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3D form line construction by structural field interpolation (SFI) of geologic strike and dip observations

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A B S T R A C T

Interpreting and modelling geometries of complex geologic structures from strike/dip measurements using manually-drafted structural form lines is labour intensive, irreproducible and inherently limited to two dimensions. Herein, the structural field interpolation (SFI) algorithm is presented that overcomes these limitations by constructing 3D structural form lines from the vector components of strike/dip measurements. The SFI interpolation algorithm employs an anisotropic inverse distance weighting scheme derived from eigen analysis of the poles to strike/dip measurements within a neighbourhood of user defined dimension and shape (ellipsoidal to spherical) and honours younging directions, when available. The eigen analysis also provides local estimates of the plunge vector and associated Woodcock distribution properties to assure plunge-normal structural form line reconstruction with unidirectional propagation of form lines across fold and fan structures. The method is advantageous for modelling geometries of geologic structures from a wide range of structurally anisotropic data. Modelled vector fields from three case studies are presented that reproduce the expected bedding-foliation geometry and provide reasonable representation of complex folds from local to regional scales. Results illustrate the potential for using vector fields to support geologic interpretation through the direct visualization of geometric trends of structural features in 3D.

1. Introduction

Structural field data provides important information for understanding geologic structures from outcrop to crustal scales (Moores and Twiss, 1995; Fossen, 2010). They provide valuable insight into a region's deformational history especially if additional information on the relationships between different structural elements is available (Ramsay, 1967). For example, bedding and cleavage intersection angles can be used to determine fold facing directions (Borradaile, 1976). Geologic interpretation has a long and rich history of using form traces, extended and interpolated, and the patterns of these traces, to resolve complex poly-deformed structural features (Alsop and Holdsworth, 1999; de Kemp, 2000). Obtaining geometric representations of geologic structures involves modelling its geometry from the structural data using a range of scales. Traditionally this analysis has been conducted by geologists that combine field observations on locally-observed structural styles with knowledge on the regional geological setting to arrive at plausible representations on 2D maps and cross sections (Lisle, 1988). Apart from being limited to labour-intensive two dimensional projections, these knowledge-driven representations are subjective and difficult to update when new structural data becomes available. Interpolation methods have however advanced the interpretive process to resolve and visualize fold geometries and fabric trajectories with various mathematical techniques (Matheron, 1955b, 1971; Watson, 1971, 1985; Briggs, 1974; Agterberg, 1974; Charlesworth et al., 1976; Cowan, 1996; Lajaunie et al., 1997; Mitas and Mitasova, 1999; Calcagno et al., 2008). These have been applied to digitized or regional interpreted serial sections to reconstruct complex structures to regional map scales (Moore and Johnson, 2001). Iterative approaches using finite element models for fold modelling at crustal scales (Yamato et al., 2011) or outcrop scales (Frehner and Schmalholz, 2006) are becoming more common. In conjunction there is more of a trend to develop tools for analysing and parameterizing fold metrics (Stabler, 1968; Srivastava and Lisle, 2004; Lisle and Toimil, 2007; Adamuszek et al., 2011) all enhancing our abilities to achieve a 3D and 4D understanding of the more challenging structures of the earth.

Herein we present a numerical algorithm that extends earlier 2D directional data interpolation methods to the third dimension by generating reproducible 3D vector field representations of

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geological structures from structural measurements. The 3D structural field interpolation (SFI) algorithm uses the three vector components derived from the strike/dip measurements and also uses the younging directions (depositional top) if these are available. A component of this work is the proper assignment of polarity to dip vectors derived from strike/dip measurements. The vector polarity assignments are made such that the interpolation of the dip vectors produces a vector field that traces the geometry of the underlying geology as recorded in the structural data. The younging directions, if available, are incorporated into the interpolation, which helps in better constraining opposing limbs of fold structures. When younging directions are unknown or when applied on foliation data, the reconstructed structural form lines are also produced, but with the assumption that opposing attitudes from girdle (great circle) distributions are due to folding. As a result, fan structures are not automatically honoured. However, if fan structures are known to exist, they can be modelled by assigning the appropriate younging directions to the strike/dip measurements. Other difficulties in modelling vector fields, as with any interpolation method, can be attributed to the distribution of data with respect to scale, which can result in under representation or smoothing of structural forms. The core notion here is that we provide a tool in SFI to quickly and objectively characterize and visualize structural geometries from whole or sub-sets of the raw data.

The idea of using a “vector field” approach has been known in geology for some time (Agterberg, 1974; Barbotin, 1987; Lee and Angelier, 1994; Gumiaux et al., 2003). Applications were related to visualizing strain and vector fields in 2D. Our approach is unique in that it: (1) reconstructs structural form lines in 3 dimensions, (2) incorporates structural anisotropy, (3) infers polarity on structural measurements when younging directions are not available, and (4) uses a regional symmetry axis to decide the direction to build the structural form lines.

The structure of this paper is as follows. In Section 2, we provide a detailed description of the SFI algorithm. In Section 3, the results of three case studies are summarized with the objective of testing the general performance of the algorithm. In Section 4, the advantages and limitations of the algorithm are discussed. Lastly, we summarize our conclusions in Section 5.

2. 3D structural vector field interpolation algorithm

The SFI algorithm follows four analytical steps: (1) eigen analyses of the poles to strike/dip measurements, (2) polarity assignment of dip vectors derived from strike/dip measurements, (3) rotation of polarity-assigned dip vectors to an orientation that is normal to the plunge vector, (4) 3D structural form lines compilation. These steps are described in detail in the following sections.

Pseudocode of the algorithm is provided in Appendix 1.

2.1. Eigen analysis of strike/dip poles

Eigen analysis of the poles to the strike/dip data is an integral part of the SFI algorithm and is used to: (1) model structural anisotropies in the interpolation of strike/dip vector components, if such anisotropies exist, (2) provide an estimate of the local and global plunge vector, which are needed to generate a vector field of form lines normal to the local plunge vector for representation of structural geometry and (3) to test for distribution properties (i.e. girdle, or point cluster distributions) for data-driven recognition of fold/fan structures using Woodcock’s analysis (Woodcock, 1977).

The eigen analysis is performed on data contained within user-defined neighbourhoods centred on each input data point. Two types of neighbourhood searches can be specified, spherical and ellipsoidal. Spherical neighbourhoods can be a better choice in regions where the data is noisy and in regions where the structural trends change very rapidly. In these types of environments isotropic sampling of the data is more desirable to determine structural trends. Ellipsoidal neighbourhoods are oriented by user specification or from computed eigenvectors. When oriented by user specification structural trends can be biased along its principal axis and may be justified if some expert knowledge exists to support a stronger anisotropy. The neighbourhoods can be propagated one of two ways – 1) Minimum number of members, and 2) geometry. The local anisotropy at each input data point is modelled by constructing the following pole orientation matrix using the $\boldsymbol{N}$ normal vectors ($\boldsymbol{n_i}$) derived from structural measurements found within its neighbourhood

$$\begin{bmatrix} \sum_{i=1}^{N} n_{ix}^2 & \sum_{i=1}^{N} n_{ix}n_{iy} & \sum_{i=1}^{N} n_{ix}n_{iz} \\ \sum_{i=1}^{N} n_{iy}n_{ix} & \sum_{i=1}^{N} n_{iy}^2 & \sum_{i=1}^{N} n_{iy}n_{iz} \\ \sum_{i=1}^{N} n_{iz}n_{ix} & \sum_{i=1}^{N} n_{iz}n_{iy} & \sum_{i=1}^{N} n_{iz}^2 \end{bmatrix}. \quad (1)$$

Upright poles are assumed for structural measurements that are not attributed with younging direction. Eigen analysis of this matrix yields eigenvalues, $\boldsymbol{E_1}$, $\boldsymbol{E_2}$ and $\boldsymbol{E_3}$ with

$$E_1 < E_2 < E_3 \quad (2)$$

and eigenvector matrix, $\boldsymbol{V}$,

$$V = \begin{bmatrix} e_{1x} & e_{2x} & e_{3x} \\ e_{1y} & e_{2y} & e_{3y} \\ e_{1z} & e_{2z} & e_{3z} \end{bmatrix} \quad (3)$$

where $\overrightarrow{e_1}, \overrightarrow{e_2}, \overrightarrow{e_3}$, are the eigenvectors associated with the eigenvalues $\boldsymbol{E_1}$, $\boldsymbol{E_2}$ and $\boldsymbol{E_3}$. These eigenvectors locally define the principle directions of structural anisotropy.

The local plunge vector for an input data point is the eigenvector $\overrightarrow{e_1}$ (associated with eigenvalue $\boldsymbol{E_1}$) obtained from the data point’s pole orientation matrix (Eq. (1)). This eigenvector describes the direction in which the poles vary the least. The global plunge vector is calculated in the same way, by eigen analysis of the pole orientation matrix of all structural measurements.

From the above eigen analysis the Woodcock parameter $\boldsymbol{K}$ (Woodcock, 1977) defined by

$$K = \frac{\ln\left(E_3/E_2\right)}{\ln\left(E_2/E_1\right)} \quad (4)$$

is computed to classify orientation distributions into one of two categories – clusters ($K > 1$) and girdles ($K \leq 1$). Supported fold structures are marked by girdle distributions, while cluster distributions describe orientations that are roughly pointing in the same direction. The computed K parameter is used for two purposes. First, it is used for determining whether or not there is a supported fold structure from a collection of structural measurements not attributed with younging direction. This knowledge allows us to infer the younging direction and is used to assign the appropriate polarity to dip vectors. Second, if a girdle distribution is indicated, the computed plunge vector ($\overrightarrow{e_1}$) is assigned to the associated input data to reconstruct the true (plunge-normal shape) geometry of the structures. Neighbourhoods that do not possess a girdle distribution are assigned the global plunge vector.