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Sheath folds as a strain gauge in simple shear

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ABSTRACT

We investigate initiation and evolution of sheath folds developing in multilayer sequences around slip surfaces in simple shear. The slip surface is initially circular and oriented at 135° to the shearing direction. The flow perturbation around the rotating and deforming slip surface initiates the growth of deflections of the layers, which serves as precursors for the sheath structure. The influence of the perturbed flow on the fold growth decreases with strain as the structure is moved away from the slip surface. For $\gamma > 10$, the sheath fold evolution is dominated by a passive simple shear.

We describe the fold geometry using: 1) interlimb angle (α), 2) apical angle (β), and 3) aspect ratio of the eye-structures in the section normal to the shearing direction at the fold base (R_{yz}). We show that the fold shapes developing in different interfaces can be characterized by a unique combination of the three parameters depending on strain magnitude. We present three strain gauge diagrams, which can be used to decipher strain from sheath folds based on any combination of two out of three parameters (α, β, R_{yz}).

We approximate the late evolution of the modelled sheath folds by analysing the passive deformation of cone structures in simple shear. We show that R_{yz} is asymptotically proportional to the square root of strain magnitude.

1. Introduction

Non-cylindrical fold structures, which are characterized by a sharp hinge line bend (apical angle) of more than 90° are termed sheath folds (Ramsay and Huber, 1987). In sections normal to the fold elongation, they give rise to a characteristic eye-shaped pattern. The number of closed contours seen in each section depends on the relation between the position of the section, the size of the fold, and layer thickness (e.g., Reber et al., 2012). Alsop and Holdsworth (2006) used the quotient of the aspect ratios of the outermost and the innermost closed contour to develop sheath fold classification. The authors distinguished three types of folds: analogous-eye, cat's-eye, and bull's-eye, in which the ratio of the outermost closed contour is the same, smaller, and larger from the ratio of the innermost closed contour, respectively. Further, they related the three fold patterns to the corresponding types of bulk strain deformation: plane strain, flattening, and constrictional. Reber et al. (2013a) showed that the sheath fold classification based on the contour aspect ratios may lead to erroneous results and should be carefully used for bulk strain type interpretations. Similar concerns regarding genetic interpretations based on the sheath fold classification were expressed in the work of Marques et al. (2008).

Sheath folds are found in various rock types in a broad spectrum of geological settings across a wide range of scales (Alsop et al., 2007). However, it is generally recognized that they predominantly form during high strain deformation in a simple shear-dominated regime (Cobbold and Quinquis, 1980). Various mechanisms of sheath fold formation in simple shear have been suggested in the literature (Fig. 1A). Passive amplification of a pre-existing dome-shaped layer interface perturbation is perhaps the most widespread model used to explain sheath fold development (Quinquis et al., 1978; Minnigh, 1979; Cobbold and Quinquis, 1980; Skjernaa, 1989; Mies, 1993). Approximating the initial layer interface perturbation as an upright cone, Mies (1993) used analytic geometry and graphical simulations to estimate shear strain based on 1) the aspect ratios of the contours, 2) the interlimb angle, and 3) the apical angle (Fig. 1B). Based on analogue experiments, Marques et al. (2008) showed that sheath folds can develop in perturbed layers with dissimilar viscosities of a ratio smaller than 10.

The other group of models explains sheath fold development by various perturbation mechanisms of the simple shear flow field such as 1) above a rigid corrugated basement (Cobbold and

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Quinquis, 1980), 2) around rigid inclusions (Marques and Cobbold, 1995; Rosas et al., 2002; Marques et al., 2008), and 3) around slip surfaces (Reber et al., 2012, 2013a, 2013b). Cobbold and Quinquis (1980) studied theoretically and experimentally sheath fold evolution above the corrugated surface. The authors derived a two-dimensional analytical solution for the velocity field above a rigid layer with regularly spaced grooves. Rosas et al. (2002) demonstrated how a sheath fold can develop around a rotating rigid inclusion in a shear zone. The impact of various parameters such as the shape of the inclusion and the distance of the marker layer from the inclusion was analysed. The study allowed for indicating configurations that are less likely for the sheath folds to develop. A systematic study of sheath fold formation around a slip surface was performed by Reber et al. (2013a). A range of parameters including slip surface size and orientation, strain magnitude, layer thickness, and cross-section location were investigated in terms of their impact on the aspect ratio of the outermost and innermost contours and the sheath fold length. The three-dimensional analytical flow model allowed for analysis of the structure development in high resolution. The analysis was carried out on densely spaced yz-sections. The slip surface model was also positively tested for the case of a mechanically stratified matrix with viscosity ratio less than 50 between the layers using analogue experiments (Reber et al., 2013b).

Alsop and Holdsworth (2012) presented a natural multilayer sheath fold example with rheologically distinct layering. Based on a series of sections, the authors described a three-dimensional shape of the 11 interfaces constituting the structure. They showed that the aspect ratio of the closed contours is larger in folds with larger apical and interlimb angles. Moreover, the aspect ratio increases towards the fold nose. Thus, following Alsop and Holdsworth (2006), the fold was classified as a cats-eye fold. The interlimb angle changes between 12 and 40°, whereas the aspect ratio of the closed contour observed in the most distant sections for different interfaces varies between 4 and 5.6. According to the authors, the overall geometrical analysis suggests that the fold was developed during general shear deformation due to the amplification of an initial perturbation.

In this paper, we analyse the initiation and evolution of sheath folds that form around slip surfaces in simple shear. The aim of the work is to gain a more detailed insight into sheath fold evolution. Similarly to Reber et al. (2013a), we use the analytical Eshelby solution reduced to the case of an incompressible viscous medium and an inviscid elliptical inclusion (slip surface). However, in contrast to the previous work, we focus on the three-dimensional shape analysis of individual interfaces rather than the eye-shaped structures displaying on the yz section. The approach significantly reduces the complexity of the analysis and allows for a better control on the evolution of fold shape parameters. We use the term sheath structure *sensu lato*, including all non-cylindrical folds exhibiting eye patterns in the yz section, without the apical angle necessarily below 90°.

We show that the deformation of a right cone can be used to approximate the late shape evolution of the sheath fold in the slip surface model. We derive an analytical formula for the change of the aspect ratio of the outermost closed contour, the apical angle, and the interlimb angle with strain. Finally, we present a strain gauge diagram based on a combination of two out of three parameters: 1) the aspect ratio of the outermost contour, 2) the apical angle, and 3) the interlimb angle.

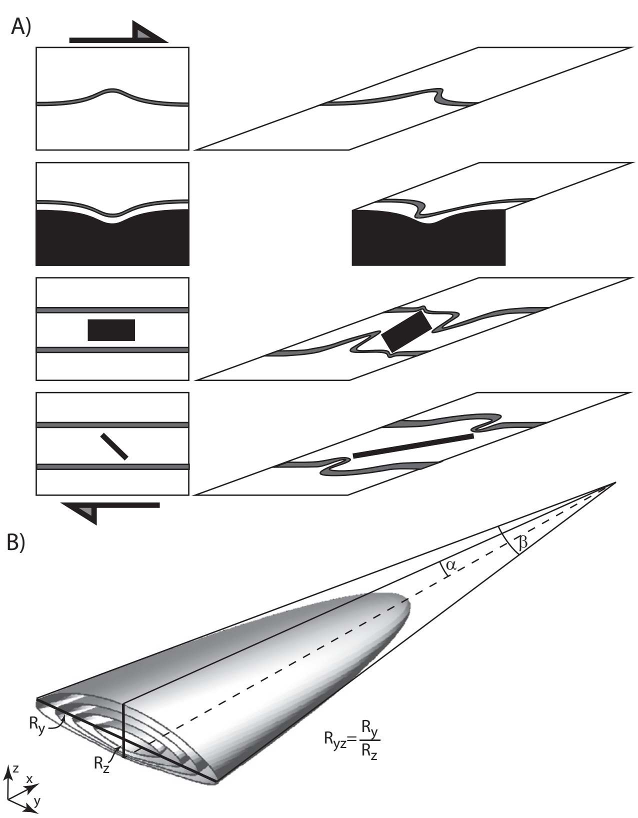

Fig. 1. A) Models of sheath fold formation in simple shear: passive amplification of a pre-existing perturbation, flow perturbation above a corrugated rigid basement, flow perturbation around a rigid inclusion, and flow perturbation around a slip surface (weak inclusion) (modified after Cobbold and Quinquis, 1980). B) 3-dimensional sketch illustrating interlimb angle (α), apical angle (β), and aspect ratio of the outermost closed contour (R_{yz}) of a sheath fold.

2. Mechanical model

We study a three-dimensional mechanical model of sheath fold development around a slip surface in simple shear up to shear strain of $\gamma = 30$. The slip surface is embedded in a homogeneous, isotropic, and linear viscous matrix. We use a Cartesian coordinate system xyz, with x parallel to the shear direction. The centre of a prescribed circular slip surface is located in the origin of the reference system. The slip surface is initially oriented at $\theta = 135°$ to the shearing direction, which corresponds to the mode I fracture orientation (Fig. 2A). The spatial coordinates are normalized by the slip surface radius. Thus, the slip surface radius is equal to 1 and its maximum vertical extent is $z_0 = 0.707$. During deformation, the slip surface can passively deform (rotate and stretch) but it cannot propagate (Means, 1989). Due to the point symmetry, we analyse only the upper part of the model. We use nine planes of passive markers that are equally distributed above the slip surface and located at z_0 = 0.8, 0.95, 1.1, 1.25, 1.4, 1.55, 1.7, 1.85, and 2.0 to visualize the fold evolution. Since no mechanical layering is present in the model, the developing folds are passive sheath folds (e.g., Cobbold and Quinquis, 1980). The fold geometry in each interface is described using the interlimb (α) and apical (β) angles. The interlimb angle is measured as the minimum acute angle between the fold limbs in the area, where the fold forms a sheath structure, whereas the apical angle is measured as the minimum angle along the hinge line, where hinge line is a curve that joins points of the maximum curvature (Fig. 1B). Additionally, we examine the development of flanking structures on the central xz-section and eye-shaped patterns on multiple yz-sections.

We track the evolution of interfaces by numerically integrating the velocity field around the slip surface with strain. The velocity