

A Workflow to Quantify Velocity Model Uncertainty

A.C. Bell (PGS), R. Lorenzo (PGS), T. Martin (PGS), D. van der Berg (PGS) & B.P. Caselitz* (PGS)

SUMMARY

A typical depth migration velocity model building project delivers final velocity model attributes and their associated seismic products. The only quantitative measures of the reliability of these data are provided through comparison with any available auxiliary data or from analysis of volumetric residual move-out. The non-linearity inherent within the tomography used to derive the earth model gives rise to multiple realizations of a solution model, which similarly honour the constraining data and yield the same convergence criterion. Therefore in isolation such data provides little useful evidence of the reliability of any individual model.

In this study we propose to use multiple realizations of the solution space in order to derive estimates of the uncertainty of an individual model. The method performs multiple random perturbations of the target model followed by tomographic inversion. A solution model population is then selected based on analysis of the volumetric residual move-out; they will comprise models exhibiting a similar level of residual move-out as the target model. This subset of realizations is then used to directly derive a model parameter variance attribute. It also provides for subsequent error envelope analysis studies at key target intervals.

Introduction

As exploration moves into areas of increasing geological complexity, 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. However, the amount of uncertainty associated with this image is not quantified.

A typical depth migration velocity model building project delivers final velocity model attributes and their associated seismic products. The only quantitative measures of the reliability of these data are provided through comparison with any available auxiliary data or from analysis of volumetric residual move-out. This may provide an indication of how well the model has converged to a solution which satisfies the observed data. The non-linearity inherent within the tomography used to derive the earth model gives rise to multiple realizations of a solution model, which similarly honour the constraining data and yield the same convergence criterion. Therefore in isolation such data provides little useful evidence of the reliability of any individual model.

In this study we propose to use multiple realizations of the solution space in order to derive estimates of the uncertainty of an individual model. The method performs multiple random perturbations of the target model followed by tomographic inversion. A solution model population is then selected based on analysis of the volumetric residual move-out; they will comprise models exhibiting a similar level of residual move-out as the target model. This subset of realizations is then used to directly derive a model parameter variance attribute. It also provides for subsequent error envelope analysis studies at key target intervals.

Method

Most industry standard velocity model building practices utilise some variant of velocity tomography based upon observed data recovered from an initial pre-stack depth migration. The tomography procedure itself comprises the following three steps:

1. Pick residuals.
2. Ray trace de-migration of the residual in the migration model followed by re-migration in the initial inversion model to create the observable data.
3. Linear inversion to update model parameter by minimising the defined cost function.

In step 2 the ray de-migration and remigration removes the dependency of the initial residual observation on the migration model. This permits the last two steps of the process to form a general building block scheme allowing for multiple serial linear inversions. Each inversion recovers greater magnitude updates which overall can diverge from a purely linear update trend (Guillaume et al 2008).

In our current tomographic inversion platform the beam migration process establishes the initial ray kinematics of the invariant data, which comprise wavelets which are extracted from the acquisition data through a multi-dimensional dip scan process (Sherwood et al, 2009), within the migration model space generating the observed data. The process of model perturbation is performed in a 'residual migration' called a forward. This applies the differential kinematic to the observed data consistent with the applied perturbation.

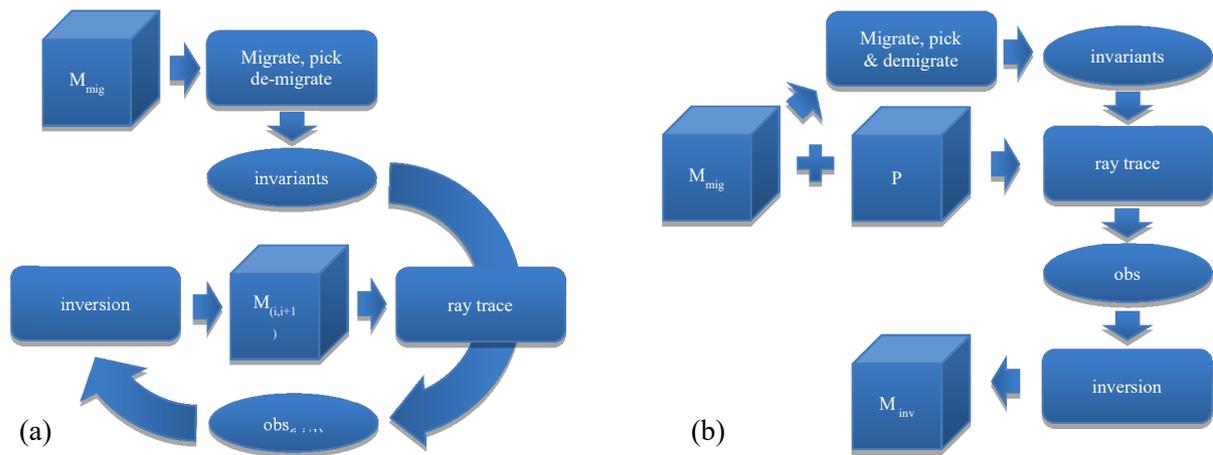


Figure 1 (a) Iterative loop employed in standard velocity tomography routines. Creation of invariant data removes the dependency of the observed data on the migration model. (b) Adapted flow employed to perform both sensitivity and uncertainty analyses.

Sensitivity analysis

In this work we consider adapting this standard procedure in order to establish the reliability of the derived models. We apply an initial perturbation to the migration model and compute the observed data from the invariants. The inversion is then run and the updated model recovered. Subsequent analysis is then performed to judge how well the inversion has recovered the initial model, given the data constraints implied by the residual observations.

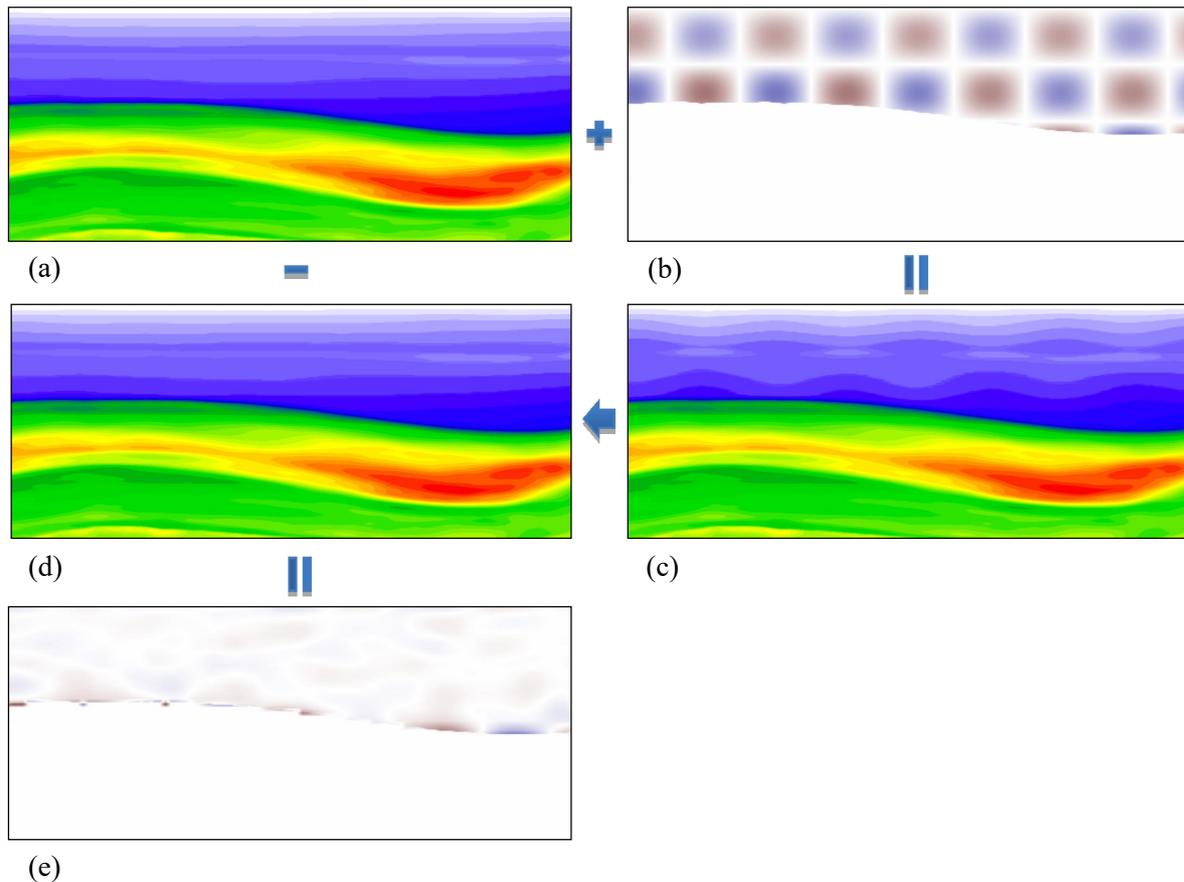


Figure 2 (a) Initial model. (b) Checkerboard perturbation. (c) Perturbed model. (d) Model recovered from inversion. (e) Difference between initial & recovered model.

We use this procedure to form the basis of a simple model sensitivity QC. We apply a checkerboard perturbation (P) to the initial model ($Mmig$) yielding model (Mo), perform a subsequent inversion and then analyse the difference (δP) between the initial and the final inversion ($Minv$) model to identify how well the perturbation has been recovered. This is summarised below:

$$Mmig + P = Mo \rightarrow \text{invert} \rightarrow Minv - Mmig = \delta P$$

The closer δP tends to zero the better the tomography has succeeded in recovering the initial model. We can use δP as an indication of the ability of the observed data to constrain the model space. By varying both the magnitude and wavenumber of the perturbations we may inform the choice over the number of tomographic iterations to perform and the smoothing parameters to consider within a particular update.

In figure 2 we see the result obtained when we applying the methodology to North Sea data. We may observe that the tomography has, in general, successfully resolved the perturbation within the Tertiary sediment cover where data exist to constrain the inversion. The inversion has performed less well adjacent to the central salt structure, where the strong velocity contrast combined with steeply dipping reflectors has reduced the inversions ability to fully remove the perturbation.

Uncertainty analysis

We may further extend the use of this procedure in order to generate some indication of the statistical reliability of a model. This analysis is based on generating a population of solution models that similarly fit the observed data. We initially generate a set of random perturbations of the target model and pass these multiple realisations through the forward / inversion loop to generate a corresponding set of solution models.

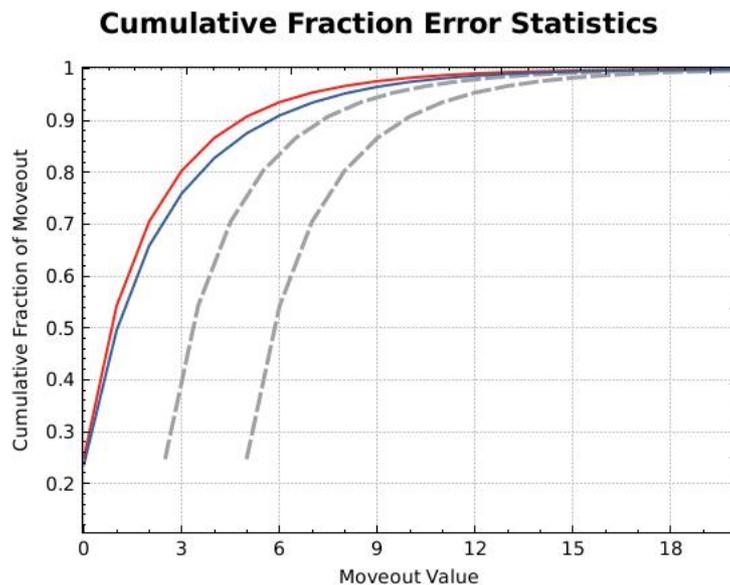


Figure 3 Cumulative residual error function used to select the ‘similar misfit’ population of model realisations. The red and blue curves present the initial and recovered model after the cycle of perturbation and inversion.

We aim to classify the realisations based on an estimation of the residual error exhibited in their respective migrated common image gathers. We analyse each solution model by assessing the fractional cumulative error (Letki et al, 2013). Figure 3 displays the error curves for the total population based on the residual recovered within the Tertiary overburden. From this analysis we select a sub-set of models which exhibit a similar cumulative error function to that of the target model. This subset of models are then used to directly produce an attribute volume based on the variance within the velocity values

returned for a particular model space cell. The sub-set of model realisations may also be used to inform the positioning error associated with a particular event. A stack image is created for each realisation about the event of interest. Each image is locally cross-correlated against the other realisations in order to establish a mean vertical position (Z_{vert}) and variance which may then be used to assess the reliability of the positioning of the target model. These data may be further decomposed into both lateral (Z_{lat}) and normal (Z_{norm}) displacement errors if we know the local 3D dip:

$$Z_{\text{lat}} = Z_{\text{vert}} / \tan(\text{dip}) \quad \& \quad Z_{\text{norm}} = Z_{\text{vert}} \cdot \cos(\text{dip})$$

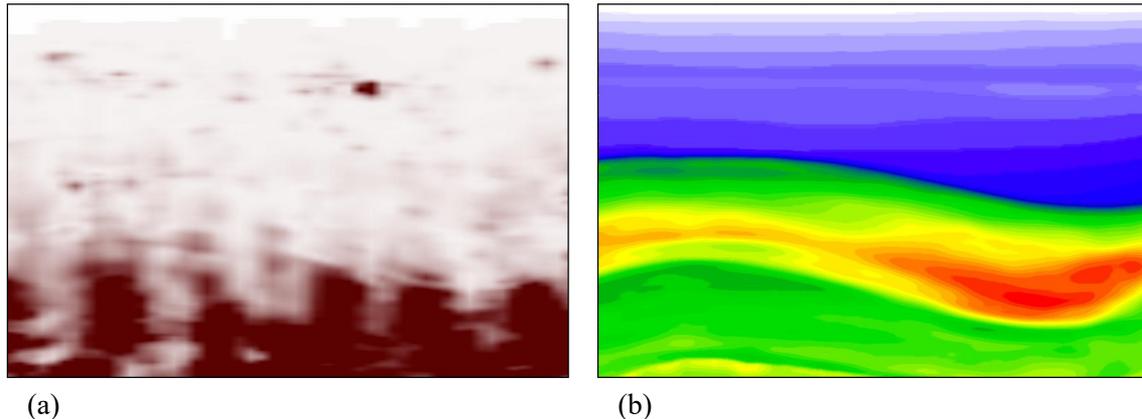


Figure 4 (a) Model variance attribute cross-section. **(b)** Velocity cross-section.

Concluding remarks

We have demonstrated an adaption to the standard tomographic model building flow in order to gain an understanding of the sensitivity of a model update to the constraining data in order to aid selection of the most appropriate constraints. We have then used this procedure to quantify an uncertainty attribute for the final model based on the variance associated with multiple realisations which exhibit a similar residual error function.

References

Bakulin, A., Nichols, D., Osypov, K., Woodward, M. and Zdraveva, O. [2009] Anisotropic model building with uncertainty analysis. *SEG Houston Exposition and Annual Meeting*.

Guillaume P., G. Lambaré, O. Leblanc, P. Mitouard, J. Le Moigne, J.-P. Montel, T. Prescott, R. Siliqi, N. Vidal, X. Zhang and S. Zimine. [2008] Kinematic invariants: an efficient and flexible approach for velocity model building. *78th annual SEG meeting*, Las Vegas, SEG workshop “Advanced velocity model building techniques for depth imaging”.

Letki, L.P., Ben-Hadj_Ali, H. and Desegaulx, P. [2013] Quantifying uncertainty in final seismic depth image using structural uncertainty analysis – Case study offshore Nigeria. *75th EAGE Conference & Exhibition incorporating SPE EUROPEC 2013*, London.

Sherwood, J.W.C., Sherwood, K., Tieman, H. and Schleicher, K. [2009] 3D beam prestack depth migration with examples from around the world. *Leading Edge*, September, 1120-1127.