Journal of Structural Geology 68 (2014) 58–65

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Domino boudinage under layer-parallel simple shear

Marcin Dabrowski [a, b, *], Bernhard Grasemann [c]

[a] *Computational Geology Laboratory, Polish Geological Institute — National Research Institute, Wrocław, Poland*
[b] *Physics of Geological Processes, University of Oslo, Norway*
[c] *Department for Geodynamics and Sedimentology, University of Vienna, Austria*

A R T I C L E   I N F O

Article history:
Received 10 December 2013
Received in revised form
15 August 2014
Accepted 7 September 2014
Available online 16 September 2014

Keywords:
Domino boudinage
Reworking
Strain gauge
High strain
Shear zones

A B S T R A C T

The boudin segments of a torn competent layer experience synthetic rotation in layer-parallel simple shear. As long as the individual segments in a boudin train are constrained by their neighbors, even a highly viscous boudin deforms internally to create the necessary space for rotation. The rotation rate is then much smaller compared to the case of an isolated segment. Hence, a small tilt of boudin segments is not indicative of low strain. The rotation rate at this stage largely depends on the aspect ratio of the boudin segments and the scaled gap width. Once the tilted boudins are no longer constrained by their neighbors, the rotation rate greatly accelerates. In the case of a low viscosity ratio between the boudins and the host, the boudin segments develop complex shapes, which may give an impression of shear-band boudins forming under the opposite shear sense. We furthermore investigate the behavior of boudin trains of finite length. The terminal segments are displaced out of the shear plane, deforming into isoclinal folds, and separate into groups of boudin segments that rotate into the shear direction and eventually lead to an overall chaotic appearance of the structure. Natural examples of domino boudinage from a high shear –strain detachment zone in the Western Cyclades (Greece) show many similarities with the modeled structures suggesting that, under simple shear deformation, the rotation and separation of boudin segments is an indicator for high shear strain.

1. Introduction

Boudin trains are stretched layers of strong rock units, which tend to break in a chain of sausage-shaped segments, while the weak rocks around them are not fractured and accommodate deformation by ductile flow (Lohest, 1909; Wegmann, 1932; Cloos, 1947). Since these early studies, a considerable variety of boudinage structures have been described resulting in a classification that is based on kinematic classes (no-slip, syn- and antithetic slip boudinage) and boudin block shapes (torn and drawn) reflecting different processes of separation of the boudin segments (Goscombe et al., 2004 and references cited therein). Furthermore, studies of boudinage provide information about the rheology of rocks and about the mechanics of the deformation (Ramberg, 1955). The process of boudinage formation and the reworking of boudin structures (Goscombe et al., 2004) have been extensively studied using analog modeling (e.g. Ramberg, 1955; Sen and Mukherjee, 1975; Neurath and Smith, 1982; Ghosh, 1988; Kobberger and Zulauf, 1995; Kidan and Cosgrove, 1996; Mandal et al., 2007; Marques et al., 2012; Carreras et al., 2013), which generally demonstrated that the initial fracture development, the mechanical anisotropy of the host rocks, and the viscosity ratio between the boudinaged layer and the host material control the subsequent boudin shape. Numerical models have been used to investigate elastic-brittle or non-linear viscous processes of fracture initiation (e.g. Bai and Pollard, 2000; Schmalholz et al., 2008; Iyer and Podladchikov, 2009; Schöpfer et al., 2011), the initial evolution of boudinage (Abe and Urai, 2012), and the ductile processes active during the reworking of the boudin trains (e.g. Lloyd and Ferguson, 1981; Mandal and Khan, 1991; Passchier and Druguet, 2002; Treagus and Lan, 2004; Maeder et al., 2009). As a corollary, most authors conclude that boudins are potentially useful strain gauges and rheological indicators, but the issue exists as to how closely deformation of a boudin train matches that of the host rock.

All the above mentioned models produce boudinage structures that resemble natural observations. A major and somewhat discouraging conclusion of these studies is that the initial fracture geometry and the orientation of the boudinaged layer, which both

* Corresponding author. Computational Geology Laboratory, Polish Geological Institute — National Research Institute, Wrocław, Poland.
E-mail addresses: mdabr@pgi.gov.pl, marcind@fys.uio.no (M. Dabrowski).

http://dx.doi.org/10.1016/j.jsg.2014.09.006
0191-8141/© 2014 Elsevier Ltd. All rights reserved.

control the shape and the aspect ratio of the boudin blocks, the competence contrast between the boudinaged layer and the host rock matrix, the type of the background deformation and the finite amount of strain all combine to control the finite geometry of the boudinage structure (e.g. Goldstein, 1988; Jordan, 1991; Swanson, 1992; Grasemann and Stüwe, 2001; Passchier and Druguet, 2002; Goscombe et al., 2004; Mandal et al., 2007). Despite the great number of combinations of these different parameters, Goscombe and Passchier (2003) concluded that asymmetric boudin geometries can be employed as practical and reliable shear sense indicators and can be used to constrain the stretching axis, provided that the fabric attractor can be identified. Unlike deformation fabrics, boudin trains are difficult to be completely reworked and obliterated and therefore multiple boudin generations can preserve palaeostretching axis directions from different deformational episodes (Goscombe et al., 2004). Interestingly, none of the existing models investigated the development of boudinage under high strain (e.g. shear strain γ larger than 10) although boudinage structures are frequently reported from highly deformed shear zones (e.g. Rosenbaum et al., 2002; Mehl et al., 2005; Schulmann et al., 2008; Campani et al., 2010; Grasemann and Tschegg, 2012).

We use the finite element code MILAMIN (Dabrowski et al., 2008) to study the reworking of torn boudins and the subsequent evolution of domino boudinage under simple shear deformation. The models investigate different initial boudin aspect ratios and viscosity ratios between boudins and host material for large shear strains ($\gamma > 10$). In this preliminary study, we investigate the simple case of ideal layer-parallel simple shear and layer-perpendicular fractures. We start our simulation at the stage, when the competent layer has already been segmented into rectangular boudin segments by extension fractures, a process that has been frequently described in nature (Ramberg, 1955; Lloyd et al., 1982; Goscombe et al., 2004).

The embrittlement of boudinaged layers in high strain zones is usually preceded by a long stage of ductile deformation and the layers are typically transposed into the shearing direction (e.g. Grasemann and Tschegg, 2012). Thus, the foliation-parallel layer orientations with respect to the shearing direction are the most common at the onset of the brittle stage (Goscombe et al., 2004), unless the far-field conditions change or the layers are introduced late in the system, e.g. magmatic dykes or metamorphic veins.

In this study, we choose an initially rectangular shape of boudin blocks, i.e. layer-perpendicular fracturing. The vast majority of boudins with blocky shape originate as so-called torn boudins (Goscombe et al., 2004). Many natural domino boudins, including the natural example presented in this study, record a rectangular boudin segment geometry, where the inter-boudin zone is perpendicular to the boudinaged layer (e.g. Lloyd and Ferguson, 1981; DePaor et al., 1991; Hanmer and Passchier, 1991; Goscombe et al., 2004). The initial sub-perpendicular orientation of the fractures is promoted by a refraction of the principal stress directions across the layer–host interface due to a high competence of the layer (Strömgård, 1973; Treagus, 1973; Mancktelow, 1993).

The results of the presented numerical models are compared with domino boudinage from a detachment zone in the Western Cyclades in Greece.

2. Model

The model is two-dimensional and consists of either a finite or infinite torn boudin train, which is oriented parallel to the shear zone boundary (Fig. 1). The boudin segments are initially rectangular, with the length L and the height H. The key geometric parameters are the initial aspect ratio of the individual boudin blocks ($A = L/H$) and the scaled width of the inter-boudin zone ($B = W/H$).

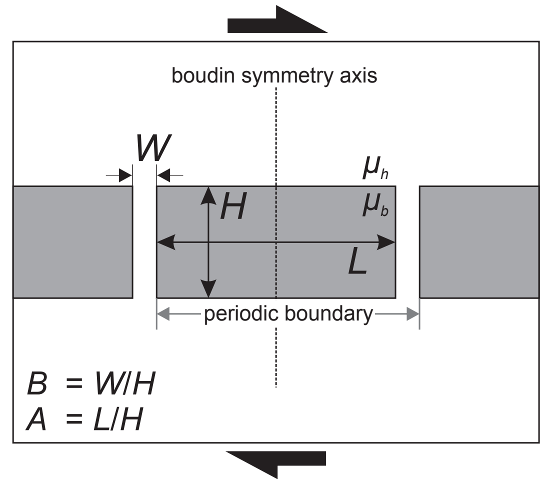

Fig. 1. Model geometry and parameters. L – length of the boudin; H – height of the boudin; A - initial aspect ratio of the boudin; B - normalized width of the inter-boudin zone; μ_b - viscosity of the boudins; μ_h - viscosity of the host.

Both the boudins and the embedding matrix are treated as incompressible Newtonian fluids in a creeping flow (Stokes flow) regime without gravity. We use m to denote the ratio between the viscosity of the boudins (μ_b) and the viscosity of the hosting matrix (μ_h). The interface between the boudins and the matrix is welded and the processes of recrystallization and reaction between the boudin and the matrix are neglected.

The model is subjected to simple shear in the far field and the velocity vectors are prescribed at to the top and bottom boundaries of the computational box. The lateral boundaries are considered to be periodic. The boudin train is placed in the center of the computational domain and the box boundaries are placed at a large distance (30–50 times the length of the boudin train elongation) from the center in order to minimize the boundary effects. In the case of an infinite train, periodic boundary conditions are used and there is only one boudin segment present in the computational model, with the lateral boundaries placed in the intervening gaps (Fig. 1).

MILAMIN (Dabrowski et al., 2008), a MATLAB implementation of the finite element method, is used to compute the flow field in and around the deforming boudin blocks. We use unstructured triangular computational meshes to accurately represent the evolving structures, with the mesh refined towards the boudin train and frequently regenerated to maintain its quality. High shear strain up to $\gamma = 50$ (dextral shear positive) was reached in some of the model runs.

We focus on monitoring the overall deformation of the boudin segments by tracking their outlines. In the case of a highly viscous boudin train, the deformation of the boudin segments is largely accommodated in the vicinity of the boudin gaps and the remaining parts of the boudin segments are chiefly subjected to rotation. We measure the amount of rotation by tracking the initial symmetry axis of the boudin segments perpendicular to the shear zone boundaries (Fig. 1). Clockwise measured angles (i.e. the rotation) are positive.

3. Results

3.1. Boudin trains of infinite length

Fig. 2 shows the results for a low viscosity ratio of $m = 10$ and a high viscosity ratio of $m = 1000$. The initial aspect ratio A of the individual boudins varies from 1 to 5 in the rows and the normalized gap width of the inter-boudin zone was initially set to $B = 0.05$.