Appraising structural models using seismic data: problem and challenges

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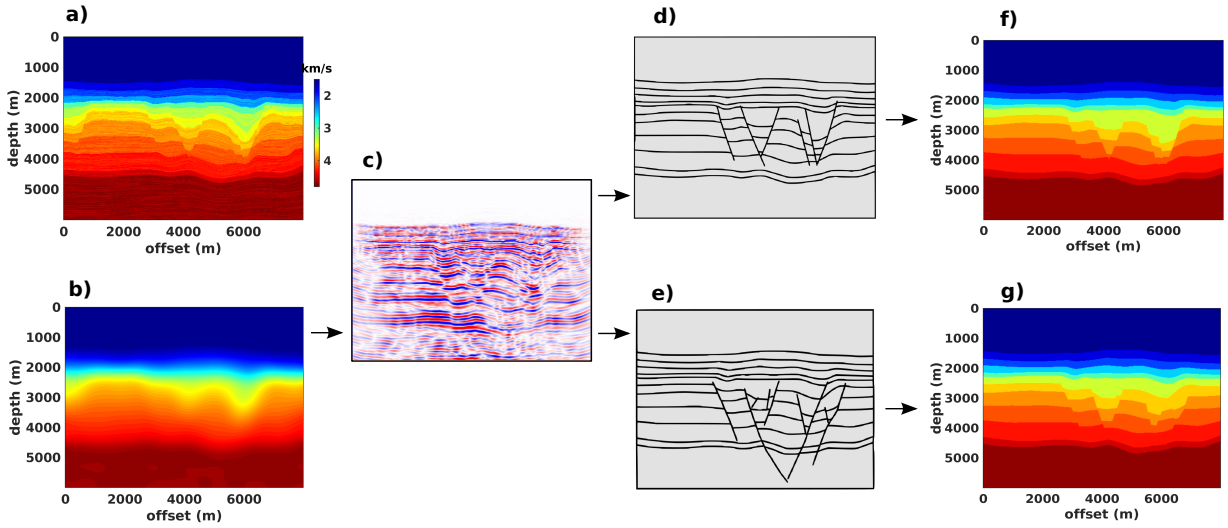

Figure 1: Illustration of interpretation uncertainty. a) The reference velocity model used in this study; it is derived from the sandbox model of Colletta et al. (1991); b) migration velocity model obtained by smoothing the reference model; c) depth migrated image of data computed from the reference model; d) and e) two probable structural interpretations from different interpreters; f) and g) macro-layered velocity models built from the migration velocity model and the structural models.

SUMMARY

Structural interpretation plays an essential role in geological model building and, as a consequence, on numerical simulations and predictions that follow. However structural interpretation can be highly subjective; a single seismic image will most often allow multiple geologically probable interpretations. In this paper, we assume we have a sampler providing multiple structural interpretations reflecting geological knowledge. We focus on the problem of appraising these models, i.e. determining which structural interpretations are more likely than others. For this, we propose to use seismic data; both vertical seismic profiling (VSP) and seismic reflection configurations are considered. We propose several ways to generate a velocity model consistent with migration velocity and with a particular structural interpretation. Last, we highlight the promises and then we discuss about the challenges of the proposed method.

INTRODUCTION

We speak of interpretation uncertainty when multiple structural models can be obtained from a single seismic image. Examples of structural uncertainties and methods to sample them can be found in Bond et al. (2007); Wellmann et al. (2010); Røe et al. (2014); Cherpeau and Caumon (2015). The problem is illustrated in Figure 1. It is then natural and of practical interest to ask ourselves which interpretations among the set of possible interpretations are more likely than others? This is the subject of this paper. In practice, such a problem can be solved by evaluating the structural models' response to some physical phenomena ; some examples can be found in Suzuki et al. (2008); Guillen et al. (2008); Cherpeau et al. (2012). In Irakarama et al. (2017), we proposed a method for appraising structural models using seismic data. The method starts from an input seismic depth image, its migration velocity model, and several structural interpretations. Each structural interpretation is then used to create a *macro-layered* velocity model. A macro-layered velocity model is simply a velocity model with structural interfaces; examples of macro-layered velocity models are shown in Figure 1 and in Figure 4. The macro-layered models are then used to compute synthetic VSP data, allowing us to rank the different structural interpretations using data misfit functions. In this paper, we attempt to extend this methodology to seismic reflection data, and discuss several ways to build macro-layered velocity models.

Appraising structural models

THEORY

A structural model is a product of two processes: depth imaging and structural interpretation. The imaging part is characterized by the migration velocity model. We will assume in this paper that the migration velocity model is kinematically accurate. Under this assumption, any data misfit resulting from a macro-layered velocity model which is *kinematically-equivalent* to the migration velocity model, is a result of interpretation inconsistencies only (as opposed to also being influenced by velocity inconsistencies). A macro-layered velocity model $\mathbf{M}_i$ is said to be kinematically-equivalent to the migration velocity model $\mathbf{M}_{mig}$ if the traveltime computed in $\mathbf{M}_i$ from a point located on the top horizon of a given layer to another point located on the bottom horizon of the same layer is the same as the traveltime computed in $\mathbf{M}_{mig}$ for the same two points; we will write this as $\mathbf{M}_i \sim \mathbf{M}_{mig}$. If two macro-layered models $\mathbf{M}_i$ and $\mathbf{M}_j$ lead to different data misfit values, we will say that they are *structurally-different*; we will write this as $\mathbf{M}_i \neq \mathbf{M}_j$. Let us define $\phi_i^d(\Omega)$ as the data space misfit value corresponding to the ith structural model, and $\phi_i^m(\Omega)$ as the model space misfit value corresponding to the ith structural model. The parameter Ω indicates that these misfits are localized in space (i.e. Ω is a subspace of the whole spatial domain). Given a sample of macro-layered velocity models $\mathscr{M}$, we consider the problem of appraising structural models to be solvable in $\mathscr{M}$ if the following conditions are met:

$$\mathbf{M}_i \sim \mathbf{M}_{mig}, \mathbf{M}_j \sim \mathbf{M}_{mig}, \mathbf{M}_i \neq \mathbf{M}_j \; ; \; \forall \, \mathbf{M}_i, \mathbf{M}_j \in \mathscr{M}, \quad (1)$$

$$\phi_i^d(\Omega) \text{ is correlated with } \phi_i^m(\Omega) \; ; \; \forall \, \mathbf{M}_i \in \mathscr{M}. \quad (2)$$

The kinematical-equivalence part ($\sim$) can be relaxed depending on how the macro-layered models are built (see the section on building macro-layered velocity models below) . One of the challenges of the method presented here is evaluating Eq. (2). In real life applications, this would not be possible as computing misfits ϕ_i^m requires the reference model, which is unknown. In synthetic studies, such as the present one, it is still a non-trivial problem to define misfits in the model space in general. As for the data misfit function, we use the general expression:

$$\phi_i^d(\Omega) = \sum_{r,s} w(x_s,x_r,\Omega)\chi\big(f_o(x_s,x_r,t), f_i(x_s,x_r,t)\big)$$
$$\text{with } \; t \in \big[t(x_s,x_r) - \Delta t \; , \; t(x_s,x_r) + \Delta t\big], \quad (3)$$

where w is a weighting function depending on the illumination in Ω; χ is a misfit functional; $f_o(x_s,x_r)$ is an observed seismogram from a shot at x_s recorded at a receiver at x_r; $f_i(x_s,x_r)$ is a synthetic seismogram computed in the candidate macro-layered velocity model $\mathbf{M}_i$; $t(x_s,x_r)$ is the traveltime from the source at x_s to the receiver at x_r; Δt is a time window which depends on the experiment.

APPLICATION TO VSP DATA

Following Irakarama et al. (2017), we can define $w(x_s,x_r,\Omega)$ in Eq. (3) as:

$$w(x_x,x_r,\Omega) = \begin{vmatrix} 0 & \text{if } \frac{L\left[\mathscr{P}(x_s,x_r)\cap\Omega\right]}{L\left[\mathscr{P}(x_s,x_r)\right]} < 0.3 \\ 1 & \text{otherwise} \, , \end{vmatrix}$$

where $\mathscr{P}(x_s,x_r)$ is the raypath from a source at x_s to a receiver at x_r; the operator $L[.]$ returns the length of a ray segment; Ω is the region which we want to evaluate (e.g. the highly faulted region enclosed in the white box in Figure 2). Figure 2 shows an example of a correlation between misfits in the data space and misfits in the model space. For a VSP application, model space misfits can be computed using a simple L1-norm between a given macro-layered velocity model and the reference velocity model; this is what was done in this experiment.

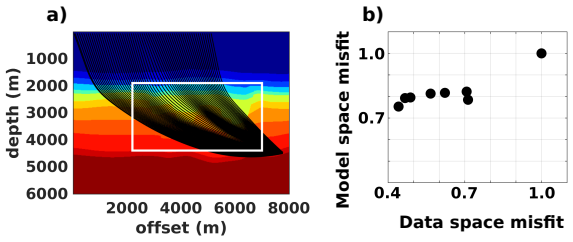

Figure 2: Application of the proposed method to VSP data. a) A macro-layered velocity model and a receiver gather illuminating the region of interest (the white box). b) Comparing misfits of 8 structural models in the model space against misfits in the data space, a clear correlation is observed.

EXTENSION TO REFLECTION DATA

To express Eq.(3) in a manner more appropriate for reflection data, we start by taking the limit of $\phi_i^d(\Omega)$ as Ω collapses to a point x, leading to:

$$\phi_i^d(\Omega)_{|\Omega\to x} = \phi_i^d(x) = \sum_{r,s} w(x_s,x_r,x)\chi\big(f_o(x_s,x_r,t), f_i(x_s,x_r,t)\big)$$
$$\text{with } \; t \in \big[t(x_s,x_r) - \Delta t \; , \; t(x_s,x_r) + \Delta t\big] \quad (4)$$
$$\text{and } \; t(x_s,x_r) = t(x_s,x) + t(x,x_r).$$

We then define the data misfit value of a region Ω by:

$$\Phi_i^d(\Omega) = \sum_x \omega(x)\phi_i^d(x) \; ; \; \forall \, x \in \Omega, \quad (5)$$

where $\omega(x)$ is a weighting function, with the possibility of $\omega(x) = 1$. Noting that Eq.(4) is simply a Kirchhoff depth migration of seismogram residuals, the weighting function $w(x_s,x_r,x)$ is identified to be Kirchhoff integration weights used in migration schemes. Figure 3 compares residuals in the model space against residuals in data space. Residuals in the data space were computed with Eq.(4). Residuals in the model space were computed by taking L1-norm of macro-layered models shown in Figure 1.f and Figure 1.g with respect to the reference model

(Figure 1.a). This type of model space residuals is correlated with data space residuals for the VSP case but not for the reflection data case. A more appropriate measure of misfit between structural models for the reflection case should mainly rely the difference of the positions of structural interfaces in different models. Such a misfit is still a subject of ongoing research. This makes it difficult for us to currently confirm that the data space misfits computed using Eq.(5) are correlated to model space misfits.

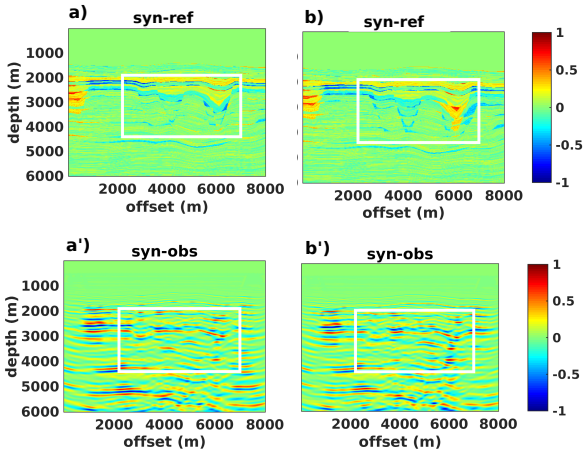

Figure 3: Application of the proposed method to reflection data. a) Residuals in the model space obtained by taking the difference of models f and a in Fig.1; a') Residuals in the data space obtained by applying Eq.(4) using an L1-norm misfit functional; b) Residuals in the model space obtained by taking the difference of models g and a in Fig.1; b') Residuals in the data space obtained by applying Eq.(4) using an L1-norm misfit functional.

BUILDING MACRO-LAYERED VELOCITY MODELS

Here we consider only situations where velocities of the ith layer can be expressed in the form:

$$v_i(x) = v_i + \delta v_i(x) \mid \text{mean}[v_i(x)] = v_i,$$

where $\delta v_i(x)$ represents high frequency variations around v_i (i.e. models of type Figure 1.a). Under this condition, the first property of a macro-layered velocity model is that it should contain information about the position of structural surfaces interpreted from the input depth migrated image. The second property of a macro-layered velocity model is that the macro-layer (constant) velocity of each layer should be equal to the layer's true mean velocity **when the interpretation is correct**. There are several ways of building macro-layered velocity models satisfying these properties.

Models not satisfying the kinematical-equivalence condition

In some cases, the kinematical-equivalence ($\sim$) condition in Eq. (1) can be relaxed. In these situations, a more probable structural model out of two possible scenarios can be interpreted as the one leading to a macro-layered velocity model which is kinematically closer (i.e. in terms of traveltimes) to the true unknown velocity model. The easiest way to build a macro-layered velocity model in this case is to paint the migration velocity model in a given structural model, and then average slowness' in each layer. When well-logs are available, macro-velocities of each layer can be determined directly from the logs (Wu and Caumon, 2016). These types of macro-layered velocity models are more suitable for VSP applications, where the proposed method becomes similar in principle to a VSP tomography problem.

Models satisfying the kinematical-equivalence condition

In cases where the kinematical-equivalence ($\sim$) condition in Eq. (1) is satisfied, a more probable structural model out of two possible scenarios can be interpreted as the one leading to a macro-layered velocity model whose structural interfaces are spatially closer to the unknown positions of the true structural interfaces in the subsurface. This case is more suitable for reflection data applications. One way to build a macro-layered velocity model for this situation is to use one of the methods presented in the previous section to build a temporary macro-layered velocity model, which is then converted to a density model. A macro-layered velocity model is then considered to be the pair (migration velocity model , density model); this way, the migration velocity model is not modified at all. Note that this requires computing synthetic data using a simulator that can handle variable density. An alternative is to compute reflectivities from the temporary macro-layered velocity model, then define the macro-layered velocity model as the sum of the migration velocity model and the computed reflectivities; this results in macro-layered velocity models of the type in Figure 4.

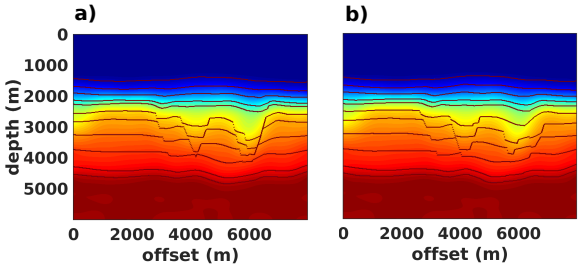

Figure 4: Example of macro-layered velocity models satisfying the kinematical-equivalence condition. a) A different version of the macro-layered velocity model in Figure 1.f.; b) A different version of the macro-layered velocity model in Figure 1.g.

DISCUSSION AND PERSPECTIVES

Reconciling geological interpretations and seismic imaging is a challenging problem. In this paper, we proposed a methodology to appraise various structural interpretations consistently with seismically-derived information. This methodology can be used to assess the likelihood of structural interpretations given some new seismic data (VSP or new reflection data) or the actual seismograms from which the reflection seismic image was generated (cross-validation of the interpretation). This method is an alternative to convolution-based validation of interpretations, which mainly considers reflectivity and does not consider seismic processing uncertainties. However, a major difficulty in our workflow is to define velocity models consistent both with the migration velocity and the structural interpretation. We started by assuming that the migration velocity is known, but in practice, it is subject to uncertainties, e.g., owing to variable illumination of the subsurface. Therefore, we think the notion of kinematic equivalence used in this paper should account for local uncertainties in the migration model. This would allow for more flexibility in combining structural interpretations and velocity models. One of the premises of this work is that structural interpretations can be ranked from seismic data. However, it is clear that multiple velocity and impedance models can be generated for a particular structural interpretation. As these two sources of uncertainty are clearly separated in our methodology, one could quantitatively assess their relative impact on the seismic response

CONCLUSION

Interpretation uncertainty is very common in structural modeling. One way to reduce such uncertainties is by determining more likely models from a set of probable candidate models. We propose a technique to achieve this type of model appraisal using seismic data. First, each structural interpretation is used to build a structural model. Then, each structural model is populated with velocity values, resulting in what we call macro-layered velocity models. The macro-layered velocity models are then used to compute synthetic data, which in turn are used to compute data misfit values allowing us to identify more likely interpretations. We also propose several ways to build macro-layered velocity models. An application is given for VSP data, as well as for reflection data. The method showed positive results for VSP data. However, we have not been able to confirm that the method works for reflection data; this is still a subject of ongoing research.

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