**Introduction**

Vertical seismic profiling (VSP) survey is used as an effective tool for target-oriented imaging around the borehole. It has the potential to provide higher resolution images than surface seismic survey because the receivers are deployed much closer to the objects to be imaged. In recent years, reverse time migration (RTM) has been widely used for VSP to detect complex geologic bodies (Van Gestel et al., 2019). However, RTM is very sensitive to the accuracy of the migration velocity model. If errors are present in the migration velocity model, the migration image may be defocused.

To partially solve this problem, Yang et al. (2019) proposed to stack the extended migration images of subsurface offset extended RTM (Sava and Fomel, 2003) within the half-wavelength limit. The consideration is that seismic waves are actually propagating in a finite-frequency band under the Earth, and the lateral migration resolution is the half-wavelength (Liner, 2016). To save the computational cost, only one random space shift is chose before applying the cross-correlation imaging condition. The resulting method is thus abbreviated as RSS-RTM (RTM with random space shift).

In this study, we apply RSS-RTM to a 2D walkaway VSP field data set. Three-component (3C) elastic seismic data were acquired. Dedicated data preprocessing is performed to get upgoing PP data as the input for acoustic RTM. The results are verified by comparing with the surface seismic PSDM image. To demonstrate the importance of proper data preprocessing, we also utilize the raw Z component to perform RTM for comparison.

**RTM with random space shift**

The imaging condition for RSS-RTM is formulated as (Yang et al., 2019):

\[
\mathbf{m}_{\text{mig}}(\mathbf{x}) = \int dx_s d\mathbf{x}_s dt d\mathbf{h}_t S(\mathbf{x} - \mathbf{h}_t, \mathbf{x}_s, t) R(\mathbf{x} + \mathbf{h}_t, \mathbf{x}_r, t),
\]

(1)

in which \(S\) denotes the source-side wavefield excited from the source location \(\mathbf{x}_s\), \(R\) represents the receiver-side wavefield propagated from the receiver location \(\mathbf{x}_r\), and \(\mathbf{h}_t\) is the random spatial shift at each time step, standing for the half offset between the sunken source and sunken receiver (Claerbout, 1985).

The conventional RTM is the special case when \(\mathbf{h}_t = 0\). In the case when errors are present in the migration velocity model, conventional RTM image may be defocused. In contrast, RSS-RTM could provide a migration image with better continuity.

**Field data test**

To demonstrate the effectiveness of RSS-RTM, we apply it to a 2D walkaway VSP data set. 3C geophones were placed at 126 recording levels along the well, with an interval of 20 m. The sources consisted of a combination of dynamite and Vibroseis truck. There are 269 shots in total and the shot interval is around 20 m, with a variation within ± 6 m. We only use 75 shots for imaging by decimating from every three shots. The entire walkaway line extends up to 7000 m. The surface offset ranges from -2985 m (SE of the well) to 4015 m (EW of the well). The acquired data has a frequency range of 5 to 80 Hz. The recording length is 6 s, with a time sampling interval of 2 ms.

During acquisition, the survey line has some minor deviations and discontinuities in the areas with local infrastructures. A 2D acquisition geometry projections for both shot and receiver lines are applied to the data as seen in Figure 1. The surface walk-away line and the receiver line have been projected to a least-square fitting line and the inline plane, respectively.

We have carried out careful preprocessing of VSP data to assist for better imaging. Figure 2 shows the main steps for the data preprocessing. After loading the data, we applied autocorrelation to the Vibroseis data to obtain the zero-phase responses. The 3C geophone records signals in three orthogonal
directions that are not necessarily along with the wave polarization directions. We applied a two-step hodogram analysis and redistribute the downgoing vertical and horizontal wave energy to different channels (DiSiena et al., 1984). The horizontal rotation was first applied between two horizontal channels X and Y. The downgoing P-wave energy is maximized in $H_{\text{max}}$ and minimized in $H_{\text{min}}$. $H_{\text{min}}$ is now rotated to the transverse direction of the source-receiver plane. The vertical rotation between Z and $H_{\text{max}}$ further redistributed the downgoing P-energy into $P_{\text{max}}$. Figure 3 shows an example shot with the offset of around 850 m. After the two-step rotations, the Direct channel was rotated towards the direct incident P-wave direction and the Radial channel to the perpendicular direction to the source receiver line. Thus, the downgoing P-waves are maximized in the Direct channel. The P-wave reflections are distributed more in the Radial channel, while the Sv-wave reflections are dominant in the Direct channel. We further applied the median filter, F-K filter, and ray-tracing based time-variant orientations to separate and enhance the upgoing and downgoing P- and S-waves. A following deconvolution is applied to improve resolution and remove multiples.

The migration velocity model is obtained from surface seismic data. It is discretized into $393 \times 1601$ grids, with the grid interval of 25 m x 5 m. Only the target area is shown in Figure 4a. The corresponding PSDM image from surface seismic data is shown in Figure 4b. The steeply dipping structure marked by red oval is not clearly resolved.
Figure 3: The preprocessing steps illustrated with an example shot. From the left to right: the raw Z and X components, the Direct and Radial channels after the two-step hodogram rotations, the enhanced upgoing P-wave shot gather, and the upgoing P-wave shot gather after deconvolution.

Figure 4: (a) The migration velocity model, and (b) the PSDM image from surface seismic data.

The conventional RTM image is shown in Figure 5a. The illumination area is smaller than the surface seismic survey. The migration smile noises are quite strong, as marked by red arrows. It is not easy to identify continuous geological structures, especially in the deep part. After RSS-RTM, the image quality becomes much better, as shown Figure 5b. The migration smile noises are effectively attenuated. Three steeply dipping reflectors are continuously revealed. The reflector marked by blue arrow has a higher resolution, and the reflector marked by red oval can be more clearly recognized than those from surface seismic PSDM image in Figure 4b.

As we have mentioned before, proper data preprocessing is very important for seismic imaging. For comparison, we use the raw Z component as the input for conventional RTM, and the result is shown in Figure 5c. It is noisier than the image in Figure 5a, especially at the shallow part. This is partially due to the S wave contained in the raw Z component. The RSS-RTM image using raw Z component is shown in Figure 5d. The image quality is better than in Figure 5c. Nevertheless, it is not easy to figure out the reflectors marked by blue box. The steeply dipping structure marked by blue arrow is not as continuous as in Figure 5b, because the P wave in other components are not fully utilized.

Conclusions

We have successfully applied the RSS-RTM to a VSP field data set. The image continuity and focusing have been significantly improved compared to conventional RTM. The VSP migration image has a higher resolution than the surface seismic migration image around the borehole. Dedicated data prepro-
Figure 5: (a) Conventional RTM image from preprocessed data, (b) RSS-RTM image from preprocessed data, (c) conventional RTM image from raw vertical component, and (d) RSS-RTM image from raw vertical component. RSS-RTM provides much better image than conventional RTM. Proper data preprocessing is important to get more reliable result.

Acknowledgements

The authors acknowledge the Singapore Economic Development Board Petroleum Engineering Professorship and the Singapore Ministry of Education Tier-1 Grant R-302-000-182-114 for their financial supports. We would also like to thank BGP for providing the VSP field data and for the permission of publication.

References