** Left - Image of walkaway VSP shot over Hess-VTI model, with angle gathers. Right - Image using isotropic model, with angle gathers

**FWI**

Finally, the utility of the image in FWI is an essential confirmation of the correctness of the approach. We synthesized a walkaway VSP over the BP/EAGE 2004 salt model (Billette and Brandsberg-Dahl (2005)), as in Fig. 1 with sparse receivers in the near-vertical part of the well, and somewhat denser ones in the lower, more deviated part; see Fig. 6. We conducted FWI with a severely smoothed starting model, and the results are shown in Fig. 7. Although the synthetic acquisition is of course ideal in terms of frequency content, etc, the exercise demonstrates that velocity updates do progress in the correct direction.
Conclusions

We have presented a methodology based on source and receiver reciprocity coupled with reverse-time-migration to achieve what we believe are superior results to more traditional wave field separation methods. Results from a number of 3D VSPs show that even when sampling is poor the results of this methodology are superior to the traditional approach. In addition, our method is fully capable of performing a full waveform inversion of any densely sampled VSP.

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References


