Earth and Planetary Science Letters 456 (2016) 26–38

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Implicit modeling of folds and overprinting deformation

Gautier Laurent [a,b,*], Laurent Ailleres [a], Lachlan Grose [a], Guillaume Caumon [b], Mark Jessell [c], Robin Armit [a]

[a] School of Earth, Atmosphere and Environment, Monash University, Australia
[b] GeoRessources (UMR 7359), Université de Lorraine-ENSG, CNRS, CREGU, Campus Brabois, TSA 70605, 54518 Vandoeuvre-lès-Nancy Cedex, France
[c] University of Western Australia, Centre for Exploration Targeting, M006, 35 Stirling Highway, Crawley, WA 6009, Australia

ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form 22 September 2016
Accepted 24 September 2016
Editor: P. Shearer

Keywords:
3D modeling
implicit modeling
geological structures
fold
foliation
vergence

ABSTRACT

Three-dimensional structural modeling is gaining importance for a broad range of quantitative geoscientific applications. However, existing approaches are still limited by the type of structural data they are able to use and by their lack of structural meaning. Most techniques heavily rely on spatial data for modeling folded layers, but are unable to completely use cleavage and lineation information for constraining the shape of modeled folds. This lack of structural control is generally compensated by expert knowledge introduced in the form of additional interpretive data such as cross-sections and maps. With this approach, folds are explicitly designed by the user instead of being derived from data. This makes the resulting structures subjective and deterministic.

This paper introduces a numerical framework for modeling folds and associated foliations from typical field data. In this framework, a parametric description of fold geometry is incorporated into the interpolation algorithm. This way the folded geometry is implicitly derived from observed data, while being controlled through structural parameters such as fold wavelength, amplitude and tightness. A fold coordinate system is used to support the numerical description of fold geometry and to modify the behavior of classical structural interpolators. This fold frame is constructed from fold-related structural elements such as axial foliations, intersection lineations, and vergence. Poly-deformed terranes are progressively modeled by successively modeling each folding event going backward through time.

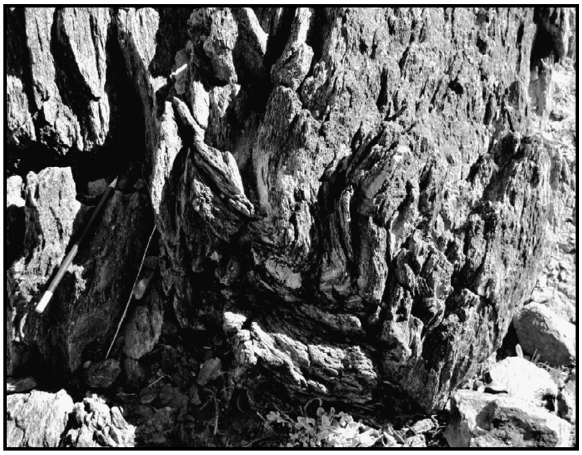
The proposed framework introduces a new modeling paradigm, which enables the building of three-dimensional geological models of complex poly-deformed terranes. It follows a process based on the structural geologist approach and is able to produce geomodels that honor both structural data and geological knowledge.

1. Introduction

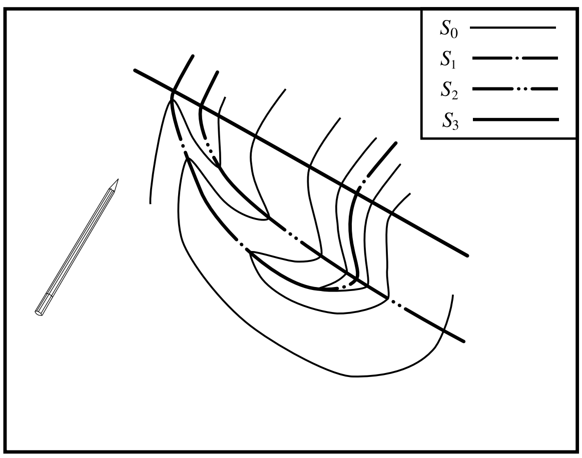
Three-dimensional modeling of geological structures is becoming an essential component of quantitative geoscientific research. For example, it helps to address challenges in sediment budget assessment (Guillocheau et al., 2012), seismic mechanism and seismic hazard studies (Li et al., 2014; Shaw et al., 2015), and natural resources characterization (Cox et al., 1991; Mueller et al., 1988; Vollger et al., 2015). However, the construction of a three-dimensional structural model from available observations remains a challenging task. 3D structural modeling techniques are essentially data-driven processes honoring spatial observations (Jessell et al., 2014). In most cases, these techniques rely on expert knowledge for overcoming the sparsity and uncertainty of available observations (Maxelon et al., 2009). Structural geology concepts are generally incorporated in the process through interpretive elements in the form of maps, cross-sections or control points (Caumon et al., 2009). Because these elements cannot be easily changed and represent the interpretation of the modeler, they also make this process slow, deterministic, and difficult to reproduce. Any expert editing is subjective and may introduce human bias (Bond et al., 2007). This limits the understanding of uncertainties, which have to be assessed for a structural model to fulfill its role (Bond, 2015; Caumon, 2010; Lindsay et al., 2012; Wellmann and Regenauer-Lieb, 2012). One way to study uncertainties consist in producing a suite of possible models instead of a single deterministic one, but this approach is limited by the necessary expert edit-

* Corresponding author at: GeoRessources (UMR 7359), Université de Lorraine-ENSG, CNRS, CREGU, Campus Brabois, TSA 70605, 54518 Vandoeuvre-lès-Nancy Cedex, France.
E-mail address: g.laurent.research@gmail.com (G. Laurent).

http://dx.doi.org/10.1016/j.epsl.2016.09.040



A. Outcrop near Eldee Creek, Australia



B. Structural interpretation

Fig. 1. Interference between multiple fold events. A: Photography of an outcrop in Eldee Creek, Broken Hill block, Australia, showing complex bedding/cleavage geometry and overprinting relationships. B: Structural analysis reveals at least three successive folding events with associated foliations. Note that the complexity of the geometry increases with the age of each deformation event.

ing of classical structural modeling approaches. Moreover, structural modeling techniques are generally limited to stratigraphic contact location and bedding orientation (Calgagno et al., 2008; Caumon et al., 2013). Some types of structural data are often ignored (Maxelon et al., 2009; Jessell et al., 2010, 2014), and part of the knowledge collected in the field is actually lost in the process of creating a geological model. A significant challenge is to formalize conceptual information and combine these with all observations.

While the modeling of faults using implicit approach is relatively developed (Calgagno et al., 2008; Cherpeau et al., 2010a, 2010b, 2012; Cherpeau and Caumon, 2015; Laurent et al., 2013), folds have received little attention. Only few contributions provide solutions to locally control fold-related geometries in interpolation methods (Caumon et al., 2013; Hjelle et al., 2013; Mallet, 2004; Maxelon et al., 2009). This is particularly difficult for hard rock terranes, where the continuity of stratigraphic layers and foliations are difficult to establish because of overprinting deformation events (Forbes et al., 2004; Ramsay, 1962) (Fig. 1).

A variety of structural modeling approaches exists, which combine numerical methods of interpolation (Calgagno et al., 2008; Chilès et al., 2004; Cowan et al., 2003; Frank et al., 2007; Hillier et al., 2014; Lajaunie et al., 1997; Mallet, 1992, 2014). Interpolation techniques proceed by geometric smoothing between data points. They perform well for dense data, but generate minimal surfaces when data are sparse, thus minimizing the curvature of the produced surfaces. However, folds are precisely characterized by specific, non-minimal curvature patterns (Lisle and Toimil, 2007; Mynatt et al., 2007).

We propose a method of interpolation which is designed to bridge the gap between data-driven and knowledge-driven methods, and addresses: (1) A better use of available data, in particular structural information related to folds. (2) The development of a time-aware data-driven method that takes into account the whole folding history. This is achieved by modifying the behavior of interpolation algorithms and incorporating a fold description in the interpolation process.

Our description of folding is based on a fold frame (Section 2), whose construction relies on observable structural elements (e.g. axial foliation). Deformation events are modeled successively by locally characterizing the relative orientation of their structural elements (Section 3). This modeling strategy is implemented in the framework of discrete implicit interpolation techniques (Caumon et al., 2013; Collon-Drouaillet et al., 2015; Frank et al., 2007; Mallet, 2014) through a set of specific numerical constraints (Section 4). The principles of this modeling strategy are illustrated on various examples of increasing complexity (Section 5).

For simplicity, we focus on the deformation of a conformable stratigraphic sequence, excluding faults, intrusions or unconformities. These geological features may be handled as proposed by Calgagno et al. (2008), Caumon et al. (2013), Laurent et al. (2013) or Røe et al. (2014).

2. Structural description of folded structures

This section presents some basic structural concepts and structural elements associated with folds. From there, we define a coordinate system used for parameterizing fold geometry and guiding fold interpolation.

2.1. Structural data and notations

Various structural observations related to folding may be used as data for building a geological model:

- **Stratigraphic observations**: They comprise the locations where a given stratigraphic contact is observed, and the orientation of bedding. These two observations are not necessarily recorded at the same locations. For example, bedding orientation may also be observed inside a given layer.
- **Direct structural element observations**: Some of the fold features can be directly observed, e.g. hinge locations, fold axis directions or axial surface orientations. These features can be observed along fold axial surfaces.
- **Indirect structural element observations**: Observations of axial surface cleavages, intersection lineations and vergence carry indirect information about fold parameters (e.g. fold amplitude, tightness, wavelength and location of the fold hinges).

The following symbols are used to refer to different stratigraphic and fold features that are considered in this study: D: deformation event, F: folding event, S: foliation field (generally a cleavage associated with a fold axial surface), L: intersection lineation (generally associated with a fold axis).

Each of these features may be indexed by a number that represents the associated relative deformation event (e.g. S_1 for the axial foliation of D_1). Bedding is referred to as S_0. When dealing with the relationship between successive folding events, the current event is denoted F_i, and any previous or later fold are respectively referred to as F_{i-1} and F_{i+1}.