A method for assessing earth model uncertainty in the Taranaki Basin, New Zealand

Edward Lewis*
PGS
Perth, Australia
edward.lewis@pgs.com

Tony Martin
PGS
Weybridge, UK
tony.martin@pgs.com

Tony Bell
PGS
Weybridge, UK
tony.bell@pgs.com

Dennis van der Burg
PGS
Weybridge, UK
dennis.van.der.burg@pgs.com

Lorenzo Russo
PGS
Weybridge, UK
lorenzo.russo@pgs.com

SUMMARY

As exploration moves into areas of increasing geological complexity and limited legacy data, reservoir evaluation is often based on the interpretation of one seismic image. Building a suitable velocity model followed by pre-stack depth migration plays an important role in the creation of this image on which economic evaluations are often based. In many cases drilling commitments are planned long in advance. Geologists have a good idea about the geometry and size of a potential reservoir but require accurate interpretation and positioning in the depth domain.

Typically, the amount of uncertainty associated with an image is poorly quantified. During a depth migration velocity model building project, such as shown here, we deliver a single final velocity model and its associated seismic products. The only quantitative measure of the reliability of the data would be through comparison with available auxiliary data or from analysis of volumetric residual move-out.

This may provide an indication of how well the model converges to a solution which satisfies the observations on the data. The high non-linearity inherent within the tomography used to generate the model yield multiple solution realizations. These honour the constraining data and yield the same convergence criterion. In isolation such data provides little useful evidence of the reliability of any one individual model.

We aim to rectify this by employing a workflow which assesses the uncertainty in our tomography process. This initially establishes both the resolution, and the degree to which the tomography fails to recover an implied perturbation. Using these criteria we generate a volume of models which equally conform to the observed data and derive confidence attributes assigned to the target model governing the image.

Here we present data from Taranaki Basin, Offshore New Zealand, and show how a model uncertainty workflow could de-risk exploration and development decisions.

Key words: velocity, uncertainty, big data, tomography, New Zealand

INTRODUCTION

Any uncertainty analysis tool for velocity modelling should help mitigate risks associated with target positioning and volumetrics. The proposed workflow quantifies the uncertainty inherent in a final velocity model and the associated image. It helps to de-risk prospects with additional volumetric deliverables to accompany velocity model building and imaging.

Reservoir evaluation is often only based on the interpretation of a single seismic image. This image is traditionally the result of a tomographic velocity model building process followed by pre-stack depth migration and is used as the basis for critical economical evaluations of either prospective or confirmed hydrocarbon accumulations. Surprisingly, the amount of uncertainty associated with the image and the velocity model that was used to generate it, are poorly understood and often not quantified. The only evaluation of the quality and reliability of the produced image is by comparison with auxiliary data such as well markers, or by assessing the overall degree of gather flatness or structural conformity in the final pre-stack depth images.

Given the significant non-linearity inherent in tomographic methods used to derive an earth model, multiple realizations of this same model can be produced that honour the constraining data and yield the same overall gather flatness. These models can vary significantly resulting in substantially different interpretations of critical reservoir features.

METHOD

Our workflow draws upon the principles of big data analysis and uses repeated and randomized sampling of the model space to derive estimates of the uncertainty of any model (Bell et al, 2016).

The resolution over which a model parameter (in this case, velocity) is constrained by the observed data (e.g. seismic gather flatness) during the tomographic inversion is dependent on many variables. These factors include the spatial sampling of the image space determined by the acquisition configuration. Resolution may also be strongly affected by the migration and inversion sampling. Subsurface geology, which will determine the local impedance contrasts that give rise to reflections from which information is extracted, can also be a source of uncertainty. Wherever such impedance contrasts are absence or sparse, velocity information will be poorly constrained.

The tomography workflow characterizing model uncertainties uses wavelet shift tomography engine (Figure 1 – left hand loop). This wavelet-oriented tomography solution where the input data is dip decomposed into wavelets (Sherwood et al 2009). These wavelets are mapped to the migrated location and then reconstructed in migrated space. A 3D residual normal moveout (3DRMO) measures the time shift (dt) to align wavelets with a reference. Finally, the velocity model is updated using the 3D shifts by solving (equation 1) in slowness.

$$ds = L^{-1} dt_{3DRMO} \quad (1)$$

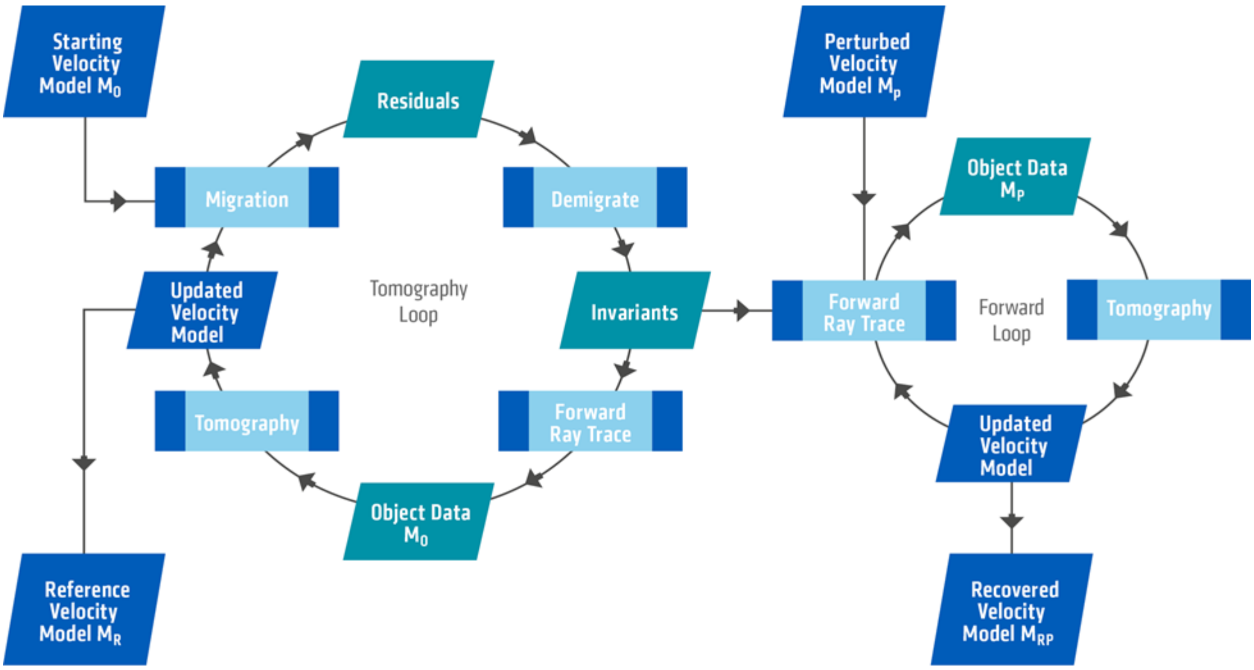

Figure 1 & Equation 1. The adapted tomography engine loop. The wavelet shift tomography loop (left) creates the reference inversion and invariants. The forward loop (right) returns the recovered models after perturbation. Following inversion the data is migrated with the recovered population.

This novel tomography method is adapted for the model uncertainty flow (Figure 1) to accommodate a large model population to both invert for and migrate with. Using a beam migration and wavelet shift tomography allows us to achieve this in a short timeframe.

The workflow is divided into four component parts. The first two steps in the workflow determine the resolution and magnitude of error recoverable by the inversion, given a specific dataset. The final two steps create a model population, invert for and migrate with each of these to produce attributes of model uncertainty and spatial reliability. These attributes are client deliverables.

RESOLUTION ANALYSIS

The resolution which a model is constrained by the data during a tomographic inversion is dependent on many variables. These include the spatial sampling of the image space; limitations caused by the acquisition geometry and the sub-surface reflectivity. To understand the achievable resolution, we employ a checker-board test to assess the resolution of the tomographic inversion to resolve anomalies within the model (Figure 2).

The individual cells in the checker-board have a known the spatial wavelength. The inversion is then run and the updated model recovered. Analysis is then performed to judge how well the inversion has recovered the model modification. The ability of the inversion to recover the perturbation is a quantitative measure of the resolution provided by the data in constraining the model.

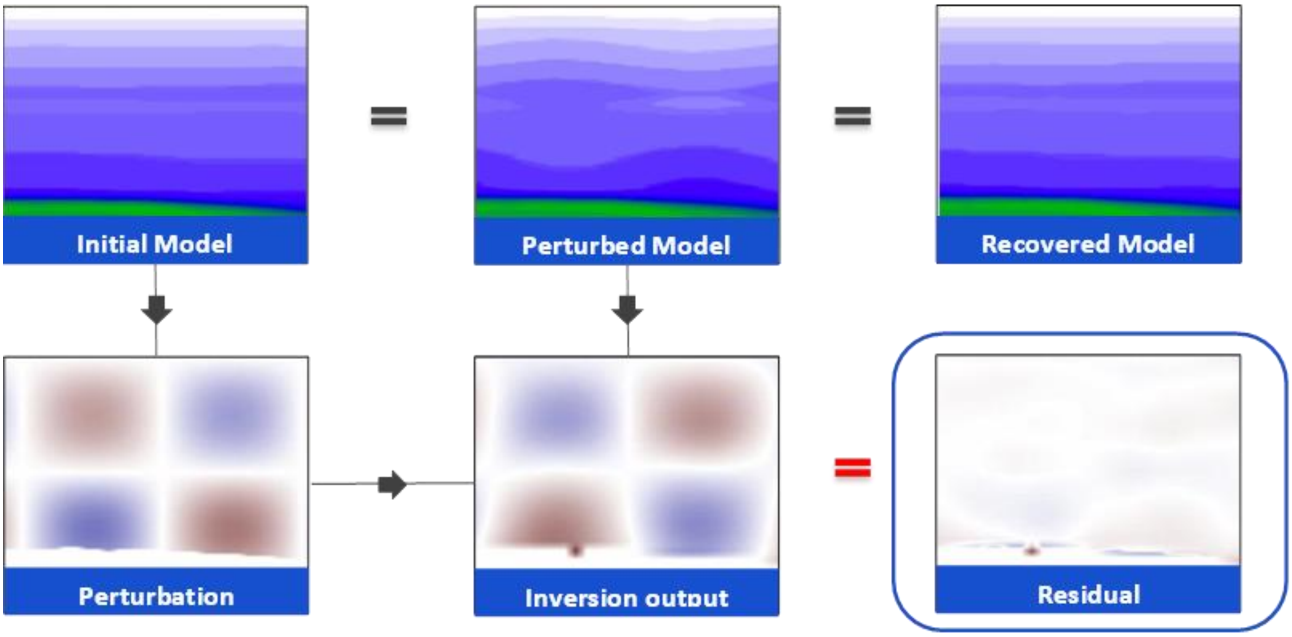

Figure 2. The use of a checker-board test to understand the resolution and amplitude updatable in the model based on the data. The calculated residual is used to derive the uncertainty metrics.

We then analyse the correlation between the perturbation and the residual from the inversion. This metric quantifies whether the inversion is able to recover the spatial perturbation and establishes the resolution limit of the data. The information is then used to constrain the model population by rejecting those models that are unable to recover the perturbation.

AMPLITUDE ANALYSIS

Once the resolution of the model has been determined, we generate a random amplitude series and apply them to the model in the form of a checker-board perturbation. This is undertaken to optimize the creation of the model set by establishing a maximum level of amplitude perturbation the tomography is able to recover.

From this we generate migrated gathers and determine a quantitative measure of the volumetric model error based upon the move-out error in the common image gathers. A threshold is determined based on the measured move-out of the data from the initial, perturbed and recovered models. This metric indicates the maximum error recoverable by the inversion.

The resolution and amplitude analysis are carried forward to create the model population. Additionally, we may use the resolution and amplitude analysis during the velocity model building phase to define the optimal parameterization to employ within a given tomographic inversion. Following the creation of the model population, we invert (Figure 1 – right hand loop) and migrate the entire model set. The products of this process are then used to generate attributes that inform on the statistical reliability of a model.

ATTRIBUTE GENERATION

The mean, variance and standard deviation parameters are computed from the model population for each cell. These mean, variance and standard deviation cubes may be co-rendered with the residual move-out volumes in order to visualize the spatial constraint of the model attribute (see Figure 3).

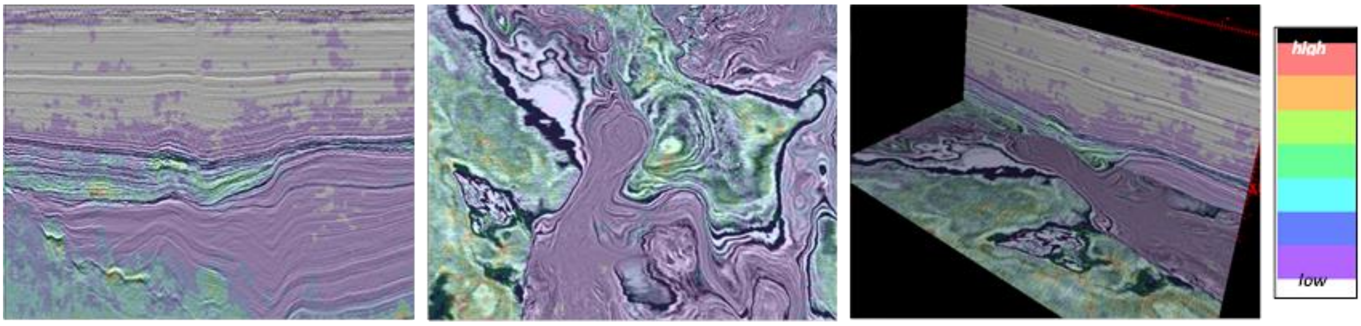

Figure 3. Model population deviation co-rendered on inline section (left); a slice (middle) and 3D cube (right).

The model realizations may also be used to inform on the positioning error. This is done in two ways. The first is based on the spatial reliability at a given target event. An error envelope is determined using the image population from the migration of the entire model set. Using correlation analysis we construct a mean vertical position and error envelope. This is adjusted to account for local dip giving a 3D error envelope. The second method uses model integration to create a volumetric 1D depth error.

All the aforementioned products are deliverables provided as part of the workflow. The deliverables help mitigate risks associated with generating a single model and image in traditional processing projects and are explained in the following case study.

CASE STUDY

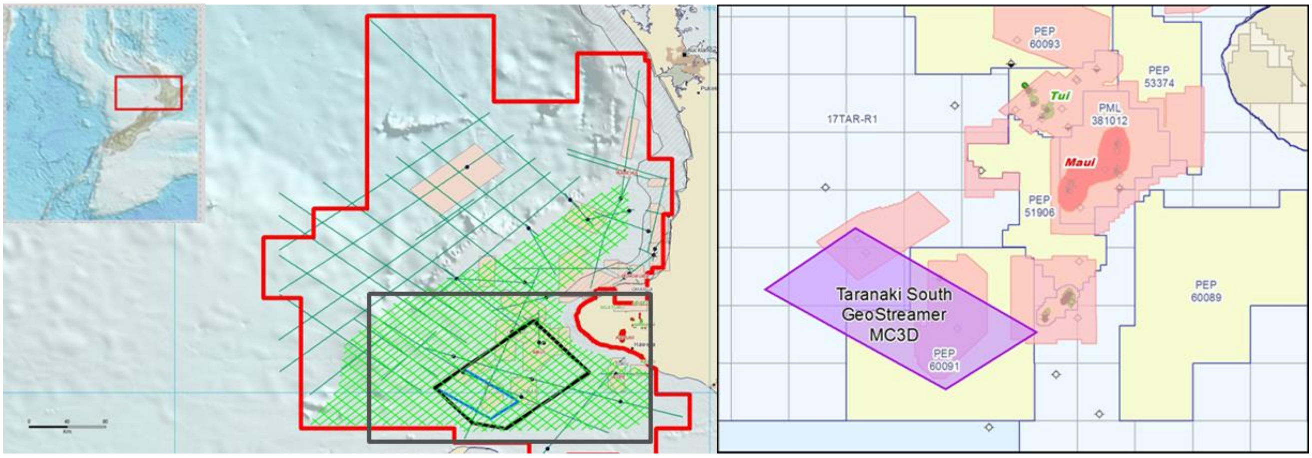

Figure 4. Case Study Area – offshore New Zealand. Survey area covering PEP 60091 in the South Taranaki Basin

Input data for this project is narrow azimuth dual sensor acquisition, 12 cables with 150m separation and triple source. Towing three sources decreases crossline bin spacing. To improve efficiency we can increase cable separation. This is important in areas where narrow weather windows mean that acquisition time can be limited. The pre-processing flow is state of the art, with wavefield separation to remove the ghost effects, deblending of sources and wave extrapolation surface related multiple attenuation.

The velocity model building was done using a combination of reflection tomography, full waveform inversion and wavelet shift tomography techniques. Anisotropy was incorporated at an early stage and updated throughout the model building sequence.

An example of the integrated use of the velocity model uncertainity metrics are presented in Figure 5. The model population variance cube generated with the new model uncertainty workflow is superimposed with the underlying 3D seismic image and the error envelope analysis for a given target. The combination of these additional deliverables provides interpreters with important information as to the local reliability of the seismic image that they are seeking to extract reservoir information from. As shown in Figure 5 (right) additional information about the local illumination strength, for example, can be added to highlight any possible correlations between poor illumination and high model uncertainty.

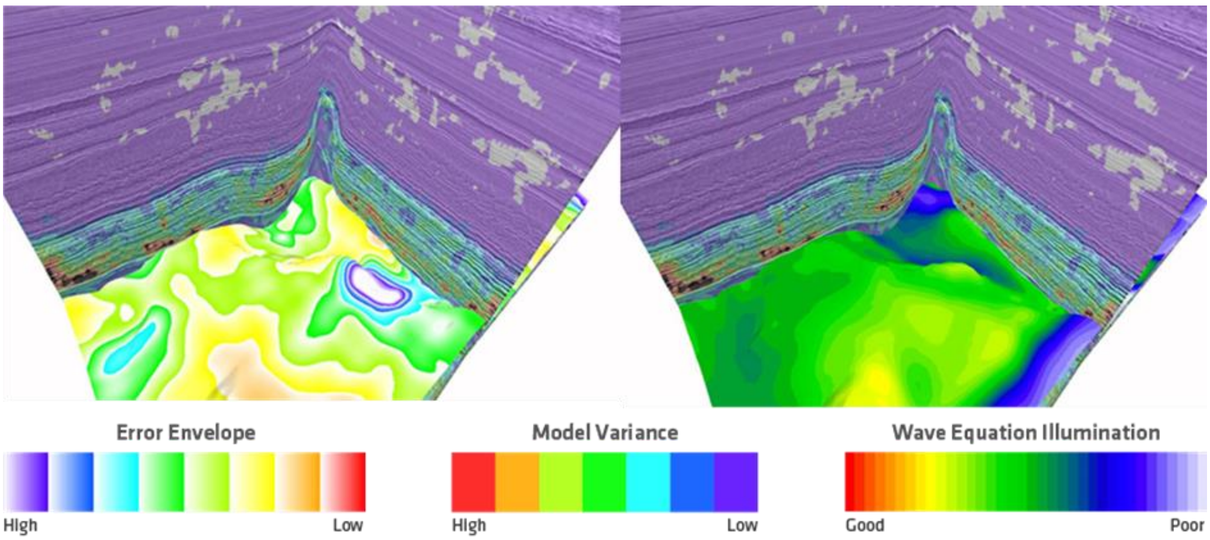

Figure 5. Seismic data with co-rendered model uncertainty variance attribute, error envelope analysis for one horizon (left) and illumination distribution on the same surface generated by wavefield extrapolation (right).

CONCLUSIONS

We demonstrate that uncertainty in velocity model building can be quantified by the presented method. This measure of uncertainty can be represented by a number of attributes, some relating to the model population and others quantifying the spatial reliability. These attributes form part of the deliverables from a project and can be interpreted alongside more traditional single structural images or AVO products.

We have shown the applicability of these products in an exploration setting in offshore New Zealand. These products can be used in exploration and development to de-risk decisions made on seismic products.

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