Introduction

Fault interpretation, and structural interpretation in general, can be challenging because of complex wave interactions in fault zones and limited seismic bandwidth. A single seismic image can lead to multiple structural interpretations, reflecting structural interpretation uncertainties. Typically, this uncertainty is captured by generating several possible structural geometries, see for example Bond et al. (2007). However, it is often difficult to determine quantitatively which of two possible structural interpretations is more likely than the other. This problem, which is the subject of this paper, will be referred to as *structural model appraisal* or *structural interpretation appraisal* hereafter. To be quantitative, such an appraisal usually requires the computation of misfits functions between some synthetic data computed in the structural models of interest and observed data. The better structural model of two possible candidate models is then chosen to be the one with a lower misfit value. For example, Suzuki et al. (2008) and Cherpeau et al. (2012) have used flow data to validate and constrain structural models; Foss et al. (2008) and Guillen et al. (2008) have used potential (gravity and/or magnetic) data for the same purposes.

In this paper, we consider appraising structural models using seismic waveform from a VSP (vertical seismic profiling) experiment. We have already shown in an earlier paper (Irakarama et al., 2016) that for very simple synthetic cases, it was possible to constrain structural models using VSP seismograms. We now attempt to show that this is also possible for more complex and realistic models under certain conditions. We give a conceptual model behind the proposed method and the conditions under which it is expected work.

Method and Theory

The problem at hand is illustrated in Figure 1: given a depth migrated seismic image, its migration velocity, and several structural models interpreted from the seismic image, how can we asses the likelihood of each structural interpretation using seismic waveforms? To answer this question, we propose the following methodology. First, we create *macro-layered* velocity models using the structural models and the migration velocity model, each structural model leading to a single macro-layered velocity model. Second, we compute synthetic data by solving the acoustic wave equation in each macro-layered velocity model, which allows us to compute a misfit value for each structural model. Here, a *macro-layered* velocity model is simply a velocity model with geological interfaces; two examples of macro-layered velocity models are shown in Figures 1.e and 1.f.

A structural model is a product of two processes: (1) depth imaging and (2) structural interpretation. We will therefore assume that any data misfit associated to a structural model can only be a result of imaging velocity inconsistencies and/or interpretation inconsistencies. In this paper, we assume that the migration velocity model is kinematically accurate. Because we are only interested in evaluating the interpretation part of structural models, we require all macro-layered velocity models to be *structurally-traveltime-equivalent* to the imaging velocity model $\mathbf{M}_{mig}$, but yet *structurally-different* from one another; that is to say, any pair of macro-layered velocity models $\mathbf{M}_i$, $\mathbf{M}_j$ must satisfy:

$$\mathbf{M}_{mig} \sim \mathbf{M}_i \ , \ \mathbf{M}_{mig} \sim \mathbf{M}_j \ , \ \mathbf{M}_i \neq \mathbf{M}_j \ , \tag{1}$$

where $\sim$ stands for structurally-traveltime-equivalent and $\neq$ stands for structurally-different. The first part of the condition (structurally-traveltime-equivalent) should be defined to guarantee that none of the macro-layered velocity models modifies the imaging part of a structural model, i.e. the position of a structural surface in a macro-layered model $\mathbf{M}_i$ should not change if data computed from $\mathbf{M}_i$ are migrated using $\mathbf{M}_{mig}$ or $\mathbf{M}_i$ itself. If this condition is violated, then we can expect the data misfit associated to the structural interpretation that led to $\mathbf{M}_i$ to be influenced by velocity inconsistencies introduced by the way $\mathbf{M}_i$ was built, as opposed to being mostly influenced by interpretation inconsistencies. The second part of the condition (structurally-different) should be defined to guarantee that we will be able to discriminate different interpretations using seismic waveform misfits.

Let us start by giving one possible definition of *structurally-traveltime-equivalent*. Given a migration model $\mathbf{M}_{mig}$ bounded on top by the surface S_{top} and at the bottom by the surface S_{bot}, we denote the raypath of a ray traced from x_s to x_r using $\mathbf{M}_{mig}$ as $\mathscr{P}(x_s,x_r,\mathbf{M}_{mig})$, and define

$$\mathbb{P} = \{\mathscr{P}(x_s,x_r,\mathbf{M}_{mig}) \mid x_s \in S_{top}, x_r \in S_{bot}\};$$

we also denote the traveltime between two points p_1, p_2 along a ray traced in a velocity model $\mathbf{M}_k$ as $\Delta t(p_1,p_2,\mathbf{M}_k)$. Let an arbitrary layer in the macro-layered model $\mathbf{M}_i$ be bounded on top by the horizon h_{top} and at the bottom by the horizon h_{bot}, then we say that the macro-layered model $\mathbf{M}_i$ is equivalent to the imaging velocity model $\mathbf{M}_{mig}$ if the following condition is satisfied:

$$\Delta t(p_1,p_2,\mathbf{M}_{mig}) = \Delta t(p_1,p_2,\mathbf{M}_i)\ ,\ p_1 = \mathscr{P} \cap h_{top}\ ,\ p_2 = \mathscr{P} \cap h_{bot}\ ,\ \forall \mathscr{P} \in \mathbb{P}\ . \tag{2}$$

The structural-traveltime-equivalence between two macro-layered velocity models and the same migration model does not necessarily entail the structural-traveltime-equivalence between the two macro-layered models as the two macro-layered models might have different top and/or horizons for a given layer.

Now let us give one possible definition of *structurally-different*. Given a source located at x_s and a receiver located at x_r, let $f_1 = f_1(x_s,x_r,t)$ and $f_2 = f_2(x_s,x_r,t)$ be seismograms computed in macro-layered velocity models $\mathbf{M}_1$ and $\mathbf{M}_2$ respectively. Then $\mathbf{M}_1$ and $\mathbf{M}_2$ are structurally-different if the following condition satisfied:

$$\sum_{r,s} \sigma[f_1 - f_2] < n_s n_r \sigma[noise]\ , \tag{3}$$

where the operator $\sigma[.]$ returns the standard deviation, and n_s, n_r are the number of sources and receivers. The *noise* in Eq. (3) includes everything not accounted for in our simulations, for example all scattering from thin-layer structures usually present in observed data but not included in our macro-layered models, and other sources of noise encountered in practice. If a population of macro-layered models contains a pair of models such that Eq. (3) is not satisfied, then we can not expect to tell apart the two models reliably.

If one of two structural models is exact, and Eq. (1) is satisfied, then we can in principle answer the question "which one of the two models is more accurate?" regardless of the source-receiver geometry. In practice however, we usually have two inexact structural models such that one might be more accurate than the other at some locations, but worse at other locations. In such cases, a more reasonable question to ask would be "which one of the two models is more accurate in the specific region Ω?". This question can be answered in principle if the available data illuminates Ω, we can therefore define a misfit function of the form

$$\phi_d^i(\Omega) = \sum_{r,s} w(x_s,x_r,\Omega)\chi\big(f_o(x_s,x_r,t), f_i(x_s,x_r,t)\big)\ ,\ \text{with}\ \ t \in \big[t(x_s,x_r) - \Delta t\ ,\ t(x_s,x_r) + \Delta t\big]\ , \tag{4}$$

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 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 (for example frequency content of the data). Note that Eq. (4) is localized in time (in the data space), which also implicitly localizes the misfit in space (in the model space). The subscript d indicates that this misfit is defined in the data space. We can also define a misfit in the model space $\phi_m(\Omega)$ of the form

$$\phi_m^i(\Omega) = \sum_{x} w(x)\chi\big(\mathbf{M}_r(x), \mathbf{M}_i(x)\big)\ ,\ \text{with}\ \ x \in \Omega\ , \tag{5}$$

where $\mathbf{M}_r$ is the reference velocity model (which is not macro-layered in general). Then we consider the question "which one of the two models is more accurate in the specific region Ω?" to be meaningful only if $\phi_d^i(\Omega)$ and $\phi_m^i(\Omega)$ are statistically correlated for all models in a population $\{\mathbf{M}_i\}$.

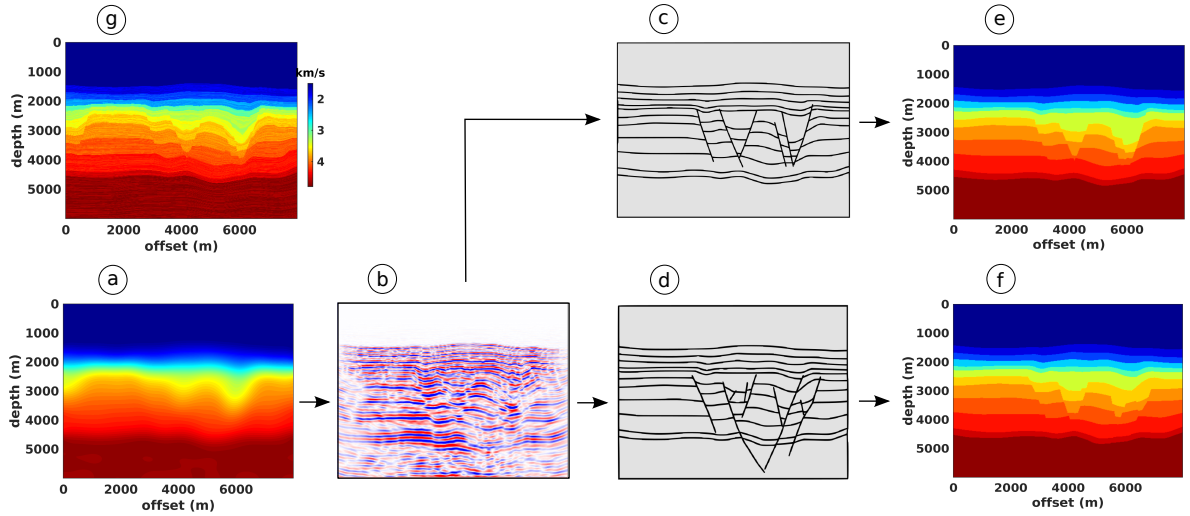


Figure 1 *Interpretation uncertainty in structural modeling. a) A kinematically accurate velocity model used for depth imaging; b) depth migrated image; c) and d) two possible structural interpretations; e) and f) example of two different of macro-layered velocity models, the examples presented here only satisfy Eq. 2 approximately; g) the reference model.*

Examples

We started with a structural model built from the sandbox experiment of Colletta et al. (1991), to which we added some fine layering structures in order to obtain a realistic model (Landa and Thore, 2007) to use as the reference model (Figure 1.g) . We then computed synthetic acoustic data, which were migrated using a kinematically accurate velocity model to obtain a depth image (Figure 1.b). The migrated image was then interpreted by different geoscientists, leading to multiple structural models (2 of which are presented in Figures 1.c and 1.d). We would now like to rank the different structural models, using the migration model as an input. The success or failure of the method will be determined by how well ϕ_d and ϕ_m are correlated, as described in the previous section. Obviously, it is impossible in practice to verify this condition because of the unknown reference structural model needed to compute $\phi_m(\Omega)$.

In this example, we used $\Delta t = 80\delta t$ ($\delta t = 0.004$s) in Eq. (4) and defined $w(x_s, x_r, \Omega)$ as

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

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 highly faulted region in the model (the white box in Figure 2). We used $w(x) = 1$ in Eq. (5). Figure 2.b shows a comparison of misfit values in the model space against misfit values in the data space. Both misfits in the data space and in the model space were computed using the L2 norm as the misfit functional χ in Eq. (4) and Eq. (5). Figure 2.c compares the ranking of the different structural interpretation in the model space against ranking the in data space. The curve in Figure 2.c happens to be a straight line in this example; although a positive result, this can not be expected to be always the case in general, and nor is it a requirement of the proposed method as we are only looking for a statistic correlation between ϕ_d and ϕ_m as mentioned in the previous section.

Conclusions

We propose a methodology for appraising structural interpretations using VSP data. Each structural interpretation is used to construct a macro-layered velocity model, which in turn is used to compute synthetic data. The synthetic data are then used to compute misfit values for each interpretation. We test the method on different interpretations from a single seismic image and show that it is possible to

evaluate structural models if an appropriate misfit function is used. However only a limited number of models has been tested and results appeared to be sensitive to the choice of misfit functionals; current work involves defining more suitable misfit functions and finding alternative ways for building macro-layered models. In the future, we will consider the possibility of applying the method using reflection data misfit functions.

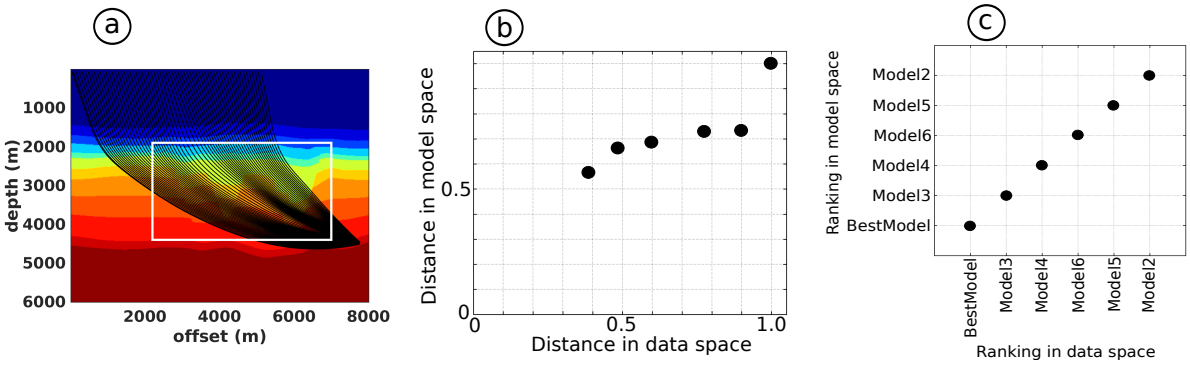


Figure 2 *Appraising structural interpretations using seismic misfits. a) Example of a receiver gather that illuminates the region of interest (the white box); b) misfits in model space vs misfits in data space; c) ranking in model space vs ranking in data space.*

Acknowledgements

This work was performed in the frame of the RING project at Université de Lorraine. We would like to thank the industrial and academic sponsors of the RING-Gocad Consortium managed by ASGA for their support. We would also like to thank Paradigm for providing the SKUA-GOCAD software and API used for structural interpretation/modeling, and for building velocity models.

The traveltime maps needed for Kirchhoff depth migration and for determining first arrivals of waveforms were computed using the Madagascar software freely available from www.ahay.org.

The different seismic interpretations used for this work were performed by: Christelle Butault, Francois Bonneau, Guillaume Caumon, Jonathan Edwards, and Paul Angrand.

References

Bond, C., Shipton, Z. and Jones, S. [2007] What do you think this is? Conceptual uncertainty in geoscience interpretation. *GSA Today*, **17**, 4–10.

Cherpeau, N., Caumon, G., Caers, J. and Lévy, B. [2012] Method for Stochastic Inverse Modeling of Fault Geometry and Connectivity Using Flow Data. *Mathematical Geosciences*, **44**, 147–168.

Colletta, B., Letouzey, J., Pinedo, R., Ballard, J.F. and Balé, P. [1991] Computerized X-ray tomography analysis of sandbox models: Examples of thin-skinned thrust systems. *Geology*, **19**, 1063–1067.

Foss, S.K., Rhodes, M., Dalstrom, B., Gram, C. and Welbon, A. [2008] Geologically constrained seismic imaging - Workflow. *Geophysics*, **73**, E313–E319.

Guillen, A., Calcagno, P., Courrioux, G., Joly, A. and Ledru, P. [2008] Geological modelling from field data and geological knowledge: Part II. Modelling validation using gravity and magnetic data inversion. *Physics of the Earth and Planetary Interiors*, **171**, 158–169.

Irakarama, M., Cupillard, P. and Caumon, G. [2016] Reduction of fault uncertainties using vertical seismic profiling data. In: *78th EAGE Conference and Exhibition*. Vienna, Austria.

Landa, E. and Thore, P. [2007] Realistic Finite Differences Modeling - A Case Study. In: *69th EAGE Conference and Exhibition incorporating SPE EUROPEC 2007*. London, UK.

Suzuki, S., Caers, J. and Caumon, G. [2008] Dynamic data integration for structural modeling: model screening approach using a distance-based model parameterization. *Computational Geosciences*, **12**, 105–119.