Journal of Structural Geology 87 (2016) 19–29

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Parasitic folds with wrong vergence: How pre-existing geometrical asymmetries can be inherited during multilayer buckle folding

Marcel Frehner*, Timothy Schmid

Geological Institute, ETH Zurich, Switzerland

A R T I C L E I N F O

Article history:
Received 20 October 2015
Received in revised form
2 March 2016
Accepted 5 April 2016
Available online 9 April 2016

Keywords:
Parasitic folds
Buckle folds
Fold vergence
Asymmetric folds
Structural inheritance
Finite-element method

A B S T R A C T

Parasitic folds are typical structures in geological multilayer folds; they are characterized by a small wavelength and are situated within folds with larger wavelength. Parasitic folds exhibit a characteristic asymmetry (or vergence) reflecting their structural relationship to the larger-scale fold. Here we investigate if a pre-existing geometrical asymmetry (e.g., from sedimentary structures or folds from a previous tectonic event) can be inherited during buckle folding to form parasitic folds with wrong vergence. We conduct 2D finite-element simulations of multilayer folding using Newtonian materials. The applied model setup comprises a thin layer exhibiting the pre-existing geometrical asymmetry sandwiched between two thicker layers, all intercalated with a lower-viscosity matrix and subjected to layer-parallel shortening. When the two outer thick layers buckle and amplify, two processes work against the asymmetry: layer-perpendicular flattening between the two thick layers and the rotational component of flexural flow folding. Both processes promote de-amplification and unfolding of the pre-existing asymmetry. We discuss how the efficiency of de-amplification is controlled by the larger-scale fold amplification and conclude that pre-existing asymmetries that are open and/or exhibit low amplitude are prone to de-amplification and may disappear during buckling of the multilayer system. Large-amplitude and/or tight to isoclinal folds may be inherited and develop type 3 fold interference patterns.

1. Introduction

Parasitic folds are very characteristic features in geological multilayer buckle folds and are treated in almost every traditional and modern structural geology text book (Fossen, 2010; Price and Cosgrove, 1990; Ramsay and Huber, 1987; Twiss and Moores, 2007). During polyharmonic folding (Ramsay and Huber, 1987), different wavelengths are established by layers of different thicknesses (according to Biot's dominant wavelength theory; Adamuszek et al., 2013; Biot, 1961; Fletcher, 1977) resulting in folds with smaller wavelength situated within folds with larger wavelength. The folds with smaller wavelength are termed parasitic folds or second-order folds (as opposed to the first-order folds with larger wavelength).

Parasitic folds develop simultaneously with the larger fold; hence they share the same (or similar) fold axis orientation and axial plane orientation as the larger fold. This similarity of style and attitude of different fold orders are known as the Pumpelly's rule that emphasizes the "*general parallelism which exists between the minute and general structure*", an observation that Pumpelly et al. (1894) made in the Green Mountains in Massachusetts. As a result, parasitic folds exhibit a characteristic asymmetry (or fold vergence), often referred to as S- and Z-shape on either limb of the larger fold and symmetric M-shape close to the hinge of the larger fold. Until De Sitter (1958) introduced the term parasitic fold, such second-order folds were also referred to as drag folds (Ramberg, 1963; Williams, 1961).

The development of parasitic folds has been studied analytically (Hunt et al., 2001; Ramberg, 1964, 1963; Treagus and Fletcher, 2009), as well as in analog (Ramberg, 1964, 1963) and numerical models (Frehner and Schmalholz, 2006). All these studies agree that parasitic folds develop by a combination of buckle folding on two different length scales. When a multilayer stack experiences layer-parallel shortening, all layers start to buckle; but the thin layers develop finite amplitudes prior to the thicker layers and develop short-wavelength symmetric folds (Frehner and

* Corresponding author. Geological Institute, NO E3, ETH Zurich, Sonneggstrasse 5, Switzerland.
E-mail address: marcel.frehner@erdw.ethz.ch (M. Frehner).

http://dx.doi.org/10.1016/j.jsg.2016.04.004
0191-8141/

Schmalholz, 2006). These folds are then sheared into an asymmetric geometry (S- and Z-folds; following Pumpelly's rule) on the limbs of larger-wavelength folds, which develop finite amplitudes slightly later. In the hinge area of these larger folds, shearing is less marked and the parasitic folds remain symmetric (M-folds; Frehner and Schmalholz, 2006). Even studies not specifically focusing on the development of parasitic folds reproduced this two-stage development in multilayer folds (Schmalholz and Schmid, 2012).

Pumpelly's rule seems to be axiomatic. Van der Pluijm and Marshak (2004) wrote: "*In any case, remember that a pattern of fold vergence opposite to that in Figure 10.16 (a "Christmas-tree" geometry) cannot be produced in a single fold generation (Figure 10.17). In fact, this geometry is diagnostic of the presence of at least two fold generations.*" Indeed, an alleged wrong fold vergence in geological field studies is usually used to argue for two distinct tectonic folding phases. For example, Froitzheim et al. (1994) observed folds on the decameter-scale in the Silvretta nappe (Austroalpine basement; SE Switzerland) that have the wrong vergence for their position within the Ducan synform and Pleuger et al. (2008) observed outcrop-scale folds in the Monte Rosa nappe (Middle Penninic basement; NW Italy) that have the wrong vergence for their position within the Vanzone antiform. In the first case, Froitzheim et al. (1994) interpreted the observed folds to originate from an earlier deformation phase than the larger-scale synform; in the second case, Pleuger et al. (2008) interpreted the observed folds to be younger than the larger-scale antiform. Similarly, Duncan (1984) interpreted minor folds with wrong vergence in the Thor-Odin gneiss dome (Shuswap metamorphic complex, Canadian Cordillera) to originate from a later deformation phase than the larger-scale Pingston fold.

Harrison and Falcon (1934) demonstrated that orogen-perpendicular gravitational collapse can result in a wrong vergence of second-order folds. However, this explanation was suggested for massive limestone formations and is not applicable to the examples above. Llorens et al. (2013b) demonstrated that higher-viscous layers oriented obliquely in a ductile shear zone can develop different vergences during a single simple-shear deformation event or even unfold completely while other layers remain folded. However, their numerical simulations mimic ductile shear zones and not smaller-scale parasitic folds within a larger-scale fold structure and are therefore not directly applicable to the problem at hand.

Here we present a feasibility study to investigate if second-order folds with wrong vergence can occur in multilayer buckle folds generated during only one single deformation phase. In particular, we test if a pre-existing small-scale asymmetry in the multilayer stack (e.g., from non-planar sedimentation and diagenesis) can survive the buckling process and can therefore be inherited as an asymmetric fold with wrong vergence. To test this, we apply a 2D finite-element model to simulate multilayer buckle folding of Newtonian materials.

2. Numerical method and setup

We use the same numerical model that has been explained in detail and successfully benchmarked in Frehner and Schmalholz (2006) and Frehner (2011). The method is based on the finite-element spatial discretization method (Zienkiewicz and Taylor, 2000) using triangular T7/3 isoparametric elements (Cuvelier et al., 1986). The model solves the Stokes equations in 2D plane-strain formulation in the absence of gravity coupled with an incompressible linear viscous (Newtonian) rheology; hence we model the slow viscous deformation governing buckle folding. We use perfectly body-fitting Lagrangian meshes, which allow modeling sharp viscosity jumps across interfaces between individual layers of the multilayer stack (Deubelbeiss and Kaus, 2008).

2.1. Model setup

The initial model setup and boundary conditions are depicted in Fig. 1 and detailed values for the model setup are provided in Table 1. The model consists of three high-viscosity layers (viscosity η_L) intercalated with a low-viscosity matrix (viscosity η_M). The two outer layers have equal thickness, H_0, and a distance to each other of also H_0. Sandwiched between them, the third layer is ten times thinner (thickness $h_0 = 0.1 \times H_0$). All model dimensions are normalized using the thickness of the thick layers (i.e., $H_0 = 1$); all model viscosities are normalized using the matrix viscosity (i.e., $\eta_M = 1$) (Table 1).

To initiate buckling of the two thicker layers, we impose a sinusoidal initial geometry on their interfaces according to

$$y_i(x) = -A_{\text{outer}} \sin\left(\frac{2\pi x}{\lambda_d}\right) + c_i, \quad (1)$$

where $y_i(x)$ is the y-coordinate (as a function of the x-coordinate) of the ith interface (i.e., bottom and top interface of the bottom and top thick layer), A_{outer} is the amplitude of the sinusoidal geometry, and c_i is a constant value chosen for each interface such that the layers have the desired thickness and distance to each other. The wavelength of the sinusoidal initial geometry, λ_d, corresponds to the dominant wavelength of the two-layer system (i.e., neglecting the thin central layer) according to Schmid and Podladchikov (2010):

$$\lambda_d = 2\pi H_0 \left(\frac{2\eta_L}{6\eta_M}\right)^{1/3}. \quad (2)$$

Note that the x-axis origin is located at the inflexion point of the outer thick layers (Fig. 1) to be consistent with Equation (1) and the

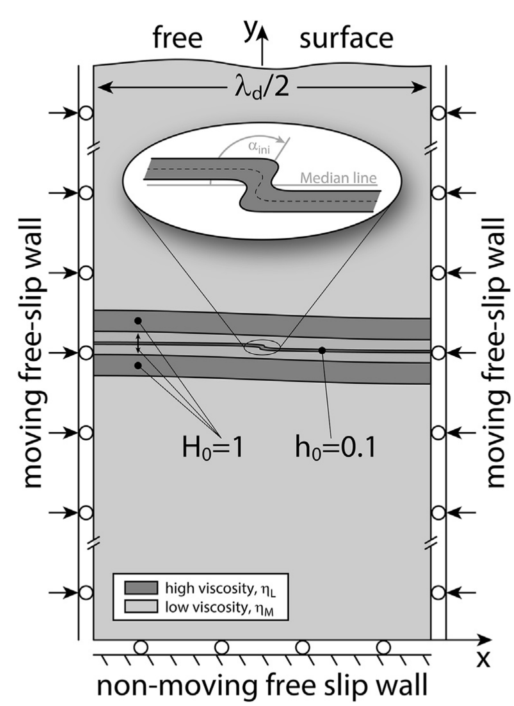

Fig. 1. Sketch (not to scale) of the 2D numerical model setup. A 3-layer system is intercalated with a background matrix of low viscosity. The distance between the two outer layers is equal to their individual thickness, H_0. The central layer with a 10-times smaller thickness, h_0, is sandwiched between them. The zoom shows the initial asymmetry of the central layer with the initial skew angle α_{ini}. Note that the x-axis origin is located in the model center.