Seismic imaging with multi-layer tomography

Patrice Guillaume,1* Jean-Philippe Montel, 1 Steve Hollingworth,1 Xiaoming Zhang,1 Anthony Prescott,1 Mathieu Reinier,1 Richard Jupp,1 Gilles Lambaré,1 Owen Pape1 and Alexandre Cavalié1 describe the application of multi-layer global tomography to improve the velocity inversion workflow in the modelling and imaging of seismic data.

Pre-stack depth migration (PSDM) for seismic imaging is now commonplace within the oil and gas industry, used for its ability to provide accurate imaging, well ties, and well plans. Quality is not solely due to the choice of imaging algorithms; it is also necessary to consider the velocity model and how it is built.

The use of grid-based reflection tomography is generally accepted as the standard for velocity model estimation. Reflection tomography is driven by dip measurements taken from image gathers, with the assumption that reflection events will be flat if the velocity and anisotropy are correct. Deriving a velocity model which yields the optimum image for reservoir level studies can be a very time-consuming process, particularly in areas with complex geology.

Improving the efficiency of PSDM projects to permit earlier prospect evaluation has become increasingly important. However, maintaining the desired level of model quality within an acceptable timeframe is a significant challenge for existing tomography techniques. The application of a new ray-based multi-layer approach for reflection tomography and the use of a new hybrid velocity model format (Guillaume et al., 2012) together overcome many of the limitations of tomographic methods typically employed on PSDM projects.

Global tomography, i.e., handling the entire model within a single framework of a cell-based model, is unable to accurately represent major velocity and anisotropy contrasts and will not correctly reposition boundaries during the inversion process. In areas with complex geology, these limitations prompt the use of a layer stripping workflow, where the model is subdivided into layers corresponding to major velocity contrasts. However, such a workflow is time-consuming and prone to velocity errors being propagated into deeper layers as the model building progresses.

The development of multi-layer tomography, which utilizes a new hybrid model representation, allows geological boundaries to be explicitly defined, rather than relying on an indirect representation within a regular grid. Hence the horizons can be accurately represented and repositioned by map migration within the inversion. This allows all units in the model to be updated simultaneously without the need for a layer stripping workflow. The result is a more efficient velocity inversion workflow and improved quality of both models and imaged seismic data.

Global tomography and layer stripping

In order to fully appreciate the benefits of multi-layer tomography, it is first necessary to understand the mechanics and limitations of older methods, namely global tomography and layer stripping. Many regions of the world exhibit complex geology with significant velocity and anisotropy contrasts which present major challenges for standard grid-based tomography methods (Figure 1). Using reflection tomography to globally update a model which contains such contrasts can introduce significant errors into the inverted model in the vicinity of the layer boundaries, such that the positions of the layer boundaries in the model become decoupled from the corresponding reflector positions in the updated seismic image.

To help overcome these issues, layer stripping approaches can be used to enable accurate repositioning of velocity and anisotropy boundaries (Evans et al., 2005; Jones et al., 2007). The model is divided into a set of layers defined by major velocity boundaries, which are updated iteratively in a top-down manner. For the update of a particular layer, the velocity and anisotropy from the target layer are allowed to ‘flood’ through the boundary position. Residual move out (RMO) information from PSDM image gathers is used only for the layer to be updated. Following a tomographic update of the layer velocities, the data are re-migrated and the correct position of the base of layer boundary is reinterpreted prior to final calibration to the wells. For a typical North Sea project, as many as six iterations of layer stripping may be required to correctly handle all the major velocity and anisotropy contrasts exhibited by the geology.

As well as being time-consuming, layer stripping is also prone to serious velocity errors. Since the method only treats one layer at a time in a top-down manner, it precludes any intercommunication between connected model layers during the inversion process; it ignores RMO information in other layers whose raypaths may have passed through the updated layer and have therefore accumulated depth delays associated with that layer. This is why layer stripping can be highly unstable for layers which have poor or sparse RMO.

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information. In addition, it is common practice to ‘freeze’ a layer once it has been updated. While this avoids corrupting the depth position of carefully interpreted layer boundaries, it also results in residual velocity errors being propagated into deeper model layers.

**Multi-layer tomography**

Multi-layer tomography is an extension of non-linear slope tomography (Guillaume et al., 2008; Montel et al., 2009). A key feature is a new hybrid velocity format, which uniquely defines the velocity and anisotropy parameters for each model layer as a mesh, while also carrying precise information for the geological layer boundaries.

Data for multi-layer tomography consist of a set of dense dip and RMO picks picked on initial PSDM stacks and common image gathers respectively, along with a set of horizons picked on an initial PSDM stack. Both dip-RMO picks and horizons are kinematically demigrated to build kinematic invariants and horizon invariants respectively (a zero-offset kinematic demigration is performed for the horizons). These invariants together provide a description of the dip and RMO in the demigrated domain and allow rapid evaluation of the effects of model changes by remigrating the invariants rather than a slower remigration of the input seismic data.

The update of the hybrid model (the velocity and the horizons) is done by a non-linear iterative relaxation method. During each iteration, the velocity inside the layers is first updated by non-linear slope tomography and then horizons are updated by map migration from top to bottom. The non-linearity of the process is ensured by the kinematic remigration of kinematic invariants and of horizon invariants. Convergence is rapidly obtained after typically five non-linear updates within the inversion.

Since the layer boundaries are repositioned by map migration during the inversion process, preserving their travel time, the traditional layer stripping workflow can be discarded and all layers in the model updated simultaneously.

RMO information from all layers contributes to the global inversion scheme, resulting in a significant improvement in overall model stability. Furthermore, the integrated horizon information in the hybrid model allows each model layer to be uniquely parameterized and constrained to achieve the best possible inversion result. Layers no longer need to be frozen during the inversion process, since the method will allow any layer to be updated during model building without compromising the result. In addition, since the entire initial model is updated during each pass of multi-layer tomography, improvements to the imaging at deeper reservoir levels can be monitored at all stages of model development.

Improvements in model accuracy and stability naturally translate into improved seismic images with better focusing, more consistent amplitudes, and less reflector distortion.

Discarding the traditional layer stripping workflow and returning to a global approach for complex layered geology also yields significant efficiencies in model building and interpretation effort.

**Offshore Netherlands case study: Example 1**

In the Q7/Q10 area of the Dutch North Sea, velocities are strongly controlled by the stratigraphy, with large velocity contrasts between layers. Large-scale faulting can displace the high-velocity chalk, so that it is adjacent to the slower Middle and Lower Cretaceous sediments. This type of geology is very challenging for conventional grid-based tomographic approaches, necessitating the use of a layer stripping approach. In this example we compare model and image results obtained using standard layer stripping and multi-layer tomography.

Model building and imaging of the area was initially completed using a traditional layer stripping workflow. This consisted of five iterations of velocity inversion, structural
re-interpretation, and residual well calibration. The initial model was constructed from supplied horizons and velocity profiles estimated from well data within the area. A 1D horizon-based update was carried out for the first iteration in order to introduce the long wavelength velocity variations for each of the model layers. This was followed by four iterations of layer stripping (Figure 2).

In order to assess the potential benefits of multi-layer tomography and the new hybrid velocity model to the area, the initial model and initial RMO picks were used to perform velocity inversion, updating the entire model from top to bottom. Layer boundary repositioning was handled within the tomography and results were calibrated to the well data post inversion. Only two passes were required, as the model converged rapidly. The overall model building duration was significantly reduced compared to the layer stripping approach.

Comparison of the models from the two approaches (Figure 3) clearly demonstrates an increase in stability and geological consistency with the multi-layer approach. This is particularly noticeable within the Middle Cretaceous and Jurassic, where velocity anomalies are clearly present in the layer stripping result, due to the propagation of shallow velocity errors from layers which have been ‘frozen’. Conversely the multi-layer inversion

![Figure 2](image2.png) A velocity model schematic depicting a series of layers with significant differences in velocity. This is a classic example of North Sea geology. The traditional layer stripping approach subdivided the update into five iterations. The first iteration (Iter1) was a 1D global pass to generate a smooth set of starting values. The next two passes (Iter2, Iter3) updated the Tertiary and chalk respectively. The final two passes (Iter4, Iter5) updated the Middle Cretaceous through to the Triassic and base of the model.

![Figure 3](image3.png) A comparison of the final velocity models generated by the two different tomography methods. The results of the layer stripping approach (A) contain model instabilities in the Middle Cretaceous and Jurassic layers (arrows). Multi-layer tomography provides improved stability and geologic consistency (B).
produces a much simpler and more geologically consistent velocity distribution. Comparison of the PSDM results also reveals a significant improvement in imaging. Reflectors located within the Middle Cretaceous and beneath the thrust fault show less image distortion and a marked improvement in continuity sub-BCU (Figure 4). Imaging of the complex faulted section within the Middle/Lower Cretaceous is also significantly improved, with better sub-fault reflector continuity down to the Jurassic (Figure 5).

**Offshore Netherlands case study: Example 2**

Our second case study exhibits typical geological structures from the North Sea area (Figure 6). It centres on a large Zechstein salt dome bordered by two basins composed of Triassic and Jurassic sediments on one side and only Triassic on the other side. We observe strong velocity contrasts at the top and bottom of the chalk but also at the Base Cretaceous Unconformity and the salt. These strong vertical contrasts need to be considered during the depth velocity model building, which is an ideal case for multi-layer tomography.

In this context, multi-layer tomography allowed us to build a consistent seven-layer TTI model in only two passes. For comparison, the velocity model was also updated in parallel using the layer stripping approach (Figure 7). The PSDM result obtained from the multi-layer updated model is superior to that obtained from the layer stripping approach, demonstrating the improved accuracy of the new multi-layer approach (Figure 8).

**Conclusion**

The application of multi-layer tomography for imaging of areas with complex geology provides significant advantages...
Figure 6 Another classic example of North Sea geology, this velocity model is divided into a set of model building units (MBU) separated by horizons. In the traditional layer stripping workflow the velocity model is updated sequentially from MBU1 to MBU6. The Base Cretaceous Unconformity is the base of MBU3, while the chalk is MBU2 and the Tertiary is MBU1, with strong velocity contrasts at each boundary. Jurassic sediments form MBU4 while Triassic sediments make up both MBU5 and MBU6. The salt is of Zechstein age.

Figure 7 This depth velocity model comparison between the layer stripping (a) and the multi-layer (b) approaches shows the extra detail and character captured by the multi-layer method.

Figure 8 This PSDM comparison between the layer stripping (a) and the multi-layer approaches (b) shows the kind of detailed imaging improvements which multi-layer tomography can provide.
over traditional approaches to tomography. It removes limiting assumptions of previous approaches. The entire model can be updated during each iteration of tomography, as all layer boundaries are repositioned by integrated map migration during the update of velocity and anisotropy parameters. Residual move out from all model layers can contribute to the inversion result producing improvements in both velocity model stability and seismic imaging. Traditional methods can be replaced with an efficient global inversion without compromising on quality.

Benefits of multi-layer tomography include: better images, which reduce interpretation uncertainty and improve well planning; better velocity and anisotropy models, to improve well ties in depth; and reduced turnaround time, which is always welcome.

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References

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References

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