Targeted vs. regional model building and imaging
A case study from offshore Sabah Malaysia

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Introduction

Multi-Client (MC) surveys are typically large and regional in scope, and while modern acquisition and imaging technologies may be employed, inherently the MC survey is intended to serve as an exploration survey; it cannot be expected to deliver the exact requirements for specific exploration targets across the entire survey area. Accordingly it is not uncommon for companies that lease MC data to reprocess with the intention of better defining a specific play or target. It is important, therefore, that the underlying integrity and robustness of the data can serve as a reliable platform to facilitate effective reprocessing of the data, for future pre-stack analysis such as seismic inversion and quantitative studies, and for high-end structural imaging.

In 2016 a MC survey covering 5100 sqkm was acquired in Block ND5, offshore Sabah, Malaysia. The block covers a series of extensional sedimentary basins created from the opening of the South China Sea. The main reservoir targets are thought to be Miocene carbonate platforms and pinnacle reefs developed on the Mid-Miocene Unconformity. The new broadband seismic data has also revealed the possibility of a deeper, clastic play in pre-rift sediments. These were only very poorly imaged on legacy 2D seismic but now the petroleum potential of both horst and extensional tilted fault-blocks plays can clearly be implied.

Recognizing that limitations exist in the velocity model building and imaging of specific targets in the MC3D processing workflow, an area was identified as a candidate for reprocessing using a more costly, technically advanced model building and imaging workflow. This paper presents a case study demonstrating the improvement.

Regional methodology update

Dual-sensor streamer acquisition provides the low frequency content required for advance model building. After the completion of the time processing, the pre-processed dataset was used to run an implementation of Beam Pre-Stack Depth Migration (BPSDM) (Sherwood et al., 2009), allowing calculation of 3D RMO attributes for reflection tomography updates. Reflection tomography is nowadays a very common and robust tool to update velocity models. Key horizons can be picked and incorporated into the grid-based reflection tomography updates. Various levels of detail depending on the wavelength selected for the update can also be achieved.

Anisotropic parameters Delta and Epsilon (Thomsen, 1986) along with Slope-X and Slope-Y are also introduced to perform Tilted Transverse Isotropic (TTI) migrations and tomography updates to position the complex structures more accurately. Furthermore, Q tomography is performed to compensate the effect of gas saturation and in the absence of specific horizons in the affected shallow section it was performed over the full section. To conclude with the regional velocity model building exercise, basement floods were tested and applied as the absence of deep reflections prevent meaningful updates using reflection tomography.

Kirchhoff depth migration was selected as it is a robust and economical algorithm to image large and complex surveys. In order to work properly, a smooth velocity model is required. It is challenging to ray-trace accurately through complex velocity models presenting sharp velocity contrasts as the ray tracings will behave erratically. This makes Kirchhoff depth migration an ideal companion to reflection tomography as even though our updated velocity conforms well to the structure observed in the survey (Figure 1) it lacks the spatial and vertical resolutions to resolve the targeted areas. Kirchhoff migration suffers from additional limitation in areas of poor reflectivity where migration noise contaminates the weaker primary signal. To resolve those issues, an approach using high-definition velocity update combined with a sophisticated imaging technique was necessary to improve the seismic image.

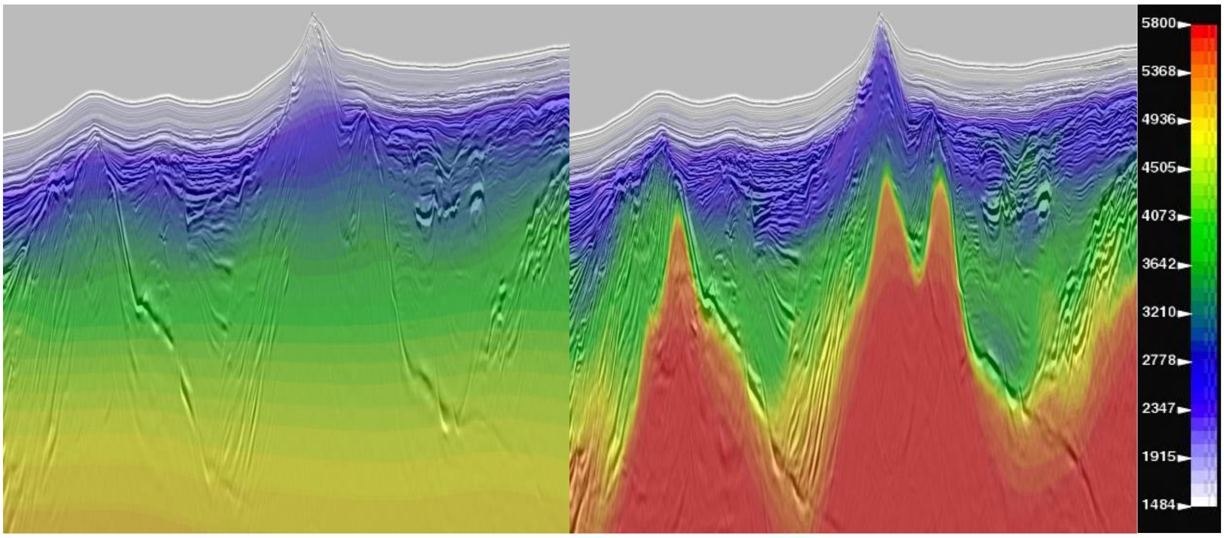

Figure 1 *Initial (left) and final (right) regional velocity models overlaid on BPSDM outputs*

Targeted methodology update

Starting from a smoother version of the final regional ND5 velocity model, a targeted methodology for high-end velocity updating was implemented. Interpretations of shallow gas clouds and carbonate units were refined. Using these horizons, gas clouds and carbonate units were targeted by reflection tomography updates to minimize the related velocity errors. The same gas cloud interpretations were also used to run targeted Q-tomography as we anticipated that energy dissipation and velocity dispersion were principally linked to the partial gas saturation within the gas clouds. The derived Q model reached values below 20 inside the gas clouds. Using low Q and velocity anomalies during Q-migration led to amplitude and structural restoration of the seismic events below the gas clouds.

With the main velocity anomalies positioned in the velocity model, and leveraging the low frequency and deep penetration associated with dual-sensor broadband seismic (Carlson et al., 2007), reflection Full Waveform Inversion (FWI) was used to refine the velocity model. An acoustic two-way wave equation with pseudo-analytical extrapolation was used to perform shot modelling (Etgen and Brandsberg-Dahl, 2009). By calculating and minimizing the data misfit between modelled and recorded shots, high-resolution velocity models may be derived. This is solved mathematically by computing the second order derivatives of the objective function with respect to the model parameter. Due to the prohibitive cost of calculating and storing the matrix, a gradient representing the first order of the objective function is computed and solved in an iterative approach (Tarantola, 1984).

To determine the optimal starting frequency for FWI, input gathers filtered down to 4Hz are used. At this frequency, the risk of cycle skipping between the modelled and recorded shots is low. Trials showed that the starting frequency could be increased to 8Hz. Three passes of reflection FWI were then run with increasing frequency content from 8Hz to 16Hz, and finally 24Hz. The maximum depth reached by FWI being a function of the maximum frequency and source-receiver offset, our FWI 8Hz update reached down to 5km whereas the latest update with frequency up to 24Hz had a more limited impact in the mid to deep section. More uplift was seen using the low frequency range whereas the impact of the highest frequency was more limited as the shallow section was well updated already.

At each step, several QC products were generated. Cross-correlation maps deriving time-shift errors between recorded and modelled shots were produced at various offset ranges over the full survey to confirm the convergence of the updates. Another data domain QC included direct comparison between modelled and recorded shots to insure reflections related to expected velocity contrast are generated (Figure 2). The better matching between the modelled shots after the FWI updates and the recorded shots confirm that a more correct velocity model was derived.

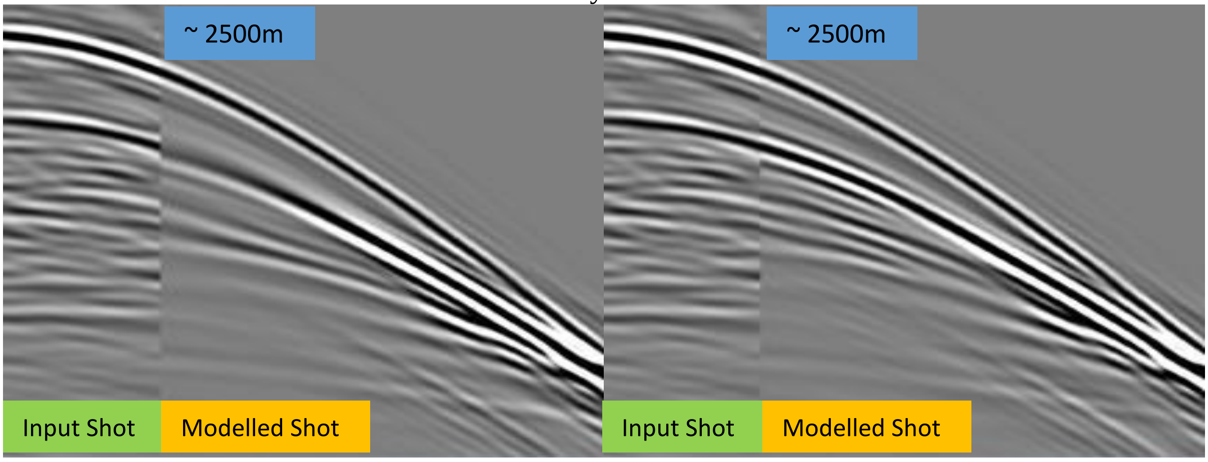

Figure 2 *Input and modelled shots at 8Hz before (left) and after (right) first pass reflection FWI*

Finally, image domain QC is performed with velocity models at each iteration used to run BPSDM with Common Depth Point (CDP) gathers, stacks and gamma volumes produced (ratio between migration and geological velocities). All these QCs validate the velocity updates performed.

Results

The FWI methodology applied on this targeted imaging project produced a high-resolution model of the subsurface that is structurally consistent with the seismic image (Figure 3). Global cycle-skipping QC, shot QC and migration outputs all show that the targeted methodology improved the overall gather flatness and structural image compared to the previous regional exercise. A velocity of around 1350m/s from shallow gas clouds was captured and therefore corrected sags present in the previous products (Figure 4, blue circle). The Q anomaly compensates the absorption from the gas clouds and restores the amplitudes in the section affected. Faster velocity in the carbonate units also removes the structural distortion observed below those geo-bodies. Moreover, in order to make better use of this high-resolution velocity model, one-way Wave Extrapolation Migration (WEM) up to 50Hz was used for final migration production. This was selected as it can handle strong lateral velocity variations, allows multi-pathing and enhances the signal to noise ratio in the targeted areas compared to KPSDM. The continuity of major marker horizons in the mid to deep section have clearly been improved (Figure 4, green circle) and in areas where high structural dips are encountered these are now far better resolved (Figure 4, red circle). This has correspondingly improved the geological interpretation of the deeper areas of the seismic volume that was not possible on legacy data.

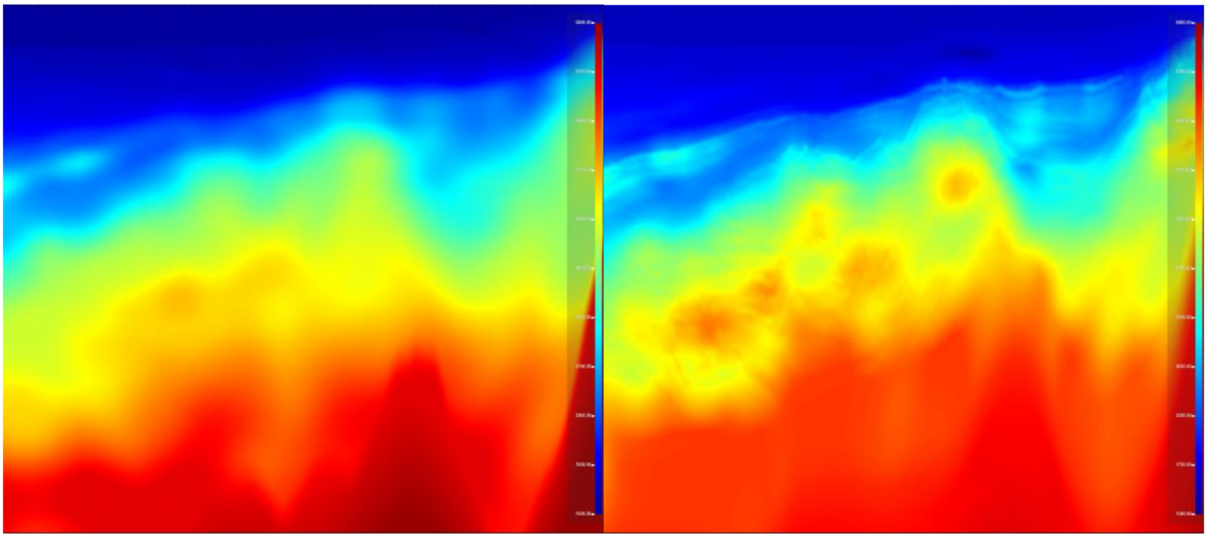

Figure 3 *Regional velocity model (left) and targeted FWI velocity model (right)*

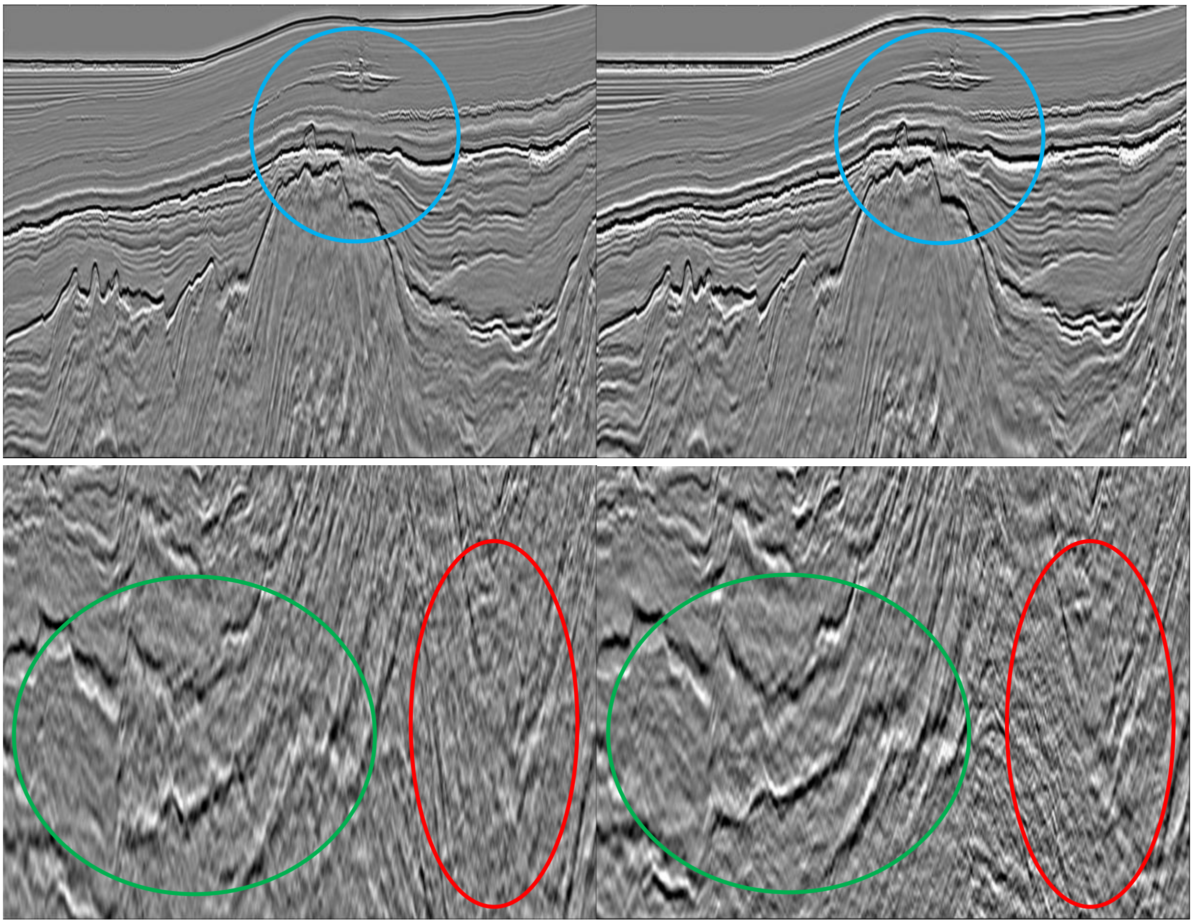

Figure 4 *Q-TTI-KPSDM limited to 50Hz post-migration with final regional model (shallow and deep, left) and 50Hz Q-TTI-WEM using final targeted velocity model (shallow and deep, right)*

Conclusions

MC3D velocity building and imaging using conventional tomography tools is regional in scope and fit for purpose for exploration. However, reprocessing and imaging using higher end applications will provide significant uplift provided the underlying seismic data is acquired and pre-processed to a standard that supports the hi-end applications. Detailed velocity, Q and anisotropic models were the key in this survey to properly image and de-risk a potential prospect. The information extracted from the migrated image but also from the high-resolution updated models can be later used for in-depth analyses including targeted structural interpretations, seismic inversion and quantitative studies.

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