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Practical Aspects of Subsalt Tomography Using Reverse Time Migration Based Angle Gathers

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SUMMARY

Due to the accuracy of the Reverse Time Migration (RTM) algorithm, RTM angle gathers show more coherent and correct moveout subsalt events than Kirchhoff offset gathers, potentially providing a more reliable input for tomography. We have developed a robust, efficient, RTM angle gather generation method. It has the flexibility to incorporate geological knowledge for low signal-to-noise (S/N) areas. Because angle gather tomography targets subsalt areas, it is not necessary to trace rays through salt, thus avoiding the limitations of ray-based tomography, making it a useful tool for subsalt velocity model building.

Introduction

Deriving the subsurface velocity model from the seismic data set is a key step in seismic imaging. Tomography has been used routinely as a velocity model building tool based on the depth domain common imaging gather (CIG) implementation. Firstly, CIGs are constructed by running Kirchhoff migration using the current velocity model. Next, moveout residuals, picked from CIGs, are back-projected along ray paths through the velocity model by conventional tomography. The accuracy of the tomography solution is constrained by the limitations of ray tracing. Ray tracing is a good approximation of wave propagation for high frequencies (i.e. short wavelengths). It is valid when the velocity model is smooth on the scale length of a wavelength. This validity condition breaks down in the vicinity of a salt boundary with a sharp velocity contrast. When rays fail to go through the salt accurately, ray tracing cannot match the surface offset information, so the back projection of surface-offset-indexed migration residual is not accurate. Not only the ray tracing through strong velocity contrast is difficult, the conventional Kirchhoff CIGs will fail to provide adequate S/N and with proper moveout events under these strong velocity contrast, due to the single arrival ray tracing in the Kirchhoff algorithm.

Reverse Time Migration (RTM) is a wave equation solution and propagates two-way band limited waves properly. It therefore has the ability to image subsalt areas. The output of angle-domain common image gathers (ADCIG) from RTM provides improved inputs both in better signal-to-noise ratio and in more accurate moveouts to the tomographic update of subsalt velocity model.

Angle information from RTM angle gathers provides the initial shooting direction for ray tracing from the reflection point, to ensure the repeating of wave paths during imaging. By limiting ray tracing to the subsalt sediment areas, conventional ray-based tomography can be implemented in a more effecticent and target-oriented manner. Subsalt tomography based on RTM angle gathers takes advantage of the superior accuracy of RTM propagation and the efficiency of ray-based tomography for inversion. In this paper we present a cost effective approach to generating 3D RTM angle gathers and discuss various practical aspects of RTM angle-gather tomography and their influence on velocity model building in subsalt areas.

Method

Figure 1 shows the source and receiver propagation wavefield for RTM through a complex salt body. For RTM, the receiver wavefield is generated by injecting the received trace backward at each time propagation step, so the wavefield (Figure 1b) becomes much more complex compared to the source wavefield (which only injects the source once, Figure 1a). Consequently, we should be able to get a more reliable angle propagation for the source wavefield than for the receiver wavefield. We extend the idea proposed by Zhang and McMechan (2011) (for a 2D simple synthetic case) to 3D and apply it to real data. The basic idea is that RTM angle gathers can be generated from the source wavefield propagation direction and structure dip (Figure 1c). One way to calculate the source wavefield propagation is to use the Poynting vector (Yoon and Marfurt, 2006) to compute the direction of energy flux in the space-time domain. Structure dip (reflection surface dip) can be obtained by calculating the dip from the RTM images.

Since only the relatively simple source wavefield propagation is used, this approach can generate more reliable angle gathers. Compared to conventional RTM, the extra cost is in the calculation of the source wavefield propagation and the conversion, for every shot, to subsurface reflection angle by combining with the structure dip and then stacking together. This approach is much more efficient compared to other methods (Xu et al., 2010). This makes it possible to generate dense RTM angle gather outputs for the subsequent subsalt tomography updates and for post-migraton enhancements such as residual multiple attenuation and flattening before stack.. One challenge for subsalt RTM angle gather generation is the fact that the signal-to-noise ratio is often low due to poor illumination.

Our approach benefits from the stacking of RTM images to improve the signal-to-noise ratio for structure dip.

In structurally complex areas, interpretation guided structure dip estimation could help further reduce the uncertainty in the estimation step. Determining the azimuth and dip of the reflection surface based on *a-priori* knowledge of the subsalt structure would also help to suppress noise in the angle gathers.

(a) (b) (c)

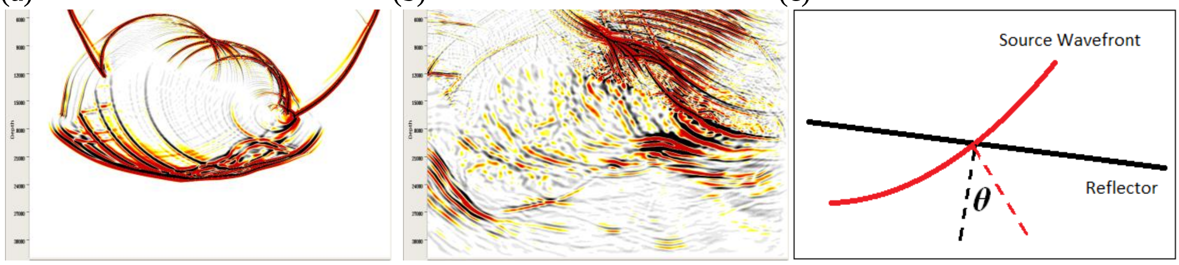

Figure 1: *(a) Source side wavefield. (b) Receiver side wavefield. (c) Incident angle is the difference between source wavefront and reflector normal direction.*

The coarse shot spacing and cable spacing typical in seismic acquisition causes sampling issues in the angular domain (Tang et al., 2011). Uniform receiver spacing introduces irregular sampling in the angular domain. For shallow reflections, near angles are under-sampled and large angles are over-sampled, while for deep events, under-sampling is observed at large angles due to inadequate surface offset coverage. This leads to problems for curvature picking when the velocity model is inaccurate. Depth- and angle-variant extrapolation is implemented to mitigate the under-sampling issue in the angle gathers. The Jacobian of transformation between subsurface azimuth and dip and acquisition surface coordinates can be used to determine extrapolation width. Figure 2 shows the improvement in continuity of angle gathers after extrapolation.

(a) (b)

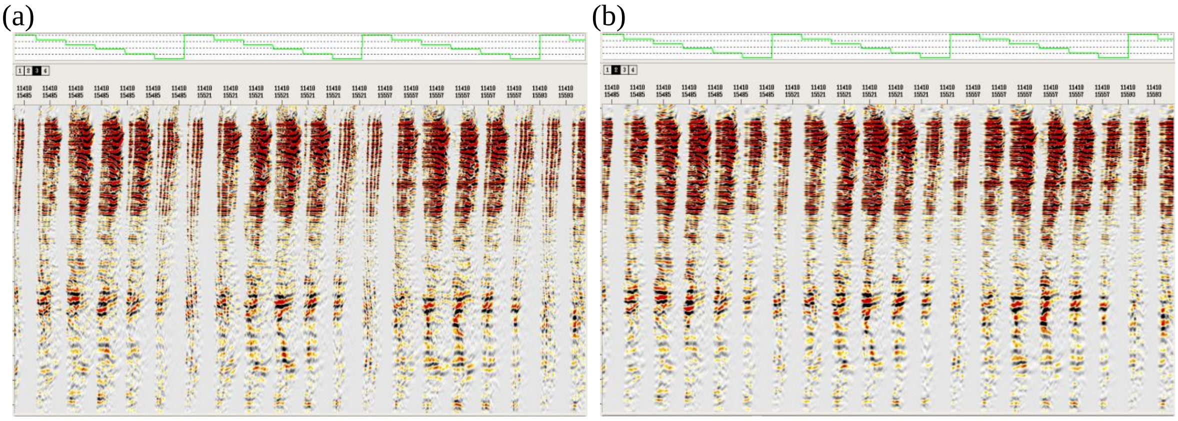

Figure 2: *(a) RTM angle gather before extrapolation, (b) After extrapolation. Azimuth is 0 - 150 degrees with spacing of 30 degrees, plotted on top of the figures. 90 degrees is the dominant survey direction.*

The role of Wide Azimuth (WAZ) data in subsalt imaging is firmly established. WAZ acquisition provides rich azimuth coverage that gives good illumination in subsalt areas. Furthermore, two orthogonal WAZ surveys can be merged to provide close to full azimuth data in an existing WAZ area (Cai et al., 2011; Baldock et al., 2011). In turn, the enhanced azimuth information gives a significant uplift in our ability to refine azimuth-dependent velocity variations at subsalt area. For WAZ acquisition, the CMP binned data is typically partitioned into azimuth sectors. Curvature picking and ray-tracing are performed for each azimuth sector separately; the ray paths for the different azimuth sectors are then combined by weighting, based on coherency attributes and solved by inversion.

Automatic common image gather curvature picking, extracting moveout residuals, is important in tomographic inversion. The conventional CIGs are usually indexed by surface offset (Figure 3a). This kind of CIG suffers from migration artifacts, if the data contain multiple arrivals, when the velocity model has strong lateral variations. These artifacts create difficulties for tomography. In contrast, ADCIGs from the output of RTM indexed by local reflection angle and azimuth angle are clean and provide accurate information between moveout and local incident angle. In this case, however, the hyperbolic curvature assumption is no longer valid because residual curvature is indexed by the reflection angle. Compared to offset gathers, angle gathers appear to be stretched at small angles and squeezed at large angles, (Figure 3b) due to the uniform angular sampling corresponding to the irregular offset sampling. The hyperbola equation is revised to adapt the relationship between moveout and angle by incorporating the depth and offset ratio.

(a) (b)

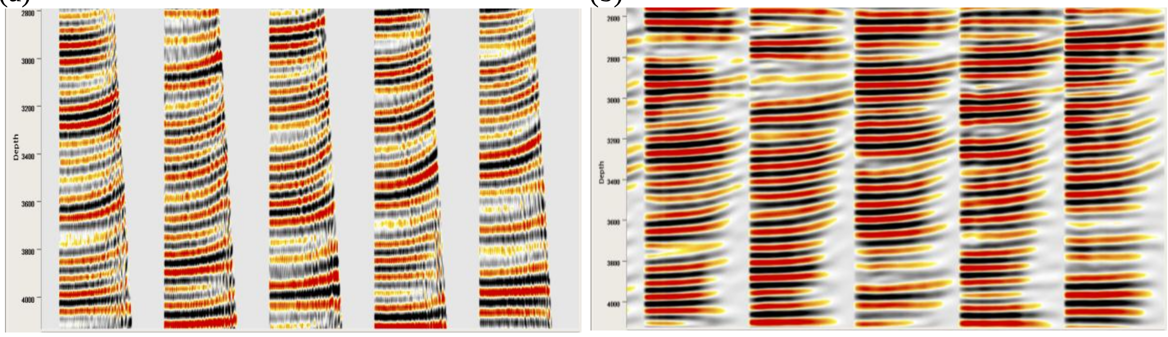

Figure 3: *(a) Kirchhoff offset gathers. (b) RTM angle gathers.*

Overall, tomography tries to solve an ill-posed inversion problem in a least-squares sense. Thus it is important to make it as well-conditioned as possible. Proper regularization is applied using geological constraints to make the model conform to geological dips. It also helps reduce ambiguity in null space and stabilizes the inversion problem. For low signal-to-noise area, like the root of a salt body, this constraint helps generate a geologically feasible velocity model that fits the data.

Examples

Subsalt tomography using RTM angle gathers was tested on data from TGS' Kepler WAZ survey in the Gulf of Mexico. After the salt model was built, Tilted Transverse Isotropic (TTI) Kirchhoff with turning waves and TTI RTM were used to generate Kirchhoff offset gathers and RTM angle gathers.

(a) (b)

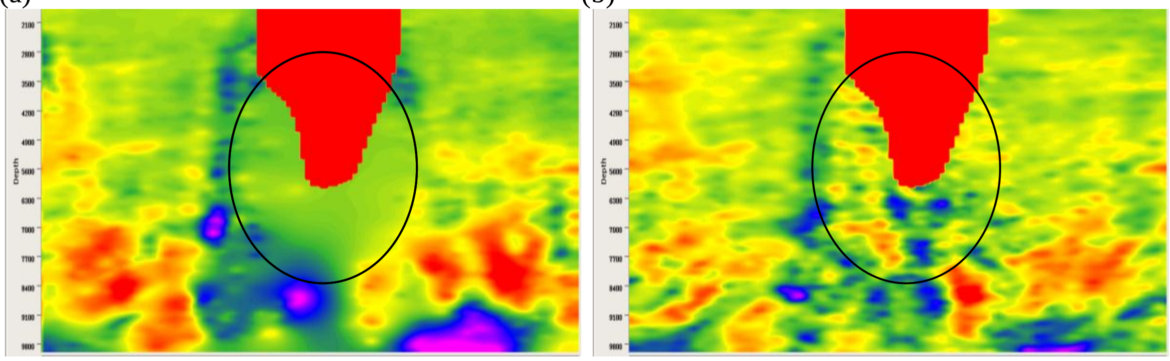

Figure 4: *(a) Residual picking from Kirchhoff offset gathers. (b) Residual picking from RTM angle gathers. Salt body is plotted in red.*

Figure 4 shows the residual picking for 90 degree azimuth, which is the dominant survey direction, on the two gathers. In a sediment-only area, the two approaches have a very similar pattern in curvature picking but different values because angle gathers have different curvature shapes compared to offset gathers. Beneath the salt body, however, (inside the circle), RTM angle gathers have more coherent picking than Kirchhoff offset gathers. This is because RTM wave propagation is more accurate than Kirchhoff beneath salt. The ray tracing for tomography will use the RTM angle gather's angle as its take-off angle then start from the reflection point and stop at the base salt to avoid going through salt. After the velocity update, TTI migration is used to generate stack images for comparison, Figure 5 demonstrates that the velocity update based on RTM angle gathers gives better focusing of reflections in subsalt areas, resulting in structures that are more continuous and suitable for interpretation.

(a) (b)

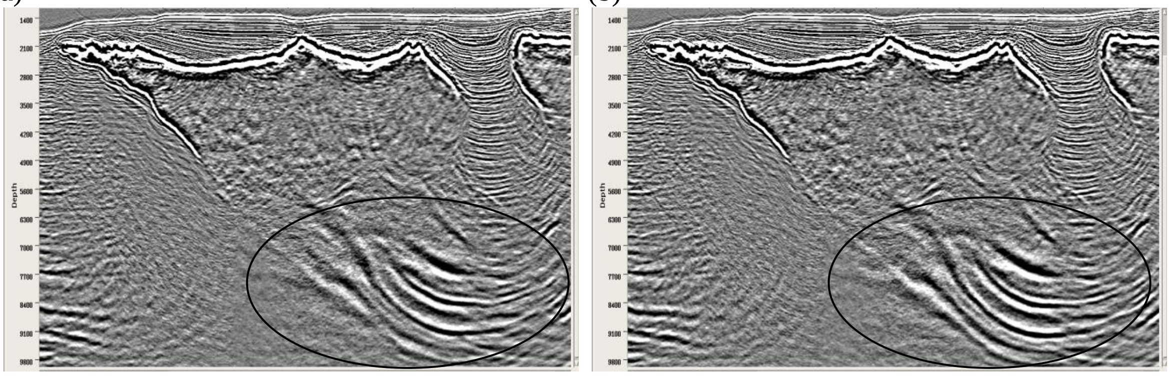

Figure 5: *(a) Stack image before subsalt tomography update with RTM angle gathers. (b) Stack image after update.*

Conclusions

We have developed a robust and efficient RTM angle gather generation method. RTM angle gathers show more coherent events than Kirchhoff offset gathers in subsalt areas, thus they provide a more reliable input for tomography. Since the angle gather tomography targets subsalt areas, it does not need to trace rays through salt and thus avoids the limitations of ray-based tomography. It can be a useful tool for subsalt velocity model building.

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