Controlled beam migration: a versatile structural imaging tool

Vetle Vinje,1* Graham Roberts2 and Roger Taylor 2 discuss an enhancement of Gaussian beam migration for depth imaging in complex geological environments supported by a number of case studies.

G aussian beam pre-stack depth migration was described by Hill in his 2001 paper. It came at an interesting time for the seismic industry as exploration and development was becoming focused on more complex structural plays in areas such as the North Sea and the Gulf of Mexico. One of the challenges relating to this was finding a suitable multi-arrival imaging method to provide reliable images in complex velocity regimes which often contained salt bodies.

In this context single-arrival Kirchhoff algorithms had reached the limit of velocity model complexity that they were suitable for, resulting in incomplete images and the familiar migration artefacts (‘smiles’). Multi-arrival Kirchhoff algorithms were being developed, but the run-time cost of incorporating several arrivals and associated travel-time tables into the migration made them an unattractive option. There was also the issue of how to manage the amplitude contributions for these multiple arrivals. Multi-arrival Kirchhoff faced competition from the widespread introduction of one-way wavefield extrapolation methods (WEM or wave equation migration), which were seen to be the answer to the multi-pathing problems of the day. However these were still very expensive in relation to the available compute power and lacked many of the attractive features of Kirchhoff migration, such as steep dip imaging and the inclusion of anisotropy, TTI in particular.

Gaussian beam migration presented an opportunity to achieve efficient multi-path imaging, and retain the useful features of Kirchhoff migration which the WEM algorithms lacked. CGGVeritas implemented beam migration (Gray et al., 2002) and has used it extensively as an imaging tool for areas of complex structure (Notfors et al., 2006; Sun et al., 2007; Roberts et al., 2008). Recent further development of the method has resulted in an enhanced version known as controlled beam migration (CBM), a versatile and valuable addition to the depth imaging toolbox. We will demonstrate the benefits of CBM with a selection of examples from around the world which range from the re-processing of legacy data to complex PSDM velocity model building and the imaging of the latest wide-azimuth datasets.

**Principles of Beam migration**

Hill (2001) describes the theory and application of pre-stack Gaussian beam depth migration. The method is based on beams formulated from rays which provide the kinematics and the amplitude weights of the migration. The methodology is developed for common-offset, common-azimuth data, and the migration itself is performed in the ray parameter domain. Consequently, it is well suited for application to conventional narrow-azimuth seismic datasets. As it is a ray-traced method like Kirchhoff it retains many of the Kirchhoff features such as steep dip imaging and efficient incorporation of TTI anisotropy. This makes it an attractive proposition for areas such as the Gulf of Mexico and the North Sea where salt bodies create both steeply dipping events and multi-pathing arrivals.

It is useful to compare the basic principles of Kirchhoff and beam migration. The fundamental mechanism of Kirchhoff migration is the mapping of an acquired time sample to all subsurface locations along the isochrone where the sum of the source and receiver ray path travel time \((t_s + t_r)\) equals the time \(t\) of the sample.

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map multi-arrivals. In other words, if in theory we have the potential to map all possible rays, then we should be able to migrate all possible arrivals. This is in contrast to Kirchhoff migration which only uses rays to generate travel times.

Recent developments of beam migration by CGGVeritas to extend its abilities as a structural imaging tool have resulted in CBM. It shares the same basic principle as beam migration and as such it can be considered a ‘full’ migration which does not require a priori structural information other than the migration velocity model. The main benefits of CBM compared to beam migration are the enhancement of the signal-to-noise ratio of images and the enhancement of steep dips which are both extremely valuable for imaging complex structure.

Applications of beam and controlled beam migration

One of the strengths of beam migration is its convenience. It is fully compatible with the well-established narrow-azimuth common-offset processing workflows, and the more recent wide-azimuth common-offset vector workflows used for Kirchhoff migration. This means that it can easily be incorporated into existing PSDM projects as a final migration product and used for the generation of migrated gathers for velocity analysis.

As mentioned earlier there are several features of beam migration which make it a useful structural imaging tool. The multi-pathing enables it to construct coherent images in the presence of complex velocity structure, which are often heavily contaminated by migration artefacts on Kirchhoff images. The ray/beam basis for the method means that it can image steep and overturned structures, and that both VTI and TTI anisotropy are relatively easy to accommodate. This is complemented by the familiar Kirchhoff ability to efficiently produce target-oriented output (i.e. test lines and gathers) which can be used to quickly validate complex models.

Velocity model building for PSDM projects in complex environments can involve multiple iterations of model update and migration, particularly in scenarios which include salt bodies or anisotropy. It can represent months of work, a large part of which may be interpretative picking of salt body geometry or target horizons for well ties. By offering an efficient multi-pathing migration which is faster than WEM methods and which naturally produces common image gathers, beam migration can play a part in reducing the project cycle-time. CBM in particular can make a significant contribution. Its ability to enhance signal content and steep dips provides a ‘clean’ image which facilitates structural interpretation, potentially speeding up the various interpretation phases of a PSDM project. These benefits are also relevant for the migrated gathers, which are correspondingly ‘clean’ and have better defined events. This results
in higher quality residual move-out information for use in velocity tomography which leads in turn to a higher quality final velocity model and ultimately a superior final image.

Case studies
Beam migration has been used extensively around the world by CGGVeritas to address a variety of imaging challenges:

Example 1: Structural imaging of salt diapirs
The first example comes from the North Sea Central Graben and demonstrates how beam migration improves imaging in the presence of large velocity contrasts, where multi-pathing is likely to occur. Figure 3 shows an inline section through a salt diapir migrated using a final velocity model. The Kirchhoff image is contaminated by migration artefacts related to the discontinuities in the ray paths (and hence travel-time tables) at the salt boundary. The Kirchhoff migration ‘smiles’ interfere with the steeply dipping events on the salt flank resulting in a poor image.

By comparison the beam migration which incorporates multiple arrivals smoothes through these single arrival ray path discontinuities to provide an image relatively free from artefacts. The result is much improved imaging of the steeply dipping sediments on the salt flank.

Example 2: Velocity model building with tabular salt
Sub-salt exploration in the Gulf of Mexico has been a driving force for the development of PSDM algorithms and workflows. The process of velocity model building in this scenario is a lengthy one requiring several iterations to build an accurate salt model and then to update a sub-salt sediment velocity field. Figure 4 shows an example of CBM used for the salt model migration run. At this point the salt body interpretation has been completed and the sub-salt velocity update is starting. Single-arrival Kirchhoff migration is unable to provide a clear image of the pre-salt sediments due to the complex overburden. One-way WEM with its more rigorous treatment of the complex wavefield propagation through the salt is able to generate a clear image of the sediments. The CBM performs very well here and produces a comparable or even better result, with the base of salt and sub-salt sediments very clearly defined. The significance here is that the better the quality of the image and the migrated gathers (in terms of coherent events and signal content), the more effective the velocity update will be, which will lead to better final PSDM results as described earlier.

Example 3: Structural imaging of fractured basement
This unusual example comes from offshore Vietnam where fractured granitic basement forms a reservoir. The productive zones in the basement are the steeply-dipping major fractures which have associated fracture and solution porosity. Data
Figure 6 Comparison of wide-azimuth data imaged with common-offset vector domain Kirchhoff (top), and CBM (bottom) PSDM. The data is from an onshore USA survey over a salt diapir. A 3D CBM COV image gather used in the velocity model building with wide-azimuth tomography is also shown. The CBM image provides improved imaging of the more complex sedimentary structures around the right-hand salt body, and exhibits higher signal content. Despite the wide-azimuth geometry there is an illumination hole below the diapir.

was originally processed with Kirchhoff PSDM which identified some potential drilling targets. The dataset was later reprocessed with CBM and Figure 5 compares the results. The combination of multi-pathing, enhanced steep dips, and improved signal-to-noise ratio provided by CBM makes a huge impact on the imaging result. The basement-sediment contact and the internal fractures are clearly visible both in vertical sections and in depth slices (as shown), allowing more effective identification of drilling targets.

Example 4: Wide-Azimuth imaging onshore
Wide-azimuth datasets are regularly acquired onshore and imaging workflows have been developed to respect their azimuthal content. The conventional narrow-azimuth common-offset approach has been expanded to the common-offset vector (COV) domain to honour the azimuth of offsets. Figure 6 shows a comparison of Kirchhoff and CBM images from a COV workflow for a wide-azimuth land survey over a salt diapir in the USA. The CBM result shows an incremental uplift over the Kirchhoff result, reducing the noise and providing better imaging of the more complex sedimentary structures around the right-hand salt body. However, despite the wide-azimuth geometry there is an illumination hole below the centre of the diapir.

Figure 6 also shows a 3D CBM COV image gather from the survey. The gather contains offsets in the inline and crossline direction which means that velocity analysis and residual moveout picking are now 3D issues. As before, CBM can facilitate automatic picking of these events (now surfaces within the 3D gather) by improving the signal content. This provides better quality residual moveout information to the wide-azimuth tomography and will result in an improved final velocity model.

Example 5: Imaging low-fold onshore data
Land datasets, as well as being intrinsically noisy, can have irregular acquisition geometry and low-fold which will exacerbate the noise problem during imaging. Although data interpolation/regularization can reduce holes in coverage and improve the uniformity of offset classes, there is a limit to what can be achieved particularly at the longer offsets where the gaps in coverage are most pronounced.

Figure 7 shows data from a legacy land survey over a salt feature in North West Europe which was the subject
of a recent reprocessing project. The fold of the data is low and variable and the coverage for mid-to-long offsets is sparse. Kirchhoff migration is noisy throughout and is unable to provide a coherent image below the salt, as expected. The CBM image benefits from a marked improvement in the signal content which brings out the fine structural details such as the faults. Most importantly it provides a more coherent image of the base of salt and the sub-salt reservoir interval.

Summary

Although beam migration started out as a niche imaging application to fill the gap between Kirchhoff and one-way WEM methods, it is now established as a powerful and versatile imaging tool in its own right. This is demonstrated through the range of applications and geographical extent of the case studies presented here.

We anticipate that beam migration will continue to be a valuable part of the imaging toolbox for some time to come. Although the problems of imaging steep dips have been solved with the introduction of two-way WEM methods (Reverse Time Migration), it is still prohibitively costly to use it iteratively for TTI velocity model building. This leaves beam migration as the only efficient multi-arrival method which can perform both of these functions. Irrespective of how long this advantage exists, the fact remains that beam migration is efficient, effective, and fits conveniently into conventional workflows for narrow- and wide-azimuth datasets. In particular ‘enhanced’ beam migrations such as CBM can improve images for data with poor signal content.

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References


