Journal of Structural Geology 56 (2013) 129–141

Contents lists available at ScienceDirect

Journal of Structural Geology

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

The development of sheath folds in viscously stratified materials in simple shear conditions: An analogue approach

Damiano Dell'Ertole*, Wouter P. Schellart

School of Geosciences, Monash University, Melbourne, VIC 3800, Australia

ARTICLE INFO

Article history:
Received 28 May 2013
Received in revised form
30 August 2013
Accepted 11 September 2013
Available online 20 September 2013

Keywords:
Sheath fold
Simple shear
Ductile deformation
Analogue model

ABSTRACT

Sheath folds are highly non-cylindrical folds occurring in a variety of geological settings, and have been studied using different approaches. With the present work, we provide a quantitative analysis of the generation and development of sheath folds in a viscously layered system in simple shear conditions. The sheath folds develop from an initial non-cylindrical deflection located on the highly viscous layer. The analogue experiments investigated the influence of (1) variations in the viscosity ratio between the high viscosity layer and the matrix (η_{hvl}/η_m), (2) variations in the ratio between the amplitude of the initial deflection and the thickness of the high viscosity layer (A_f/T_{hvl}), and (3) progressive simple shear (γ). The results show that increases in η_{hvl}/η_m will produce progressively less elongated sheath folds, while increases in A_f/T_{hvl} will result in more elongated sheath folds. We present regime diagrams with η_{hvl}/η_m and A_f/T_{hvl} for different shear strains illustrating under which conditions sheath folds form. In case the original deflection amplitude and layer thickness as well as γ can be retrieved for sheath folds in nature, then their geometry can be used to quantify the effective η_{hvl}/η_m.

1. Introduction

Sheath folds are defined as folds whose hinge line is curved more than 90° within the axial surface (Quinquis et al., 1978; Ramsay and Huber, 1987; Skjernaa, 1989; Marques et al., 2008). According to Skjernaa (1989), it is possible to define sheath and tubular folds (which are a sub-class of general sheath folds) using geometrical parameters, which are: the hinge line angle ω (with the hinge line lying on the xy plane), and the Cartesian axes x (direction from the centre of the elliptical fold section to the fold nose) and y (major axis of the elliptical section perpendicular to the x axis), as shown in Fig. 1.

Sheath folds have been recognized in rocks that have endured different deformation histories, and they occur in nature at a wide range of scales, from <mm to >10 km (Goscombe, 1991; Berlenbach and Roering, 1992; Alsop, 1994; Searle and Alsop, 2007; Bonamici et al., 2011). They have been reported in numerous places around the globe and in rocks of different type and ages, including various grade metamorphic facies in the Appenninic and Alpine orogenic belts in Europe (e.g. Kligfield et al., 1981; Crispini and Capponi, 1997; Musumeci and Vaselli, 2012), Palaeozoic orogenic belts such as in Europe and Australia (e.g. Alsop and Carreras, 2007; Marques et al., 2008; Goscombe, 1991; Bonamici et al., 2011), Proterozoic belts (e.g. Foster and Gray, 2000; Forbes et al., 2004), and Archean cratons such as in Scandinavia and India (e.g. Park, 1988; Srivastava, 2011). They have been reported in unconsolidated sediment layers in Palaeozoic and Cenozoic turbidites (e.g. McClelland et al., 2011; Alsop and Marco, 2013), and in ignimbrites of various ages (Branney et al., 2004; Andrews and Branney, 2011). Different models have been proposed to explain their formation, including: conditions of pure shear, either plane strain or constrictional (Borradaile, 1972; Mandal et al., 2009), diapirism or three-dimensional differential (i.e. non-planar) flow (Skjernaa, 1989), and simple shear conditions (Rosas et al., 2002; Marques et al., 2008; Reber et al., 2013a,b).

In nature, sheath folds are most commonly observed in shear zones (Skjernaa, 1989; Marques and Cobbold, 1995; Alsop and Holdsworth, 2006), and for this reason this work focuses on the development of sheath folds in shearing conditions. Over the last four decades, the mechanisms producing complex deformations in shear zones have been studied intensely using field-based investigations (e.g. Carreras et al., 1977; Cobbold and Quinquis, 1980; Ramsay, 1980; Skjernaa, 1989; Ildefonse et al., 1992; Ez, 2000; Alsop and Holdsworth, 2004, 2006, 2012; Carreras et al., 2005; Sengupta et al., 2005; Alsop and Carreras, 2007; Searle and Alsop, 2007; Marques et al., 2008). There

* Corresponding author. Room 127, Building 28, School of Geosciences, Monash University, Clayton Campus, VIC 3800, Australia. Tel.: +61 (0)3 99051127.
E-mail address: Damiano.DellErtole@monash.edu (D. Dell'Ertole).

0191-8141/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2013.09.002

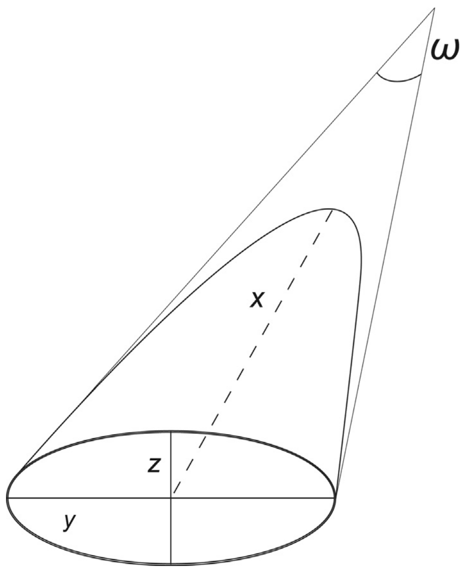

Fig. 1. Sketch of the geometry of a sheath fold. The parameters used to define the sheath folds are the ratio between the *x* axis (or cone axis, following Skjernaa (1989)) and *y* axis and the hinge line angle ω.

have also been several studies presenting scaled analogue models, numerical models and analytical models of sheath fold formation to investigate the different physical conditions under which they might form (e.g. Cobbold and Quinquis, 1980; Marques and Cobbold, 1995; Rosas et al., 2001, 2002; Marques et al., 2008; Mandal et al., 2009; Reber et al., 2013a). The recent study from Marques et al. (2008) has in particular focused on the influence of the viscosity ratio within a layered system on the development of sheet folds. However, these authors did not test the influence of the thickness of the high-viscosity layer on sheath fold development, and the combined effects of viscosity ratio and relative thickness on the sheath fold formation for progressive shear strain increments. A very recent analogue modelling study investigated the influence of viscosity ratio and layer thickness on sheath fold formation using a multi-layer system with a weak inclusion deformed under simple shear conditions (Reber et al., 2013b). The work provided insight into the influence of viscosity ratio and layer thickness on sheath fold formation, but it could not systematically investigate the influence of simple shear magnitude on sheath fold formation due to the opaque nature of the multi-layer system.

In the current work we present results from analogue models of simple shear of a high-viscosity layer with a non-cylindrical perturbation embedded within a low-viscosity (transparent) matrix. We systematically investigate the influence of viscosity ratio, perturbation amplitude to layer thickness ratio, and the amount of simple shear on the formation of sheath folds. The results provide new insight into the potential suitability of sheath folds observed in nature for determining the sense of shear and the amount of shear in a shear zone, and their potential suitability to determine the effective viscosity ratio between different rock layers in a sheath-fold geometry. The results will demonstrate that in order to quantify the amount of shear strain from a sheath fold in nature, the amplitude of the initial deflection as well as the viscosity ratio between the layers should be known.

2. Experimental procedure

We have investigated the progressive deformation of a non-cylindrical perturbation for a high-viscosity layer embedded within a low-viscosity matrix experiencing simple shear. With this set-up, we have performed two sets of experiments, with the first set investigating the effects of variations in the viscosity ratio between the layers, and the second set investigating the effects of variations in the thickness of the high viscosity layer.

2.1. Apparatus

In order to study the development of sheath folds in simple shear regimes, a dedicated shear tank has been designed and built. The apparatus is capable to impose a laminar Couette flow, which is the laminar flow of a viscous fluid in the space between two parallel boundaries, one of which is in relative motion to the other (Fig. 2). The apparatus can operate at a range of different velocities selected by an electronic controller. The machine consists of four Perspex segments that act as sidewalls, a top boundary and a bottom boundary. The front and rear walls and the top lid are mobile. Front and rear walls consist of stacks of thin Perspex plates (15 plates in each stack): the front and rear plates that are positioned at the

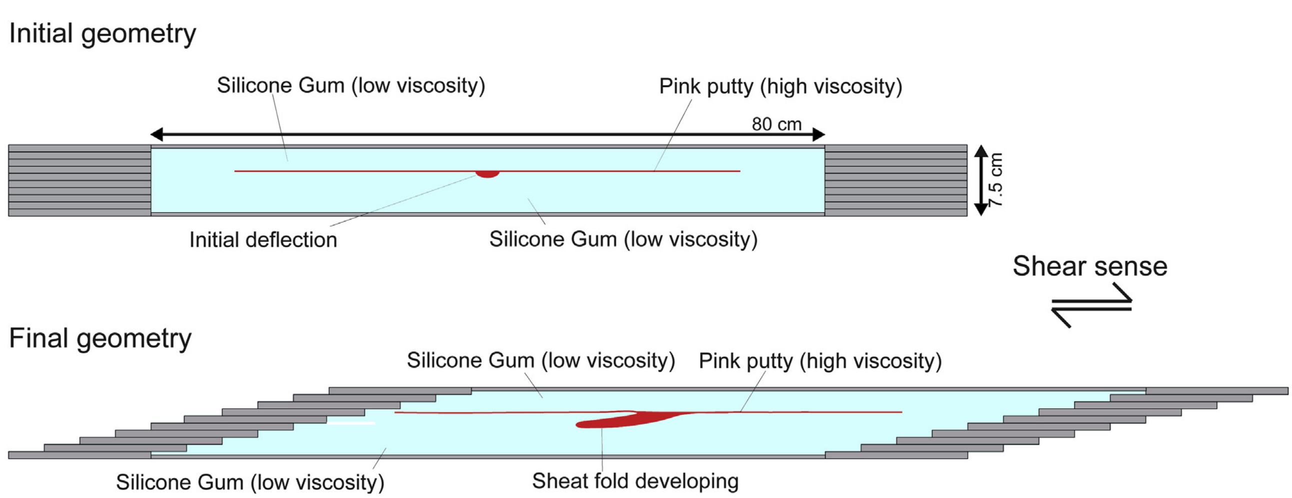

Fig. 2. Sketch of the shear apparatus, showing the geometrical configuration at the initial and final stages of the experiments. The grey colour indicates the machine's boundaries, the light blue colour indicates the PDMS matrix and the red colour is used for the high viscosity layer. Arrows indicate the shear direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)