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Integrating fault kinematics into implicit 3D modelling of fault networks

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SUMMARY

Existing 3D geological modelling methods do not incorporate fault kinematics and do not have any way of modelling interacting fault networks, e.g. duplex systems, flower structures and listric fault systems. It is difficult to build models that honour both geological observations and fault kinematics because fault kinematics are not used to constrain the resulting geometries. In this study we introduce a new method for modelling faults within implicit 3D geological modelling systems where the fault kinematics are incorporated by restoring the model domain. Our approach is capable of building models that honour both structural geological data and fault kinematics. Because our approach uses the kinematics of the faults it is also possible to model interactions between co-eval faults where the resulting geometry is the result of combining the fault displacements. We demonstrate this with two synthetic examples: a normal fault system and a duplex system.

Key words: inverse problem, structural modelling, folding,

INTRODUCTION

Understanding and characterising the geometry of faults and fault networks is important for understanding structural architecture in many geological settings. Fault networks and geological interfaces can then be used for further analysis including resource estimation and numerical modelling. Existing 3D geological modelling methods are limited in how they incorporate fault kinematics and do not have any way of modelling interacting fault networks, e.g. duplex systems, flower structures and listric fault systems. It is difficult to build models that honour both geological observations and fault kinematics because the kinematics are not used to constrain the resulting geometries.

Three dimensional geological models are a representation of subsurface geology and usually consist of surfaces that represents geological interfaces and features (Caumon et al., 2009). There are two main approaches for representing these surfaces in the 3D model: explicit and implicit. The explicit approach represents the geometry of the surface directly where the surface exists, e.g. using a triangulated surface. The implicit approach represents the surface by an isovalue or level-set of an implicit function. Building surfaces using explicit surface representation generally involves the geologist's subjective user input and is similar to drawing polylines in a GIS environment. Implicit surface representation allows for the model to be represented as a function of the geological data (and/or knowledge). In this work we will focus on implicit modelling methods due to the more objective approach to model building.

The aim of implicit surface representation is to find the function that best fits the observed data (geological interfaces, orientation of geological units). Two approaches have been popular: 1) co-kriging or radial basis functions (Calcagno et al., 2008; Cowan et al., 2003; Hillier et al., 2014) where the function is estimated using a combination of local basis functions and a polynomial drift term and; 2) discrete implicit modelling (Caumon et al., 2013; Frank et al., 2007), where the function is estimated on a predefined volumetric mesh (e.g. Discrete Smooth Interpolator is a piecewise linear interpolant defined on a piecewise tetrahedral mesh).

Modelling faults in implicit modelling systems is challenging because faults are discontinuities in the geological interfaces. This means that the implicit function representing the geological interface needs to be discontinuous at the location of the fault but should maintain continuity between the geological layers if the fault were removed. There are two main approaches that have been used to add fault into implicit modelling methods: 1) represent the hanging wall and footwall of a fault by different implicit functions and use Boolean operations to define the boundary of the function (Caumon et al., 2013; Cowan et al., 2003; Frank et al., 2007). This approach means that the displacement of the fault will be determined by the observations in the footwall and hanging wall of the fault. It is suitable for areas where there is enough data on both the footwall and the hanging wall. The second approach (2) involves directly incorporate the discontinuity of the fault into the drift function in the implicit interpolant (Calcagno et al., 2008; De La Varga et al., 2019; Marechal, 1984). Neither of these approaches directly incorporate fault kinematics into the 3D modelling. This is problematic when modelling layers that are subparallel to the fault or where the faulted layers are deformed with complicated geometries (e.g. fold series). For example, in Figure 1a a folded series is modelled using a step function. The resulting displacement is inconsistent with the fault kinematics. The axial trace of the folds is not offset across the fault surface, the interpolant value is simply increased across the fault. This approach is acceptable where the angle between the faults and stratigraphy is high and the stratigraphy has a simple geometry. However, for faults that are subparallel to the stratigraphy or for deformed stratigraphy inconsistent kinematics can be observed. In the fold series in Figure 1a, the gradient of the implicit function does not change across the fault.

We propose a new approach for modelling faults in implicit systems where the model domain is restored prior to interpolating the faulted geological interface. The restoration is performed using a fault frame that defines the fault slip direction, fault surface and a distance along the fault strike. Figure 1b is an example of our approach applied to the fold series in Figure 1a and demonstrates the consistent fault kinematics when analysing the offset of the interpolated stratigraphy. This approach can be applied to fault networks where each slip event or fault segment is modelled backwards in time starting with the most recent, similar to recent methods for modelling folds (Grose et al., 2017; Laurent et al., 2016). We demonstrate our approach on synthetic examples of a normal fault network and a duplex system.

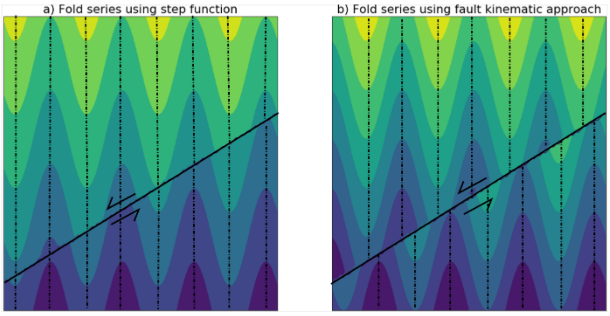

Figure 1. A comparison of step function (a) where fault kinematics are not correct and our kinematic approach (b) where the kinematics is consistent with structural geology.

FRAMEWORK FOR MODELLING FAULTS

A curvilinear fault frame (g_x, g_y, g_z) (Godefroy et al., 2018; Laurent et al., 2013) is interpolated by first modelling the geometry of the fault surface (g_x). This can be achieved by any implicit interpolation method. g_y is modelled so that the gradient of this field is parallel to observations of the fault slip direction and is orthogonal to the normal to the fault surface field (g_x). This constraint ensures that the slip direction is a vector in the fault surface. The third coordinate (g_z) is orthogonal to both the normal to the fault surface and fault slip direction. The fault coordinates are all normalised for the fault volume so that the minimum value is -1 and maximum value 1 at the tips of the fault (Godefroy et al., 2018). A volumetric displacement is calculated from the fault frame coordinates that defines the magnitude of the displacement caused by the fault. The fault displacement vector field can then be scaled by the fault displacement field.

In our implementation, we use discrete implicit modelling on a piecewise tetrahedral mesh to interpolate the fault frame coordinates and stratigraphic horizons. To interpolate faulted stratigraphy, we first restore the stratigraphic observations by moving the observation locations within the fault slip direction field by the fault displacement value. A scalar field representing stratigraphy is interpolated from these restored observations on the tetrahedral mesh. We then identify a model region to interpolate faulted stratigraphy as a subdomain of the tetrahedral mesh. The nodes for the points within the subdomain are restored using the fault direction field. The value of stratigraphy is interpolated onto these nodes using the restored stratigraphy scalar field. The nodes can then be restored to their original location and the result is a scalar field conforming to the fault geometry, honouring structural data and fault kinematics.

Our approach uses the kinematics of the fault to restore the geometry prior to faulting allowing for the interpolation of a continuous stratigraphic horizon. For this reason, it is possible superimpose multiple fault events. In a similar approach to modelling overprinting folds (Grose et al., 2017; Laurent et al., 2016) faults can be modelled backwards in time. The most recent slip event of a fault network is modelled first and then the following slip events are modelled backwards in time.

RESULTS

We demonstrate our results on two simple synthetic examples showing application of both compressional and extensional tectonic regimes. Both examples use a flat lying stratigraphic horizon for simplicity.

Figure 2 shows two examples of a listric fault network. There are two listric faults. In a) both faults share the same geometry in the detachment. In this example two fault events are superimposed shown by the yellow and black arrows. The yellow fault is modelled first and the black fault modelled second. At the detachment both faults have the same displacement direction. In b) the yellow fault has an associated antithetic fault. In this example the displacement at the detachment is only associated with the first fault.

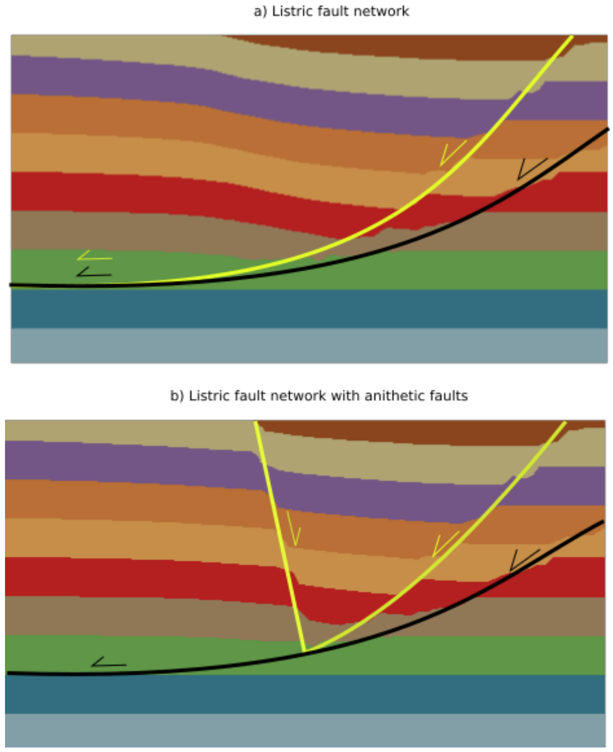

Figure 2. Listric fault networks modelled using kinematic approach. a) two listric faults with roll over anticline. b) two listric faults with antithetic faulting associated with the younger fault.

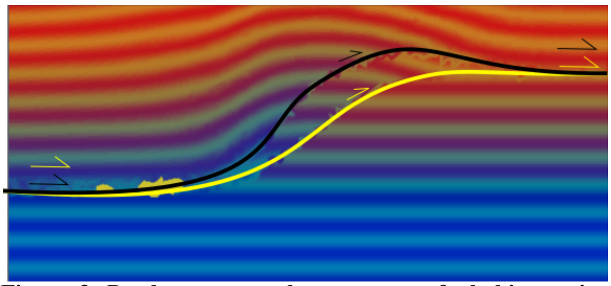

Figure 3. Duplex system where younger fault kinematics introduces local folding on the older fault geometry.

Figure 3 shows a duplex fault network. In this example there are two faults, yellow and black. The yellow fault occurs after the black fault and so the geometry of the black fault needs to reflect the deformation caused by the displacement associated with the yellow fault. Using the time aware approach to modelling fault, the most recent fault (yellow) is modelled first and then the black fault is modelled. The result is a duplex system where the older fault is deformed by the younger fault.

CONCLUSIONS

We present a new approach for incorporating faults into implicit geological modelling systems honouring fault kinematics and geological observations. Our results show that both complex extensional and compressional systems can be modelled. These approaches will form the basis for a geological inversion scheme where the displacement parameters will be optimized combining both geological observations, geological data and prior geological knowledge.

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