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Experimental study of sheath fold development around a weak inclusion in a mechanically layered matrix

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ABSTRACT

We present quantitative laboratory models investigating the mechanics of sheath fold formation around a weak inclusion in simple shear. Sheath folds are intriguing, highly non-cylindrical structures that stimulated extensive field and experimental studies, leading to an ongoing debate concerning their formation and evolution. Through a parametric study, we test the influence of a mechanically layered matrix on the development of sheath folds using silicone models. Our models show how (1) the viscosity ratio between the layers in the matrix and (2) the layer thickness control the shapes of the resulting folds and their visibility. All experiments with a weak inclusion resulted in strong deformation of the layers. An increase in viscosity ratio, however, leads to less evolved sheath folds, which are shorter and show a larger opening and dip angle. In contrast to former studies, we show that a mechanically layered matrix does not hinder the formation of sheath folds. The visibility of the sheath folds in our models strongly depends on the aspect ratio between the inclusion height and the layer thickness: we observed sheath folds for a ratio larger than 7.5. The experiments reproduced the first-order features of natural sheath folds. Our results challenge previously published studies where sheath folds were considered as purely passive structures. We demonstrate that sheath folds readily develop around slip surfaces, suggesting that this might be a relevant formation mechanism in nature.

1. Introduction

Sheath folds are quasi-conical structures with rounded apices (Fig. 1a) (Hansen, 1971; Quinquis et al., 1978; Ramsay, 1980; Skjernaa, 1989). Ramsay and Huber (1987) defined sheath folds as having an opening angle of <90° (Fig. 1c). Sheath folds are three-dimensional structures and some examples crop out fully as such (e.g., Alsop and Carreras, 2007; Quinquis et al., 1978). In general, however, sheath folds are more readily visible on cross-sections perpendicular to the shear direction (e.g., Alsop and Holdsworth, 2006), where the layers show closed contours (Fig. 1b). Although these structures are now called sheath folds, earlier terms were 'domes and basins' (Quirke and Lacy, 1941), 'closed folds' (Balk, 1953) or 'eyed folds' (Nicholson, 1963). Sheath folds occur in many rock types, such as metamorphic rocks (e.g., Carreras et al., 1977; Philippon et al., 2009; Quinquis et al., 1978), soft sediments (e.g., Alsop and Marco, 2011; George, 1990; McClelland et al., 2011; Strachan and Alsop, 2006), glaciotectonic sediments (e.g., Lesemann et al., 2010; Thomas and Summers, 1984) or ignimbrites (Branney et al., 2004). In length they may range from less than 1 mm (Berlenbach and Roering, 1992) to more than 1 km (Lacassin and Mattauer, 1985). Alsop et al. (2007) have shown that sheath folds are largely scale-invariant. Carreras et al. (1977) and subsequent workers (e.g., Alsop and Holdsworth, 2006; Fossen and Rykkelid, 1990; Minnigh, 1979; Quinquis et al., 1978) associated sheath folds with shear zones and used their shapes to infer strain magnitude (e.g. Alsop and Holdsworth, 2004), shear sense (Fossen and Rykkelid, 1990) or bulk strain type (Alsop and Holdsworth, 2006).

A simple approach to studying sheath folds is through detailed description and classification of their shapes (e.g., Alsop and Holdsworth, 2006; Skjernaa, 1989). Such an approach, however, provides few insights into the kinematics and mechanics of their development. Simple theories of buckling (e.g., Biot, 1957) are two-dimensional and predict cylindrical folds, so that they are not applicable to sheath folds. Several studies have suggested that sheath folds arise during a flow perturbation in simple shear (e.g., Alsop and Carreras, 2007 and references therein). Such a perturbation may be due to (1) a local undulation in otherwise planar and passive layering (Cobbold and Quinquis, 1980), (2) a rigid inclusion, such as a boudin (Marques and Cobbold, 1995; Marques et al., 2008; Rosas et al., 2002), or (3) a weak inclusion, such as a crack or vein (Exner and Dabrowski, 2010; Reber et al., 2012). The bulk deformation may also involve components of constriction or flattening (Ez, 2000; Mandal et al., 2009). In nature, however, the causes of sheath fold development may not be discernible, as the bulk deformation may have overprinted the initial perturbation, or the resulting sheath fold and the triggering objects may have separated during deformation.

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Fig. 1. a) Photograph of quartz layer, cropping out as sheath fold, Cap de Creus, Spain. b) Photograph of sheath fold as eye-structure in quartzite layers on cross-section perpendicular to shear direction, Oppdal, Norway. c) Sketch of a sheath fold (α denotes the opening angle of the cone). The cone is elongated in x-direction. Eye-patterns appear on yz-sections.

Early studies of the mechanics of sheath folds were mainly experimental, but some recent ones have been numerical (Mandal et al., 2009) or analytical (Reber et al., 2012). Most former studies assumed a homogeneous matrix for the development of sheath folds. In nature, however, many sheath folds in rocks involve layers of contrasting viscosities (e.g., Alsop and Holdsworth, 2006; Morales et al., 2011). Marques et al. (2008) tested the effect of a mechanically layered matrix on sheath fold development around a competent inclusion. They concluded that sheath folds do not develop when the viscosity ratio between the layers is larger than 10. However, in their experiments the ratio between the inclusion size and the layer thickness was constant, whereas Dabrowski and Schmid (2011) argued that this parameter controls the outreach of the folds into the matrix and therefore their visibility.

In this paper, we present an experimental study of sheath fold development in a mechanically layered matrix of silicone around a weak inclusion. Our experimental setup consisted of a simple shear apparatus. In a systematic manner, we tested the effects of (1) the viscosity ratio between the layers, and (2) the aspect ratio between the size of the inclusion and the layer thickness on the development of sheath folds.

2. Experimental procedure

Typically, the preparation and running of each experiment required 3 to 4 days.

2.1. Model material

To build the matrix we used polydimethyl-siloxane (PDMS-DC SGM36, Dow Corning, Great Britain, further referred to as silicone), which is a suitable model material for linear viscous processes at the strain rates such as those in our experiments (ten Grotenhuis et al., 2002; Weijermars, 1986).

For the pure silicone, we measured a viscosity of 3.5×10^4 Pa s at 21 °C. To test the effect of mechanical layering on the development of sheath folds, we needed silicones of different viscosities. To increase the viscosity, we mixed the pure silicone with inert fillers, such as fine-grained sand or iron-oxide (Weijermars, 1986) thus obtaining a maximal viscosity of 5.3×10^5 Pa s. Conversely, to decrease the viscosity we mixed the pure silicone with oleic acid (Weijermars, 1986), so obtaining a minimal viscosity of 7.2×10^3 Pa s. Thus, this procedure allowed us to produce a viscosity ratio up to 50. For details on the viscosity measurements see Appendix A.

To simulate the weak inclusion, we used a liquid soap (Arma®, Marseille). We measured the viscosity of the soap, using the same rotary viscometer as that described by Galland et al. (2006) for low viscosity fluids, and obtained a value of approximately 1 Pa s at room temperature.

2.2. Construction of models

We made the models out of fine layers of silicone, of alternating viscosities (Fig. 2b). We aimed to test the effect of the layer thickness, and especially to produce very thin layers. To do so, we adopted the following technique of Dixon and Summers (1985).

(1) We individually prepared 8 mm-thick plates of two silicones, which can have different viscosities, using a double-roller device commonly used in bakeries. To prevent the silicone from sticking to the rollers and the underlying surface, we sprayed a very thin film of water on a thin plastic sheet, before placing the layer of silicone. We also wetted the upper surface of the silicone to prevent it from sticking to the upper roller. (2) When the required thickness was reached, we dried the silicone plates and stacked them. The two silicone surfaces adhered as soon as they were in contact so that slip between the silicone layers became impossible. (3) The two-layer stack was then rolled to a final thickness of 8 mm, whereupon each layer acquired a uniform thickness of 4 mm. (4) We then cut the two-layer stack into two pieces of equal sizes, and placed them on top of each other. (5) The stack was rolled once more to a total thickness of 8 mm. It contained now 4 layers of 2 mm thickness. (6) We repeated this procedure until we reached the desired layer thickness. The preparation of the thin silicone layers is essentially the same as the preparation of butter dough.

Using this procedure, Dixon and Summers (1985) claimed that they could attain a layer thickness of 20 μm. The finest layering that we achieved was 0.5 mm. We could not produce thinner layers, as the sand grains (Ø25 μm) used as inert fillers interfered with the thin layers.

The viscosity ratio had a negligible effect on the preparation procedure described above. We assume that if the rolling is faster than the relaxation time of the individual silicones, they thin equally. During the experiments, the applied strain rates were much lower, and the silicones of different viscosities behaved differently. This technique, however, reached its limits when the viscosity ratio between the silicones was 50 or higher. In this case the layer did not thin equally anymore.

Using the above technique, we prepared six silicone multilayers (each of 8 mm total thickness), and cut them to the length and width of the experimental chamber. We placed all but one multilayer in the experimental chamber. Then, we introduced a weak inclusion, in the following way. (1) We poured liquid soap into an elliptical mold, 4 cm long, 1.5 cm high (the inclusion height, *a*) and 1 mm thick. (2) We froze the mold. (3) We made a vertical cut with a knife in the middle of the model. (4) We extracted the soap tablet from the mold and inserted it into the cut. (5) Before the soap melted, we placed the last silicone multilayer on top, so that it sealed in the soap. In this way, the inclusion became an almost planar feature, which later acted as a slip surface during deformation of the model.

2.3. Apparatus

We conducted the experiments in the simple shear machine used by Cobbold and Quinquis (1980) (Fig. 2a). The model lies in an experimental chamber, 40 cm long, 10 cm wide, and 5 cm high (Fig. 2b). The top and bottom plates of the machine move at the same speed, but in opposite directions. The end walls, initially perpendicular to the shear direction (y–z plane) consist of stacks of sliding plates