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Structural data constraints for implicit modeling of folds

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ABSTRACT

A recent method for modeling folds uses a fold frame with coordinates based on the structural geology of folds: fold axis direction, fold axial surface and extension direction. The fold geometry can be characterised by rotating the fold frame by the pitch of the fold axis in the axial surface and the angle between the folded foliation and the axial surface. These rotation angles can be expressed as 1D functions of the fold frame coordinates. In this contribution we present methods for extracting and automatically modeling the fold geometries from structural data. The fold rotation angles used for characterising the fold geometry can be calculated locally from structural observations. The fold rotation angles incorporate the structural geology of the fold and allow for individual structural measurements to be viewed in the context of the folded structure. To filter out the effects of later folding the fold rotation angles are plotted against the coordinates of the fold frame. Using these plots the geometry of the folds can be interpolated directly from structural data where we use a combination of radial basis function and harmonic analysis to interpolate and extrapolate the fold geometry. This contribution addresses a major limitation in existing methods where the fold geometry was not constrained from structural data. We present two case studies: a proof of concept synthetic model of a non-cylindrical fold and an outcrop of an asymmetrical fold within the Lachlan Fold belt at Cape Conran, Victoria, Australia.

1. Introduction

Folds are one of the most common features found in deformed rocks (Ramsay and Huber, 1987) but still present a challenge for three-dimensional structural modeling because the geometry of folded surfaces cannot be characterised from individual structural observations. Folds produce localised variations in curvature (Lisle and Toimil, 2007; Mynatt et al., 2007), however interpolation algorithms at the base of structural modeling generally fit a surface of minimal curvature (Jessell et al., 2014; Laurent et al., 2016). To model folded surfaces, the geologist is often required to use additional cross sections, level maps or other interpretive constraints such as synthetic bore holes to produce the expected geometry (Caumon et al., 2003; Jessell et al., 2010, 2014). This approach has proven operative in practice, but it is often cumbersome and reduces the objectivity and reproducibility of the modeling process. Most interpolation algorithms only consider local orientation of the surface and cannot incorporate any additional structural information or geological knowledge. These methods do not incorporate all available structural information collected by field geologists such as: lineations, foliations, overprinting relationships, fold axis, fold axial surface and vergence. This additional structural information can provide excellent constraints on complicated geometries found in hard rock terranes (Laurent et al., 2016).

In implicit modeling systems, geological surfaces such as lithological contacts, fold axial surfaces or fault surfaces are represented by isovalues of a global scalar field (Cowan et al., 2003; Frank et al., 2007; Calcagno et al., 2008; Hillier et al., 2014). The scalar field is interpolated using some of the available geological observations (*e.g.* orientation, lithology type, structural trend). A number of different interpolation methods exist (Cowan et al., 2003; Moyen et al., 2004; Aug et al., 2005; Frank et al., 2007; Calcagno et al., 2008; Caumon et al., 2013). These methods typically consider the

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final state of deformation and attempt to produce final 3D fold geometry from spatial measurements such as form lines, and strike and dip measurements. However, these methods generally use variants of isotropic Laplacian minimization, which is only appropriate when spatial observations are densely sampled. In sparse data settings, this isotropic assumption tends to generate structural geometries that are incompatible with the strong curvature anisotropy classically observed in folded terrains (Lisle and Toimil, 2007; Mynatt et al., 2007) and are highly non-developable (Thibert et al., 2005).

The problem of geometrically modeling folds has been addressed by a number of authors (Hillier et al., 2014; Laurent et al., 2016; Massiot and Caumon, 2010; Maxelon et al., 2009; Thibert et al., 2005). These approaches have provided the framework to incorporate the fold axial surface (Laurent et al., 2016; Maxelon et al., 2009; Thibert et al., 2005), fold axis (Massiot and Caumon, 2010; Hillier et al., 2014; Laurent et al., 2016) and a description of fold geometry and overprinting relationships (Laurent et al., 2016). Laurent et al. (2016) introduced a global fold frame which provides a reference coordinate system for each deformational event based on the structural elements of the fold. This allows for the geometry of older folds to be described without the effects of younger deformation events. For each folding event two rotation angles are calculated from field data: (1) the fold axis rotation angle, and (2) the fold limb rotation angle. To parametrise the variations of these two angles with respect to the fold frame, Laurent et al. (2016) use a periodical fold shape, which depends on estimations of fold wavelength, amplitude and location of fold hinges. In Laurent et al. (2016) these parameters are inferred using trial and error.

In this contribution, we present a method for directly extracting and characterising the geometry of folds from field data. The two fold rotation angles that are necessary for characterising a fold geometry can be calculated locally from field observations and interpolated throughout the model volume using multiple scalar and vector fields. We present two approaches for characterising the fold rotation angles within the fold frame: (1) standard interpolation, where there is enough structural data to characterise the fold shape, or; (2) a combined interpolation and extrapolation method using a Fourier series to represent the fold geometry. Where insufficient observations exist to characterise the geometry of the fold throughout the model volume, the Fourier series approximation of the fold geometry provides a geologically reasonable estimate that is objectively defined by the structural observations. We demonstrate these approaches on: (1) a synthetic example of a doubly plunging fold series, and (2) asymmetrical folds from Cape Conran, Victoria.

2. Related work

2.1. Structural geology of folds

Structural geologists describe the geometry of folds using the geometrical characteristics of the folded surfaces (Ramsay and Huber, 1987, p. 311–317): (1) the fold hinge is the location of maximum curvature for the folded surface, (2) the axial surface separates opposing limbs and contains fold hinges of conformable surfaces, and (3) the fold axis as either the fold hinge line or the line of intersection between the folded foliation and the axial foliation.

A planar fabric can often be observed orthogonal to the direction of principal shortening and roughly parallel to the fold axial surface (Ramsay and Huber, 1987; Hudleston and Treagus, 2010). This foliation can be used in a general case, to characterise the geometry of the axial surface away from fold hinges. This fabric is often pervasive and is commonly recorded by geologists to map the geometry of the fold axial surface. The intersection of this foliation and any older folded foliation provides a lineation that is parallel to the direction of the fold axis. These foliations and lineations can themselves be deformed by later folding events. By identifying structural elements of successive folding events and mapping their spatial distributions and overprinting relationships, structural geologists are able to unravel complicated geological structures (*e.g.* O'dea et al., 2006; Armit et al., 2012).

In a typical field mapping campaign, a structural geologist will systematically record the orientation of foliation surfaces and associated lineations (Ramsay and Huber, 1987, p. 677–678). These geometrical observations are typically interpreted and summarised onto a map as form lines. Fig. 1A shows the bedding trace of a small outcrop and Fig. 1B shows the relevant structural information that could be used to unravel the geometry of this outcrop from only selected areas. Form lines are usually a representation of the trend of observations and will often record at the scale of the map, the overprinting relationships that can be observed in and between outcrops (Alsop and Holdsworth, 1999; de Kemp, 2000; Lisle, 2003). Form lines that represent the trace of the axial surface record the location of the fold hinge.

2.2. Implicit fold modeling

Laurent et al. (2016) use the structural elements of the fold (fold axis, axial foliation and fold vergence) to define additional orientation constraints for implicit modeling. A fold frame is defined with coordinates represented by 3D scalar fields, denoted as x, y and z. Three local direction vectors (e_x, e_y and e_z) are implicitly defined by the fold frame coordinates for any location and are used to define the relative orientation of deformed foliations and structural elements. One of the main ideas of the method is to use classical interpolation (and the associated isotropic smoothness assumption) on the least deformed surfaces defining the fold frame, then to use this information to allow for anisotropic interpolation of more deformed surfaces.

For example, to model the geometry of a structure resulting from two folding events, the axial surface (S_2) of the most recent fold (F_2) would be first modeled by interpolating field observations of the axial surface or associated foliation. The orientation of the axial surface (S_1) of the older folding event (F_1) can then be constrained with respect to (S_2) using a description of the fold geometry for F_2 folds. This additional orientation constraint is in turn used for interpolating S_1 geometry and the process is finally repeated for S_0. Locally the fold geometry is constrained using a global scalar field representing the angle between consecutive foliations, *e.g.* S_1 and S_2.

The local orientation of the folded surfaces can be characterised using the local direction vectors (e_x, e_y and e_z) and two rotation angles. The fold axis rotation angle rotates e_y around e_z to give the orientation of the fold axis (L_i). The orientation of the folded foliation (S_{i-1}) is characterised by rotating the whole fold frame around the fold axis L_i by the fold limb rotation angle. The fold axis and fold limb rotation angles are the most important aspect of the fold modeling workflow because they control the geometry of the folded surface. The orientation of the folded surfaces need to fulfill the following criteria. It should be as close to the observations of the folded foliation as possible. Where no orientation constraints exist, the geometry of the folded foliation should fit the most geologically reasonable estimate, for example a folded surfaces should continue to be defined by localised variations in curvature away from observations instead of becoming a smooth surface (Jessell et al., 2014).