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A parametric method to model 3D displacements around faults with volumetric vector fields

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ABSTRACT

This paper presents a 3D parametric fault representation for modeling the displacement field associated with faults in accordance with their geometry. The displacements are modeled in a canonical fault space where the near-field displacement is defined by a small set of parameters consisting of the maximum displacement amplitude and the profiles of attenuation in the surrounding space. The particular geometry and the orientation of the slip of each fault are then taken into account by mapping the actual fault onto its canonical representation. This mapping is obtained with the help of a curvilinear frame aligned both on the fault surface and slip direction.

This formulation helps us to include more geological concepts in quantitative subsurface models during 3D structural modeling tasks. Its applicability is demonstrated in the framework of forward modeling and stochastic sequential fault simulations, and the results of our model are compared to observations of natural objects described in the literature.

1. Introduction

Faults dramatically impact fluid flow, mineralization, facies localization and the geometry and connectivity of rock units. In subsurface modeling, an accurate description of faults is therefore paramount in maximizing a model's predictive capabilities. In general, uncertainties associated with faults are significant, particularly concerning their connectivity and the displacement of surrounding rocks. These two aspects are intimately related to the kinematics and mechanics of the fault. Unfortunately, the compatibility with deformation history, tectonics, kinematics and mechanical concepts is generally secondary in current processes of quantitative 3D modeling, the main objective being to fit the data while honoring geometrical constraints such as minimizing the curvature of the structures (Caumon et al., 2009).

Typical geomodeling workflows proceed by interpolating the stratigraphic information contained in data points while faults are taken into account by introducing topological discontinuities (Calgagno et al., 2008; Caumon et al., 2009; Mallet, 2002). While such approaches have demonstrated their efficiency and are in daily use by the natural resources industry, they lack an explicit control on kinematics and mechanics, which can lead to implausible structures (Caumon et al., 2013). A validation step is then required for rejecting structurally incompatible models *e.g.* by simulating the retro-deformation that restores the geological structures to their supposed initial state (Dahlstrom, 1969; Durand-Riard et al., 2010; Maerten and Maerten, 2006; Moretti et al., 2006; Tanner et al., 2003). Even if such approaches have proved their ability to highlight certain structural inconsistencies, they imply a repeated trial-and-error process to achieve a completely kinematically compatible model, which would require prohibitive computational time. For these reasons, the introduction of kinematics and geomechanics remains a major bottleneck of geomodeling workflows, albeit crucial for the predictive capabilities of the models (Fletcher and Pollard, 1999).

Several approaches aim at producing numerical models of structural surfaces that natively honor some geological rules, for example: developability (Thibert et al., 2005), thread geometry of fault surface (Thibaut et al., 1996), sedimentation and compaction rates consistency (Mallet, 2004) and fold models (Hjelle and Petersen, 2011; Kaven et al., 2009). Because 3D displacement patterns associated with natural faults play a prominent role in fault characterization, we suggest that taking them explicitly into account while building the faults is a key aspect to increasing their consistency.

The application of such concepts to uncertainty modeling and to inverse problem solving (Cherpeau et al., 2012; Georgsen et al., 2012; Jessell et al., 2010) requires us to express a fault's displacement with appropriate parameters:

- The parameters should preferably correspond to the structural characteristics of geological objects to make their interpretation and use easier.

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• They have to be limited in number in order to maintain the dimensionality of these problems to acceptable limits.

This paper presents an approach for parameterizing the faults and their associated displacements in the form of a volumetric vector field, in a spirit similar to Jessell and Valenta (1996) and Georgsen et al. (2012). It consists of an extension of the fault parameterization presented in Cherpeau et al. (2010b, 2012). The proposed approach is based on previous work in Computer Graphics (Von Funck et al., 2006), which was first adapted to geological modeling in an earlier conference paper (Bouziat, 2012). Our paper completes this fault parameterization and introduces significant improvements to the methodology with a particular attention to fault kinematics and partitioning between near-field and far-field deformation.

Our contributions to a complete fault parameterization are:

• The definition of a 3D curvilinear fault space offering a general and appropriate frame for displacement computation (Section 3.2).
• The differentiation of the displacement evolution in the three principal directions of a fault: away from fault, along fault in the slip direction and along fault orthogonal to slip direction (Section 3.4).
• The ability to combine different flanking structures at different scales around the same fault (Fig. 10).
• The ability to use complex prior information to characterize the displacement field even when few or no data are available.
• The recourse to a time integration scheme to progressively build the displacement (Section 3.5), which allows us to combine displacements with different tectonic origins.

We present synthetic applications of this model in a forward modeling context (Section 4.1). Its integration into stochastic sequential simulations of fault networks for improving fault data clustering is also depicted (Section 4.3). Finally, adaptation to complex fault cases is presented through the example of a roll-over anticline (Section 4.2).

2. Related work

Numerous approaches have allowed fault-related displacements to be taken into account as an emerging character from either the geometrical interpolation of geological structures due to topological discontinuity introduced by faults (Caumon et al., 2009) or the geometrical and mechanical restoration of horizon structures (Durand-Riard et al., 2010; Egan et al., 1999; Maerten and Maerten, 2006; Moretti et al., 2006). For a complete fault parameterization, the associated displacements have to be explicitly integrated in the description of the fault.

The context of forward modeling requires fault operators capable of representing all possible ranges of displacements along and across faults, even when few or no data are available. To overcome this hurdle, Jessell and Valenta (1996) present several fault operators analytically modeling the 3D displacement fields associated with different kinds of canonical faults. For regional faults going through a studied domain, the displacement fields in fault blocks are modeled as pure translation or rotation. For faults of shorter extent, an elliptical decrease of slip intensity based on Walsh and Watterson (1987) is introduced.

Similar concepts of fault operator have also been developed for model editing in fault uncertainty models (Georgsen et al., 2012; Hollund et al., 2002), using two kinds of fault models: a piece-wise planar model for large faults and an elliptic model for small-scale faults. The curvature of fault surfaces can be accounted for by requiring constant distance between the displaced points and the fault surface (Georgsen et al., 2012; Jessell and Valenta, 1996). Because slip distribution is generally far more complex than depicted by classical elliptical models (Barnett et al., 1987) it is possible to derive the slip field by kriging horizon displacements projected on the medium plane of the fault (Georgsen et al., 2012).

In this paper, we present a general model based on the observation that, in spite of the wide diversity of faults, some common characteristics emerge and make it possible to describe them in a unified model, based on two main components:

• a 3D curvilinear fault frame, whose axes are oriented according to the orientation of the fault surface and the displacement direction (detailed in Section 3.2).
• the profiles of the attenuation of the displacement along the three axes.

The fault frame makes it possible to map complex fault geometries onto canonical cases, and the attenuation profiles enable the modeling of complex, theoretical and/or observed, displacement patterns. Displacement attenuation profiles are controlled by a limited set of geometric parameters, making this model compatible with both forward modeling and inverse approaches (Cherpeau et al., 2012; Georgsen et al., 2012; Jessell et al., 2010).

3. A parametric model describing fault-related displacements

3.1. General presentation of the model of displacements

The model presented in this section aims at deforming the structures cut by a fault in a kinematically consistent way. It relies on the modeling of the displacement field which represents the effects of the fault on the surrounding structures. Two kinds of displacement fields associated with faults are generally considered (Barnett et al., 1987): the far-field and the near-field, representing respectively the continuous and discontinuous parts of the displacement (Fig. 1).

The far-field describes the global displacement field in which a fault occurs. At the large scale (with regard to the size of a fault) only the far-field is perceptible. At a smaller scale, a fault localizes deformation which enables the accommodation of part of the stress related to the far-field displacements. This accommodation comes in the form of an additional displacement located around the fault, referred to as near-field. This kind of displacement affects the surrounding rocks and produces flanking structures, including normal and reverse drag (Fig. 2). These two terms designate ductile deformation of geological markers cut by a fault. They are distinguished by the direction of the curvature of the resulting folds:

• Normal drag describes a decrease of apparent displacement near the fault surface producing bending towards the opposite direction of the block displacement (Fig. 2a).
• Reverse drag is the opposite phenomenon. It corresponds to an increase of the apparent displacement near the fault surface bending the horizon towards the direction of displacement (Fig 2b).

The term “normal drag” comes from the similarity with the geometry produced by friction phenomena (Billings, 1972; Hamblin, 1965) and is now well established even if it has been recognized to be misleading (Grasemann et al., 2005; Hamblin, 1965; Hobbs et al., 1976). Indeed, the frictional resistance is unable to properly explain normal drag and would limit the development of reverse drag (Reches and Eidelman, 1995), which seems contradictory to the fact that normal and reverse drag can be observed together on a single fault.

The interpretation of fault drag is complicated by their diverse origins. The curvature of the fault surface is one of the first general effects accounting for flanking structures, *e.g.* the roll-over anticlines observed in the hanging wall of listric faults (Hamblin, 1965). The attenuation of the near-field displacement around faults of limited extent also plays a role in producing flanking structures as it naturally produces reverse drag (Barnett et al., 1987), even for planar faults. Normal drag is also likely to appear due to a low angle intersection between the marker and fault (Grasemann et al., 2003, 2005) or due to ductile deformation occurring before or in relation to fault rupture (Reches and Eidelman, 1995).