Converted-wave controlled-beam migration for vector-offset volumes
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Summary

Kirchhoff migration is routinely used for converted-wave (PS) imaging, partly because the suite of high-fidelity imaging algorithms available for PP seismic reflection data is not yet widely available for PS waves. This paper discusses the implementation issues of strong and weak TTI PS equations and presents application results for a new PS controlled-beam migration (CBM) algorithm working in the common-offset vector (COV) domain. CBM is a specialized version of Gaussian-beam migration aimed at signal-to-noise ratio enhancement.

Introduction

Converted-wave data have been processed since the early times of seismic exploration. Unfortunately, converted-wave imaging technologies have not developed as fast as P-wave technologies. In fact, Kirchhoff migration is still the workhorse routinely employed in pre-stack depth imaging projects involving converted-waves. The main advantage of Kirchhoff migration over reverse-time and beam methods is that it is flexible with respect to the migration domain (common offset or common shot) and can therefore more easily handle sparse receiver acquisition geometries, like OBC (Ocean Bottom Cable) and OBN (Ocean Bottom Node). Moreover, converted-wave Kirchhoff offset-domain image gathers (ODCIG) can be used in a joint PP and PS tomographic workflow which better constrains the seismic anisotropy of the subsurface (Audebert 2001, Tsvankin 2006, Rønholt et al. 2008).

However, the majority of Kirchhoff algorithms do not allow multi-pathing to the image points. Only a single arrival, either with minimum traveltime or shortest ray path, is typically chosen. Therefore, the resulting ODCIGs suffer from operator inaccuracies, which make automatic RMO picking prone to error in complex geological settings. As a local slant stack migration (Hill, 2001), Gaussian Beam Migration (GBM) operates in both localized space and localized angle. Therefore, GBM inherently handles multi-pathing and produces better images than single-arrival Kirchhoff by reducing artifacts and migration swings. Additionally, GBM preserves key features of Kirchhoff migration such as steep dip and overturned event imaging, efficient incorporation of anisotropy, including TTI (Notfors, 2006) and orthorhombic (Xie, 2011), which play an important role in structural imaging in general and in fault imaging in particular.

As a specialized version of beam migration, Controlled Beam Migration (CBM) enhances the signal-to-noise ratio of images and it has proven to be a powerful imaging tool which can deliver clear, easy-to-interpret structural images in complex areas (Vinje et al., 2008, Gray et al., 2009). CBM has been widely used for velocity model building, structural imaging and imaging of sparse and noisy data (Ting and Wang, 2009). The superior quality of migrated offset gathers allows for an accurate residual moveout (RMO) picking, which outperforms tomographic updates based on Kirchhoff imaging.

We have implemented a converted-wave CBM (PSCBM) which models both real and imaginary P- and S-wave traveltimes for the source and the receiver leg respectively. In the limit of TTI weak anisotropy the P-wave Eikonal equation can be exploited for S-wave ray tracing following the recipe in Tsvankin (2006). However, this approximation breaks down in complex areas with strong lateral symmetry-axis variation. For this particular situation, an exact or strong anisotropy formulation for the S-wave ray tracing is recommended.

Hill’s beam migration was originally derived for common-offset (CO) narrow-azimuth data domain, which is not the most natural choice for OBN. If the node spacing is much greater than the source spacing common-offset vector tiles become very large, containing a wide range of offsets and azimuths. However an effective regularization strategy or/and an increase in the bin size can still make PSCBM a viable option for converted-waves common-offset vector imaging.

In this paper we will present a weak and strong anisotropy PSCBM formulation and we will discuss advantages and disadvantages of imaging seabed PS-data in the vector-offset domain. Finally, we will present a comparison between PS-Kirchhoff and PSCBM stacks and gathers for an OBN field data set which has been 5D regularized in common-offset common-azimuth (COCAZ) sectors.

Anisotropic TTI ray tracing for PSCBM

Whilst CBM handles multi-pathing, it is important to keep in mind that any beam migration is based on asymptotic ray-theory. Real and imaginary travel times are computed by solving kinematic and dynamic ray tracing equations which are the first and the second derivatives of the Eikonal equation $H(x,p) = p^T p v^2(x,n) - 1$ with respect to the position $\mathbf{x}$ and the slowness vector $p$ (Cerveny, 2001). The function $v^2(x,n)$ is the squared phase velocity which, in a heterogeneous anisotropic medium, depends on medium properties in the local point $\mathbf{x}$ and on the wave direction $n = \frac{p}{\|p\|^2}$. In a TTI anisotropic medium P- and SV-waves are coupled and so are their phase velocity functions. These function are given by
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\[
2V^2_P(x, n) = V_{p0}^2 \left\{ 2(1 - f) + f + 2 \varepsilon \sin^2 \theta \right. \\
\left. \pm \left[ f + 2 \varepsilon \sin^2 \theta \right. \right. \\
\left. \left. \left( f + 2 \varepsilon \sin^2 \theta \right) \right) \right. \\
\left. \left. + 8 \left( \varepsilon - \delta \right) \sin^2 \theta \cos^2 \theta \right] \right\} \\
\]

(1)

where \( \varepsilon \) and \( \delta \) are the Thomsen parameters, \( f = 1 - \frac{V_{p0}^2}{V_{s0}^2} \)

depends on P- and S-wave velocities along the symmetry axis and \( \theta \) is the angle between the phase unit vector \( n \) and the direction of the symmetry axis. The square root sign specifies the P- (+) or the S- (-) wave phase velocities respectively. In the limit of weak elastic anisotropy, equation 1 decouples in two separate expressions for the P- and S-wave phase velocities:

\[
v^2_P(x, n) = V_{p0}^2 \left\{ 2(1 - f) + f + 2 \varepsilon \sin^2 \theta \cos^2 \theta + 2 \varepsilon \sin^4 \theta \right\} \\
\]

(2a)

\[
v^2_S(x, n) = V_{s0}^2 \left\{ 2(1 - f) + f + 2 \varepsilon \sin^2 \theta \cos^2 \theta + 0 \right\} \\
\]

(2b)

where \( \sigma = \frac{V_{p0}^2}{V_{s0}^2} (\varepsilon - \delta) \). We can get equations 2b from 2a by substituting \( V_{p0} \leftarrow V_{s0}, \delta \leftarrow \sigma \varepsilon \), \( \varepsilon \leftarrow 0 \). This approach (Tsvankin, 2006) effectively allows the use of existing P-wave ray tracing code in CBM to model PS-wave kinematics in the weak elastic case. Two different velocity models are used to compute PS-wave traveltimes:

- a P-wave \( (V_{p0}, \delta, \varepsilon, c_x, c_y) \) model for the source-side P-ray
- an S-wave \( (V_{s0}, \sigma, 0, c_x, c_y) \) model for the receiver-side S-ray, where \( c_x \), and \( c_y \) are the inline and crossline symmetry axis cosines. However, this is only an approximation, which will break down where the TTI anisotropy is no longer weak and will compromise the final image especially in the presence of steep lateral symmetry axis variations. For this particular situation, the exact or strong anisotropy S-ray tracing formulation based on equation 1 is recommended. To implement equation 1, we adjusted the ray-tracing equations which now require an extra computational effort to evaluate the derivatives of the S-wave velocity \( V_{s0} \) required by the receiver-side S-ray tracing.

OBN imaging in vector-offset volumes

In his famous 2001 paper, Hill presents a very elegant derivation for pre-stack Gaussian-beam imaging whose strength resides in the common-offset (CO) binning of the input dataset.

The local slant stack is performed in the midpoint direction where the data look geologically meaningful and less prone to aliasing problems than in the common shot/receiver domain where the reflected energy comes from more dispersed subsurface points. Moreover, the beam migration loop over the midpoint ray-parameter traces ensures the imaging of most of the multi-pathing energy in the data. By requiring CO or COV input for narrow- or wide-azimuth surveys respectively, however, any beam method is less flexible than Kirchhoff imaging in accepting input data acquired with sparse sources or detectors. If the receiver spacing is much greater than the source spacing, which is usually the case for OBN surveys, then COV tiles become very large, containing a wide range of offsets and azimuths. These need to be regularized in order to build COV volumes for migration: all offsets and azimuths need to be made equal in a given COV tile. This processing step has been performed successfully for P-wave data, but is more difficult for PS-waves.

This may at first be thought as a contraindication for COV PS-wave migration. However, relying on PS-wave 5D interpolation allows the fruition of CBM migration benefits, which, amongst the others, are sharper and cleaner images and gathers, plus the fact that gathers are a side-by-product of COV processing and computational scalability. The following real data test is the evidence that an effective regularization can still make PSCBM a viable option for converted-wave common-offset vector imaging and therefore a precious tool for velocity model building by ray-based slope tomography (Guillaume et al. 2008).

PS-regularization can be very challenging especially in the near surface, where it is most needed. (Figure 1, above 1.8 km). However, PS-regularization can still provide effective results if it is applied in a target oriented mode. Following this procedure, we can get well populated and well behaved common-offset sections that PSCBM can image and then feed into a tomographic depth model-building workflow.

Field data Example

This section will briefly describe a PSCBM result from a North Sea OBN field dataset, where the comparison with a Kirchhoff image and gathers proves the benefit of CBM in COV model building. The dataset has been acquired using 1200 seabed nodes whose spacing is 300m and a shot carpet with source spacing 30x30m. The data have been COCAZ-regularized in 8 azimuth-sectors and 8-offset rings in order to get ODCIG for PS depth velocity model building. A COCAZ cube is technically a COV cube where the vector offset is represented in polar coordinates. The CBM algorithm can image either COV or COCAZ, since the common-offset, narrow-azimuth assumption holds for both. Figure 1 shows the stacked migrated image using PS-Kirchhoff (a) and CBM (b) migration in the weak-anisotropy approximation.
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The Kirchhoff image is less continuous than the CBM stack. Overall the CBM image looks cleaner and enhances the SNR of the geological structures keeping the operator noise lower. However, CBM provides a more evident uplift in ODCIGs (Figure 2). The Kirchhoff ODCIGs (Figure 2a) are extremely noisy and in the deeper part RMO is hard to distinguish from noise. Any RMO auto picker will be prone to errors when working on these gathers. On the other hand, when we look at CBM ODCIGs (Figure 2b) The RMO trend is now much clearer and easy to be picked. A tomographic update using PSCBM picks will probably be of better quality than an update based on the Kirchhoff ODCIGs and possibly reveal some deeper structure now hidden in the background noise. As mentioned above one of the key advantages of the conventional CBM is that it enhances the imaging of structures and suppresses noise. With this example, we have that PSCBM can also facilitate PS model building.

Conclusions

Kirchhoff migration is routinely used for converted-waves (PS) imaging. In this paper we introduce a PSCBM algorithm for strong and weak TTI anisotropy. Adapting existing COV CBM code for converted-waves exposed technical challenges related to data regularization and interpolation. On the other hand, the development of a common-node CBM while not completely straightforward, has less intrinsic pre-processing difficulties. Individual nodes acquired with a dense shot carpet normally do not require interpolation. These node records are dense and suitable for RTM (Reverse Time Migration), or CBM. However, CBM in COVs has many practical advantages, making it a good candidate to become a routinely used tool for converted-wave depth model-building.

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Figure 2: Kirchhoff (a) and PSCBM common-azimuth ODCIG. The data has been COCAZ regularized for model building purposes.
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References are provided in a field on the submission website and not included here!


