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Validating 3-D structural models with geological knowledge for improved uncertainty evaluations

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Abstract

Several stochastic approaches have recently been developed to evaluate uncertainties in 3-D geological models based on imprecise geological data. Multiple models are generated through random changes of input parameters, according to defined probability distributions. This leads to a new problem: randomly generated realizations might be topologically different or they might be in contrast to expected geological constraints or settings. We present here a method to enable automatic checks of models based on reliability filters encapsulating aspects of geological knowledge. We apply those filters to a model of a graben structure and obtain an ensemble of acceptable realizations, representing the range of uncertainty, but preserving expected geological features.

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1. Introduction

Structural geological models are commonly used as the basis for subsequent mineral, energy resource, and reservoir studies. It is widely accepted that these models contain uncertainties [1, 2, 3, 4], and several methods have recently been developed to estimate, quantify, and visualize these uncertainties [5, 6, 7, 8, 9, 10, 11]. One such approach is based on stochastic simulations of geological models. Instead of a single model, multiple realizations are

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generated, in the range of uncertainties of initial geological input data and interpolation parameters. The created ensemble can then be analyzed as a representation of model uncertainties [see, for example, 7, 9, for more details on this method].

Although the stochastic approach provides a meaningful insight into model uncertainties, it can lead to problems if parameter correlations are not properly considered, or unforeseen parameter constellations lead to model realizations that violate our geological understanding and knowledge of a specific area.

The stochastic model procedure and the potential generation of unreasonable models are schematically presented in Fig. 1. The figure shows the cross-section of a simple structural model: the offset of one geological formation, represented through the top surface (blue line), along a normal fault (red line). The points show the initial position of the structural data used as model parameters, here defining the top surface and the fault plane position, and an assigned uncertainty range: we assume that the depth to the geological surface and the lateral position of the fault are not precisely known. Modeling assumptions are that the fault is planar, as well as the formation surface, which has in addition a constant dip on both sides of the fault (representing a simple translation along the fault). The area represented in the model is located in an extensional setting and a normal fault is therefore expected.

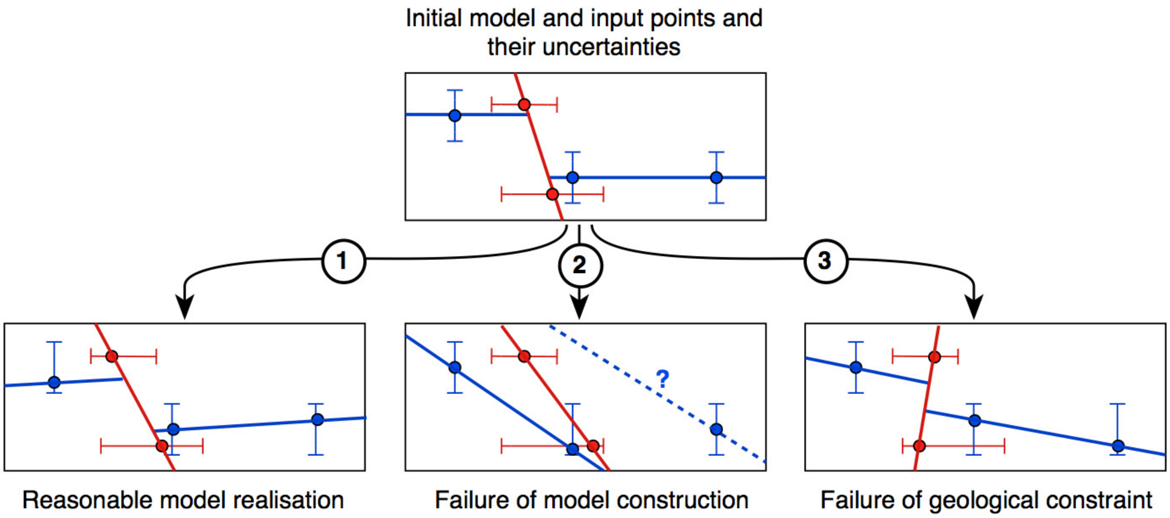

Fig. 1. Stochastic geological modeling: reasonable models and examples of model failures.

We now generate three new structural geological data sets in the range of the data uncertainties, assuming that the parameters are statistically independent. The first model realization (path “1” in Fig. 1) generates a reasonable new structural geological model where the geological surface is now dipping slightly towards the left, and the dip of the fault is decreased, but which is otherwise in accordance to the tectonic setting: it preserves the structure of the normal fault. In the second realization (path “2”), the middle point of the geological surface is moved to the left side of the fault, leading to a violation of the overall topological setting, as the point is assigned to a different compartment. We identify this failure here as a technical failure in the model construction. The third realization (path “3”) shows a structural model that produces a technically correct model (in a topological sense), but, due to the change of the fault direction, leads to a very different tectonic interpretation: from a normal fault to a reverse fault. As this is not in accordance with the general setting, we identify this behavior here as a failure to meet geological constraints.

In order to analyze these aspects, we will first present a stochastic geological modeling approach and its application to estimating uncertainties in a geological scenario of a graben structure. As model realizations in this scenario lead to violations of the type described above (see Fig. 1), we then present our approach to automatically check model realizations leading to a set of models that, as an ensemble, provide a picture of model uncertainty, while respecting additional geological constraints and knowledge.

2. Uncertainty simulation in geological models

Several methods for the estimation of uncertainties in structural geological models have recently been developed [e.g. 1, 12, 13, 14, 8, 4]. We use an here an approach based on stochastic simulations with an implicit geological modeling method based on a potential-field approach [15]. With this method, geological models are directly constructed from geological surface contact points and orientation measurements. Stratigraphic age relationships between different geological units are honored, as well as the effect of faults on geological bodies [16].

For the context of this work, one of the most important aspects of the approach is, however, that it enables the automatic model reconstruction from a changed input data set. Once a structural model is created, the stratigraphic units and faults are defined, their relationships specified, and additional interpolation parameters fixed, it is possible to change, for example, the spatial location of a surface contact point or the dip angle of a fault and to automatically update the entire 3-D structural model.

This flexibility is an essential aspect for the implementation in a stochastic simulation framework. We begin with an initial 3-D geological model. Uncertainties in input parameters are then considered through appropriate probability distributions, assigned to the parameters. Parameter correlations, if known, are taken into account. A range of probable input data sets is then generated through random draws from the parameter distributions and for each of these data sets, a model is generated. This suite of models is then used for postprocessing to determine uncertainties in the model resulting from the parameter uncertainties [7, 9].

3. Application to the geological model of a graben structure

We apply the stochastic modeling approach to the 3-D geological model of a graben structure (Fig. 2). The entire model covers an area of 1 km x 1 km, and extends to a depth of 1 km. Four sedimentary layers are modeled. They are defined to be in subsequent order and in subparallel layers. Two normal faults cut through the pile and affect all layers. A cross-section through the model with the geological surface contact points and orientation measurements that define the model is shown in Fig. 3a.

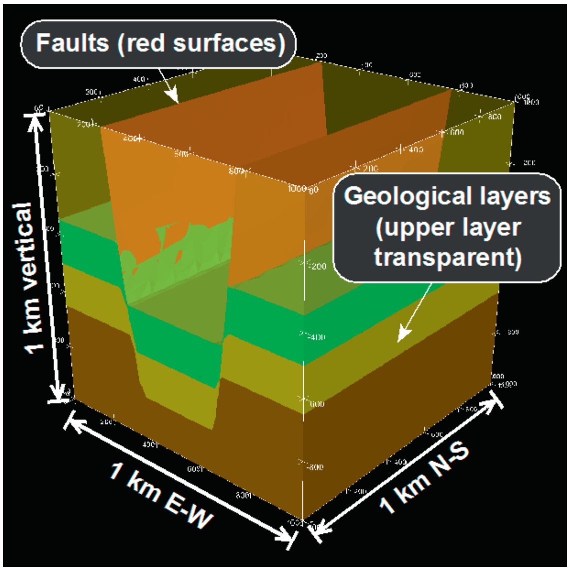

Fig. 2. Geological model of the graben structure, 3-D view.

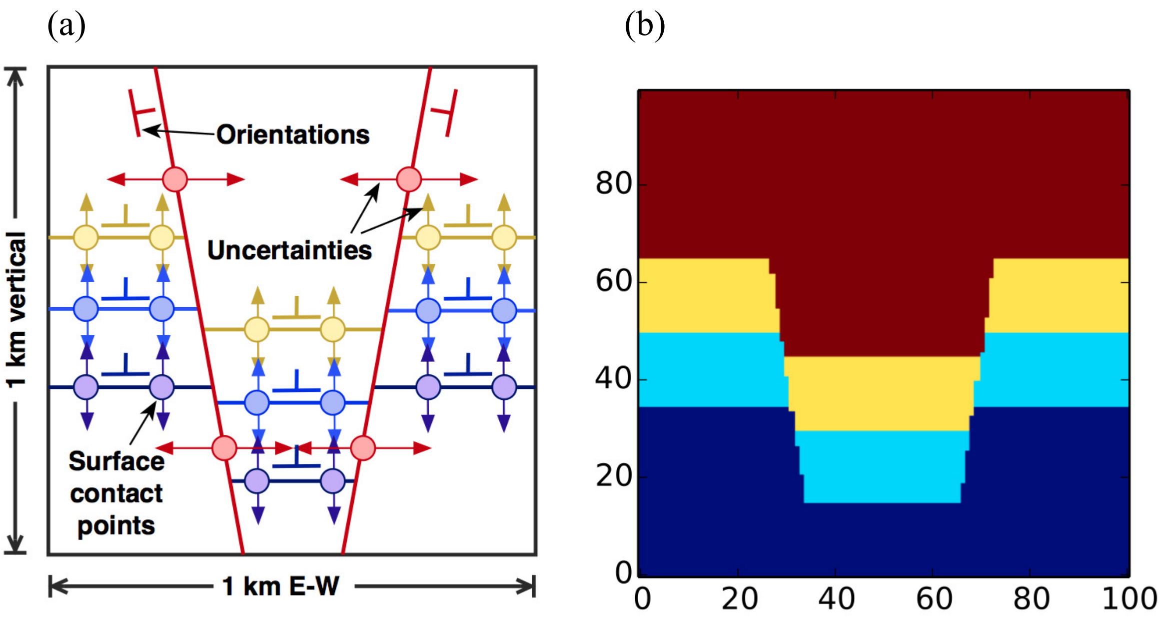

Fig. 3. (a) Schematic cross-section (East-West) with geological data (surface contact points and orientation measurements) and direction of variation in uncertainty study; (b) Model result for initial parameter setting, discretized into grid with 100x100 cells.

We now consider uncertainties in the geological parameters that define the position of the layers. Uncertainties exist about the vertical position of the contact points for the geological surfaces, and the lateral position of the faults (see Fig. 3a). We assign a normal distribution as a statistical model to all observation points with a standard deviation of σF = 100 m for faults in EW-direction, and of σz = 75 m for surface contact points in z-direction. The two points defining a surface in each fault compartment are considered to be fully correlated.

If we now apply the stochastic modeling method, we obtain a wide range of different model realizations with widely varying geological structures and shapes (Fig. 4). Some of the realizations (4,7,9 and 15) preserve the expected geological setting of two normal faults intersecting a sedimentary layer to form a graben structure. In some cases (6,8), the orientation of a fault is changed, which would lead to a different geological interpretation. In other cases (3,12), one layer is missing, and several other cases (1,2,11,14) are very different to the initial model and the geological setting it was representing.

This example is quite extreme as standard deviations for the normal distributions of the geological parameters are high compared to the scale of the model. Nevertheless, they show the types of problems that can occur, even in such a relatively simple geological model. In some cases, these model outliers might actually represent model realizations that are possible, based on the available information about contact point positions and their uncertainty. We want to consider here though that we have additional prior knowledge about the geological setting, for example from additional studies in the vicinity. In this scenario, the information could be that the model domain represents a graben structure with normal faults cutting through a sub-parallel sedimentary pile, as described above. Only realizations 4,7,9 and 15 clearly match this interpretation. The question is now: how can we automatically determine these matching realizations from a suite of generated models?

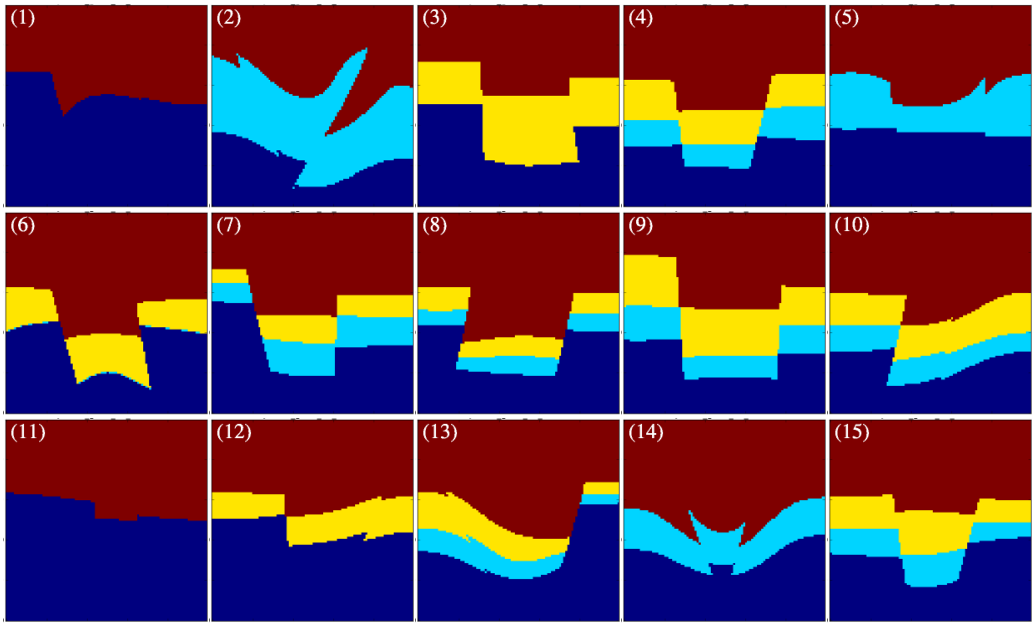

Fig. 4: E-W cross-section at position of Fig. 3 for several model realizations generated with the stochastic modeling method.

4. Integrating geological knowledge

Geological modeling schemes generally allow the integration of specific types of geological knowledge in the modeling procedure. Common are the parameterization of geological surfaces between relevant features with observation points and the gradient of surfaces with vectors (according to geological orientation measurements). The implicit geological modeling method that we use here (see above) enables, in addition, the consideration of orientation measurements anywhere within a geological body ("off-surface constraint") and age relationships (e.g. stratigraphy), as well as types of geological topologies (onlap, erosional unconformities, dykes, etc.) between bodies [16]. A rich set of geological knowledge can therefore already be included in the model construction. Still even considering this modeling information, perturbation in the range of data uncertainties can lead to unexpected model realizations (Fig. 4).

In order to resolve this issue, we define filters capturing additional aspects of geological knowledge. In the geological context of the graben structure that we examine here, additional constraints that we would like to consider are (see Fig. 5):

1. A range for the possible extend of a surface: this information might be available from geophysical data;
2. The thickness of a geological layer: for example estimated from general thickness trends of the layer in the region;
3. The offset along a fault and the type of the fault: normal vs. reverse fault and minimum offset according to the geological history of the region;
4. Variation of layer thickness in different fault compartments: this constraint is closely related to our knowledge of the tectonic and sedimentary history of an area and could be used to parameterize the effect of syntectonic sedimentation.

For the set-up of the model that we use here (Fig. 3), these constraints can be evaluated directly on basis of the geological input data. The first constraint (1 in Fig. 5) of min/max extents can directly be evaluated for a sampled value. Vertical thickness of a layer (2) can be checked for pairs of values defining lower and upper surface of a layer. Vertical offset along the fault (3) can be determined from the comparison of surface contact points on both sides of a fault. Finally, changes of layer thickness across faults (4) are evaluated from the comparison of vertical thickness in separate compartment.

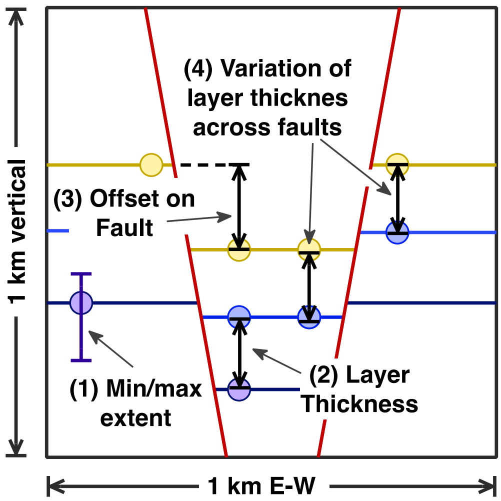

Fig. 5. Constraints to parameterize geological knowledge.

We now apply these constraints as rejection filters in the stochastic modeling workflow described above: after drawing a random sample from the parameter distributions, the filters are applied and samples that do not conform to the filters are rejected. Although this approach is quite inefficient, it is computationally feasible as it is applied directly on the level of the input data, prior to the computation of the model itself. After a desired number of valid input data sets is generated which passed the filter step, the geological models for all of these data sets are generated, and we obtain an ensemble of model realizations which reflect model uncertainties with respect to input data and honor the additional geological knowledge parameterized with the rejection filters.

For the graben example presented above, we defined 27 of these filters and applied them to the randomly generated data sets. The filters were selected to represent the additional aspects of geological knowledge that were described above. Details of the applied filters can be examined in the additional online material and the modeling scripts (see Appendix).

Several samples from the ensemble of validated geological models are shown in Fig. 6. All of these model realizations preserve the expected overall geological setting and relevant geological features of normal faults through sedimentary layers forming a graben structure. Closer examination also reveals that constraints on the continuity of layer thickness across faults are considered. Still, the variability between different model realizations due to uncertainties in the input parameters is clearly visible. The ensemble therefore captures model uncertainties, while respecting the geological knowledge of the area.

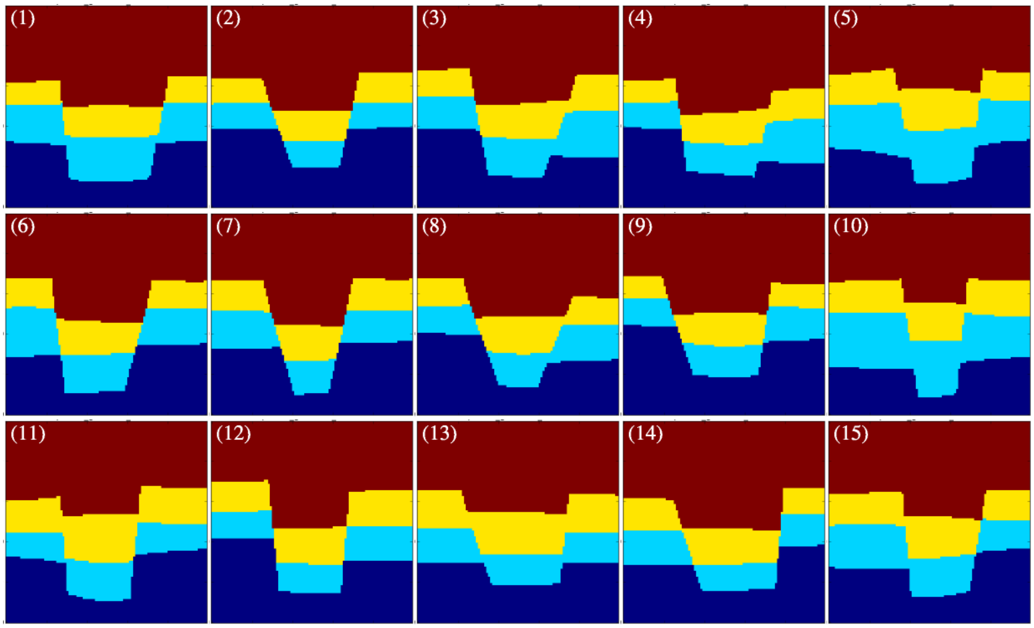

Fig. 6. Validated model realizations.

5. Discussion and outlook

The results show that we successfully implemented validation filters into an uncertainty simulation workflow for structural geological models. The presented validation method ensures that perturbed geological models honor additional geological constraints, beyond those considered with the modeling method itself. These types of constraints can take a wide range of forms. In the example case of a model representing a graben structure, constraints based on additional information (min/max position and thickness of a layer) and on the geological evolution of an area (type of faulting, continuity and thickness variation of layers across faults) were implemented. Other constraints might be relevant in settings that are typical for mineral exploration and ore body modeling. The important aspect is that these constraints are directly implemented in validation filters to automatically check model data sets. We have shown how this ensures the generation of an ensemble of models, which represents model uncertainties while respecting geological knowledge of an area.

An additional interesting aspect of the method is that we do not only obtain a set of valid models as an ensemble, but information on the rules that resulted in rejection. Furthermore, the sampled geological parameter sets could be analyzed to determine posterior distributions and evaluate parameter correlations. A detailed analysis of both of these aspects might provide interesting insights into the validity of the model assumptions and, furthermore, a meaningful parameter correlation matrix that could enable a more efficient sampling for subsequent inverse studies. A formal evaluation of these particular points is the scope of current research.

In addition to the presented application to automatically generated model suits, we propose that these types of reliability filters can be generally useful for the construction phase of geological models, even if only a single model is created, as common practice. Ideally, a set of geological motivated filters could be created before and during model construction, and every model change or extension with new data could be checked against these filters to detect potential violations with specific expected geological aspects of the domain. A mismatch could then highlight possible problems with either the recent change or the applied filter and motivate a careful revision of the latest steps. Especially in cases where one model is constructed by multiple experts, we assume that this step could be helpful to ensure an overall model correctness. Applied in this sense, the filters would act similarly to the unit testing methods in software engineering.

Appendix A. Additional material online

The methods for stochastic geological modelling and the rejection filters are implemented in Python programs. The program and the geological model used in this manuscript are available online on:
https://github.com/flohorovicic/publication_scripts/tree/master/EGYPRO

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