Journal of Structural Geology 32 (2010) 1170–1184

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Kinematic analysis of asymmetric folds in competent layers using mathematical modelling☆

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A R T I C L E I N F O

Article history:
Received 18 December 2009
Received in revised form
28 June 2010
Accepted 27 July 2010
Available online 5 August 2010

Keywords:
Folding
Strain
Mathematical modelling
Recumbent folds

A B S T R A C T

Mathematical 2D modelling of asymmetric folds is carried out by applying a combination of different kinematic folding mechanisms: tangential longitudinal strain, flexural flow and homogeneous deformation. The main source of fold asymmetry is discovered to be due to the superimposition of a general homogeneous deformation on buckle folds that typically produces a migration of the hinge point. Forward modelling is performed mathematically using the software 'FoldModeler', by the superimposition of simple shear or a combination of simple shear and irrotational strain on initial buckle folds. The resulting folds are Ramsay class 1C folds, comparable to those formed by symmetric flattening, but with different length of limbs and layer thickness asymmetry. Inverse modelling is made by fitting the natural fold to a computer-simulated fold. A problem of this modelling is the search for the most appropriate homogeneous deformation to be superimposed on the initial fold. A comparative analysis of the irrotational and rotational deformations is made in order to find the deformation which best simulates the shapes and attitudes of natural folds.

Modelling of recumbent folds suggests that optimal conditions for their development are: a) buckling in a simple shear regime with a sub-horizontal shear direction and layering gently dipping towards this direction; b) kinematic amplification due to superimposition of a combination of simple shear and irrotational strain with a sub-vertical maximum shortening direction for the latter component. The modelling shows that the amount of homogeneous strain necessary for the development of recumbent folds is much less when an irrotational strain component is superimposed at this stage that when the superimposed strain is only simple shear. In nature, the amount of the irrotational strain component probably increases during the development of the fold as a consequence of the increasing influence of the gravity due to the tectonic superimposition of rocks.

1. Introduction

Kinematic studies of folding are concerned with different types of strain patterns that appear in folded layers and the geometrical evolution of the folded layers from the initial, undeformed stage to the final fold. Kinematic folding mechanisms can be considered to be the theoretical tools that can be used in this analysis; they define rules that determine the displacements to be produced and the final strain pattern inside the folded layers. A reasonable starting point for establishing basic folding mechanisms is the experimental production of folds, comparable to natural ones. For example, the classical folding experiments by Kuenen and de Sitter (1938) using sheets of paper and rubber revealed the operation of the mechanisms that we now refer to as the flexural and tangential longitudinal strain mechanisms respectively. From this type of experiments it is possible to define the kinematic mechanisms as theoretical idealizations that can be mathematically analysed. In this way, applying the conditions required by every mechanism it is possible, from an initial configuration of a layer, to model theoretically the geometry of a folded layer and its strain pattern. The folding necessarily involves heterogeneous deformation; however, the superimposition of a homogeneous strain during folding can significantly modify the geometry of folds and their strain pattern, and this type of modification can be included as a folding mechanism in its own right.

An interesting aspect of folding kinematics is concerned with the development of asymmetric folds. According to the definition

☆ The program code ("FoldModeler") can be found in the following web page: http://www.geol.uniovi.es/Investigacion/OFAG/Foldteam.html

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doi:10.1016/j.jsg.2010.07.008

given by most authors, a fold is asymmetric when it lacks bilateral symmetry about the axial plane (Turner and Weiss, 1963, p. 122; De Sitter, 1964, p.272; Whitten, 1966, p. 601; Ramsay, 1967, p. 351). Most of the folds found in rocks are asymmetric and in many cases the degree of asymmetry is very high. Good examples are the major recumbent folds common in the hinterland of orogenic belts, the folds developed in ductile shear zones, and parasitic folds developed on the limbs of major folds. These examples illustrate the importance of gaining understanding of the folding mechanisms operating during the formation of asymmetric folds in order to further our knowledge of orogenic deformation. Most of the available studies on natural asymmetric folds place special emphasis on the shape and asymmetry of the folded surfaces or layers, but the final strain patterns or the characteristics of the progressive deformation in these folds are poorly known.

The aim of this paper is to study some general aspects of the kinematics of asymmetric folds in competent layers. Theoretical folds are modelled using tangential longitudinal strain, flexural flow and homogeneous strain. The asymmetry can be introduced via all three mechanisms. Superimposition on pre-existing folds of a general homogeneous strain, with final principal directions freely chosen will be the main source of asymmetry in our models. This modelling yields information about the final strain distributions and the progressive deformation in asymmetric folds (forward problem), and the potential for ascertaining the kinematic mechanisms that operated in specific natural asymmetric folds (inverse problem), by comparison of the geometry of these folds with theoretically modelled folds. A special attention is devoted to large recumbent folds, because they are key pieces for understanding of the structure of orogens.

The analysis is two-dimensional, considering strain in the profile plane of the folded layer. Application of the theoretically modelled folds to the analysis of the mechanisms that operate in natural folds is limited by the availability of strain measurements in the rocks. Fortunately, detailed information on the natural fold geometry and the cleavage pattern provides very useful data that can be related to the strain state and the kinematic mechanisms involved in the development of asymmetric folds.

2. On the description of asymmetric folds

A qualitative description of fold asymmetry was made by Ramsay (1967, pp. 351–352) using the letters M (symmetric), S or Z (asymmetric), in such a way that the shape of the letter describes the shape of the fold. This method is useful for the mapping of major structures from parasitic folds. From a quantitative point of view, Loudon (1964) and Whitten (1966) proposed the use of the third statistical moment of the orientation distribution of the normals to the folded surface profile to express the asymmetry of folds. Since the asymmetry depends on the relative length of the fold limbs (Ramsay, 1967, p. 351), a simple measure of the asymmetry of a fold is the ratio between these lengths. Tripathi and Gairola (1999) define the degree of asymmetry of a folded surface as the sum of two parameters, one depending on the difference in amplitude and other depending on the difference in shape. A problem with this method is that this parameter does not express the extent to which the asymmetry is due to differences in shape or differences in amplitude. In order to represent graphically the fold asymmetry in a 2D coordinate system, it is necessary to describe this geometrical feature using only two parameters. A complete description of the asymmetry of folded surfaces is not really possible with only two parameters; in fact, Twiss (1988) proposed a classification which requires six parameters for profiles of general asymmetric folded surfaces. Nevertheless, the most relevant features of this asymmetry can be characterised by the following parameters (Bastida et al., 2005; Lisle et al., 2006):

$$\text{Shape asymmetry}: S_a = A_F/A_B \tag{1}$$

$$\text{Amplitude asymmetry}: A_a = y_{0F}/y_{0B} \tag{2}$$

where A_F and A_B are the respective normalized areas (Bastida et al., 1999) of the forelimb and the backlimb (defined as the steeper and gentler limb respectively), and y_{0F} and y_{0B} are the y_0 parameters of the forelimb and the backlimb, respectively (Fig. 1a). The plot of these parameters in a graph of S_a against A_a for all the folds of a specific set, allows the visualization of the variation in asymmetry of these folds.

In order to analyse the asymmetry of the folded layer, comparison of the curves representative of the two limbs in the classifications of Ramsay (1967, pp. 359–372), Hudleston (1973) or Treagus (1982) can give a qualitative idea of the shape asymmetry. A simple parameter to quantify this aspect of asymmetry is the thickness asymmetry (T_a) (Fig. 1b), defined as the ratio between the orthogonal thickness of the forelimb and that of the backlimb for the maximum dip in the Ramsay's classification.

3. Modelling asymmetric folds: preliminary considerations

For the theoretical study of folding kinematics in individual competent layers it is opportune to use an auxiliary reference line, termed the 'guideline', which is usually, but not necessarily, positioned midway between the layer boundaries in the initial configuration. The guideline facilitates the monitoring of the layer geometry during folding. To analyse the strain in a folded layer profile it is necessary to choose a function to describe the form of the guideline. In this paper we will use functions of the conic section family (Aller et al., 2004). The conic sections have important advantages over other families of functions. They offer a good fit to the most common fold shapes and have finite curvature at all of their

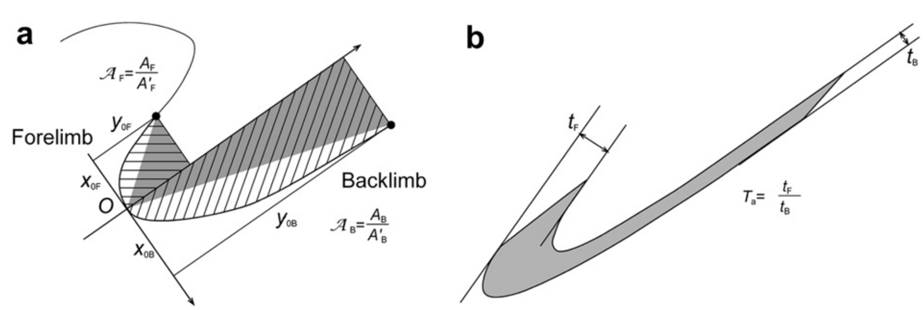

Fig. 1. (a) Parameters to characterise asymmetry in folded surfaces. The normalized area A for a fold limb is the ratio between the area A (lined) defined by the limb and the area A' (gray) of the chevron fold with the same x_0 and y_0 parameters. (b) Thickness ratio (T_a) as a measure of asymmetry in folded layers.