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Sheath fold development with viscosity contrast: Analogue experiments in bulk simple shear

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ABSTRACT

It has been shown experimentally that sheath folds can develop passively by kinematic amplification of precursor non-cylindrical deflections. However, sheath folds are most commonly multilayers where rheological contrast can be expected (non-passive sheath folding). Therefore, we studied a natural occurrence of sheath folds where layers show rheological contrast and used analogue modelling to investigate sheath fold development with viscosity contrast (μ'). The initial deflection in the experiments was always hemispherical and planar layering parallel to the shear plane. Under the chosen experimental conditions, the results show that: (1) the viscosity contrast between layers should be lower than one order of magnitude ($\mu' < 10$) to generate a sheath fold in both higher and lower viscosity layers; otherwise the higher viscosity layer behaves as effectively rigid. (2) The lower viscosity layer develops into a tubular fold dragged by the higher viscosity layer that undergoes mixed strain (low) and shear plane parallel translation (high). (3) The ratio between ellipticities of external and internal ellipses ($R' = R_e/R_i$) significantly departs from 1 as the viscosity contrast increases (e.g. $R' \approx 0.6$ for $\mu' \approx 7.5$ in the case where the higher viscosity layer caps the lower viscosity layer). This is in great contrast with passively developed sheath folds, for which $R' = 1$ when the precursor deflection is hemispherical.
From the present experimental study and previous work investigating other variables, we conclude that R' should be cautiously used and that extraction of kinematical information from sheath fold geometry alone can be erroneous.

1. Introduction

A long-term pursuit of Geoscientists has been the unravelling of the physical and chemical conditions controlling rock deformation from detailed observation of the complex geometry of deformed rocks. Sheath folds are a very good example of such complex deformation hence the attempts that have been made to deduce kinematics from their geometric characteristics. They have been recognized long ago, but the way they form and hence their meaning regarding the deformation of the rocks where they occur are still a matter of debate. Therefore, their use to extract kinematic information should be very cautious. Sheath folds occur in nature at all scales and are common in ductile shear zones and syn-sedimentary slumps. A sheath fold can be unambiguously defined as a fold whose hinge is curved more than 90° within the axial surface. It is, therefore, a purely geometric definition, without any genetic connotation. For detailed definitions of sheath and tubular folds see Cobbold and Quinquis (1980) and Skjernaa (1989). Cobbold and Quinquis (1980), Marques and Cobbold (1995), Mies (1993) and Rosas et al. (2001, 2002) have shown that sheath folds form very easily, at low strains ($\gamma \approx 5$), from any non-cylindrical deflection during simple shear deformation of viscous passive layers. Note that $\gamma = 10$ means that the displacement on a 1 m wide shear zone is only 10 m, which is very little when compared with high-strain ductile shear zones. Therefore, experimental work has shown that there is no need for previous folding or very high-strains to form sheath folds. However, Carreras et al. (1977), Ramsay (1980), Skjernaa (1989) and Carreras et al. (2005) have suggested that sheath folds can also develop from pre-existing folds.

If sheath folds are so easy to form experimentally, then why are they not so ubiquitous in nature? There are many possible answers to this question, but here we focus on one: because it is not that easy to meet the condition of passive folding in nature, for which the folded layers should be rheologically similar. Given the present knowledge of mineral and rock behaviour, it seems difficult to acknowledge that layers in a rock mass have identical rheology under identical physical/chemical conditions. Anyway, although not ubiquitous, sheath folds are quite common. Therefore, maybe

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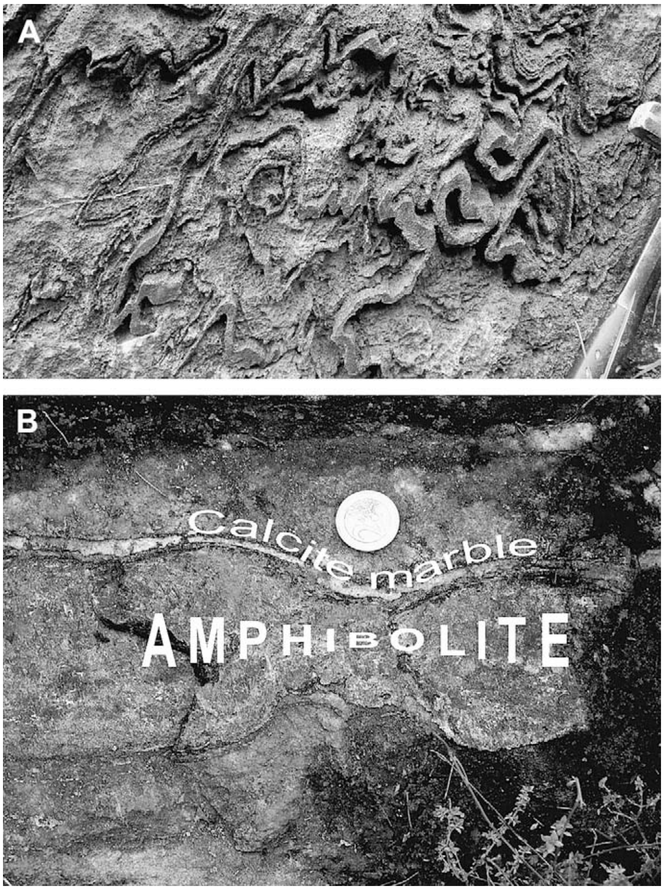

Fig. 1. An Image showing the tubular character of the studied natural sheath folds, sometimes almost circular cylinders (as opposed to most common elliptical cylinders both in nature and experiments). Darker layers in relief are amphibolites. The groundmass is mostly calcite marble being dissolved by fresh water. B – necking of an amphibolite layer indicating its stronger behaviour relative to the calcite marble.

there is no need for strict rheological similarity for sheath folds to form. Perhaps they can develop non-passively, under a limited rheological contrast. Ghosh and Sengupta (1984) and Carreras et al. (2005) have studied natural shear zones and suggested non-passive folding with highly curved hinges as a possible mechanism for the development of sheath folds. However, they did not investigate the

Table 1
Aspect ratios and R' of the 13 eye folds from marble slab (Fig. 2) from the Bragança Massif, NE Portugal

Ellipses Fig. 2	R_{yz}	$R_{y'z'}$	R'
1	11.69	5.88	1.99
2	6.50	3.93	1.65
3	10.83	16.61	0.65
4	3.05	2.29	1.33
5	2.71	5.70	0.48
6	4.09	6.06	0.68
7	3.35	2.35	1.42
8	2.56	2.43	1.05
9	3.84	3.63	1.06
10	2.35	3.63	0.65
11	11.46	22.74	0.50
12	10.73	10.24	1.05
13	2.86	2.73	1.05
Fig. 3			
1		2.1	4.7
2		2.4	4.1
3		5.0	2.0
4	9.9		

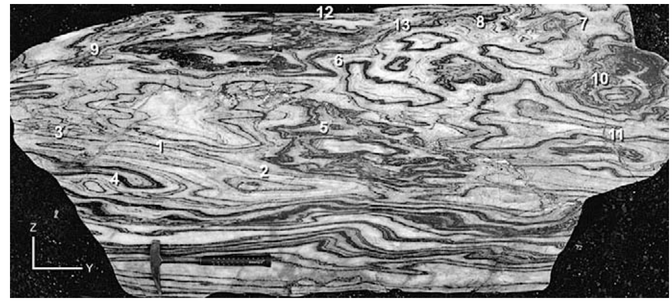

Fig. 2. Slab of interlayered marble (light) and amphibolite (dark) showing eye-like folds that correspond to sections of sheath/tubular folds whose axes (x) are normal to the observation surface. Numbers mark the measured ellipses. Hammer for scale.

rheological contrast or set a limit to it. This is the aim of the present study; to find this limit and to investigate the effects of variable of viscosity contrast on sheath fold development and geometry. In order to accomplish this objective, we isolated the variable viscosity contrast by making all other possible variables constant, like layer separation, layer thickness, layer inclination, precursor deflection shape and orientation, flow type and strain rate. The effects of most of these variables on sheath fold development have been previously studied (e.g. Cobbold and Quinquis, 1980; Skjernaa, 1989; Mies, 1993; Marques and Cobbold, 1995; Jiang and Williams, 1999; Ez, 2000; Rosas et al., 2001, 2002).

First we studied a natural occurrence in the Bragança Massif, NE Portugal, and then analogue modelling was used to try and understand how the observed sheath/tubular folds formed and evolved. Finally, the experimental results are discussed and used to conclude that sheath fold development and geometry depend on viscosity contrast. Therefore, their use as strain indicators is not unambiguous.

2. Natural occurrences

The studied sheath folds occur in a quarry within the high-grade polymetamorphic terrane of the Bragança Massif, NE Portugal. For an overview of the tectonometamorphic evolution of this

Fig. 3. Outcrop photograph of isolated sheath fold. Inset is a zoom of the upper part showing that the sheath folds are tubular, because hinges are parallel. Note the gradual decrease in R from the outermost to the innermost ellipse. This means that R' can vary from 4.7 to 1.1, depending on what aspect ratios are taken to determine R'.

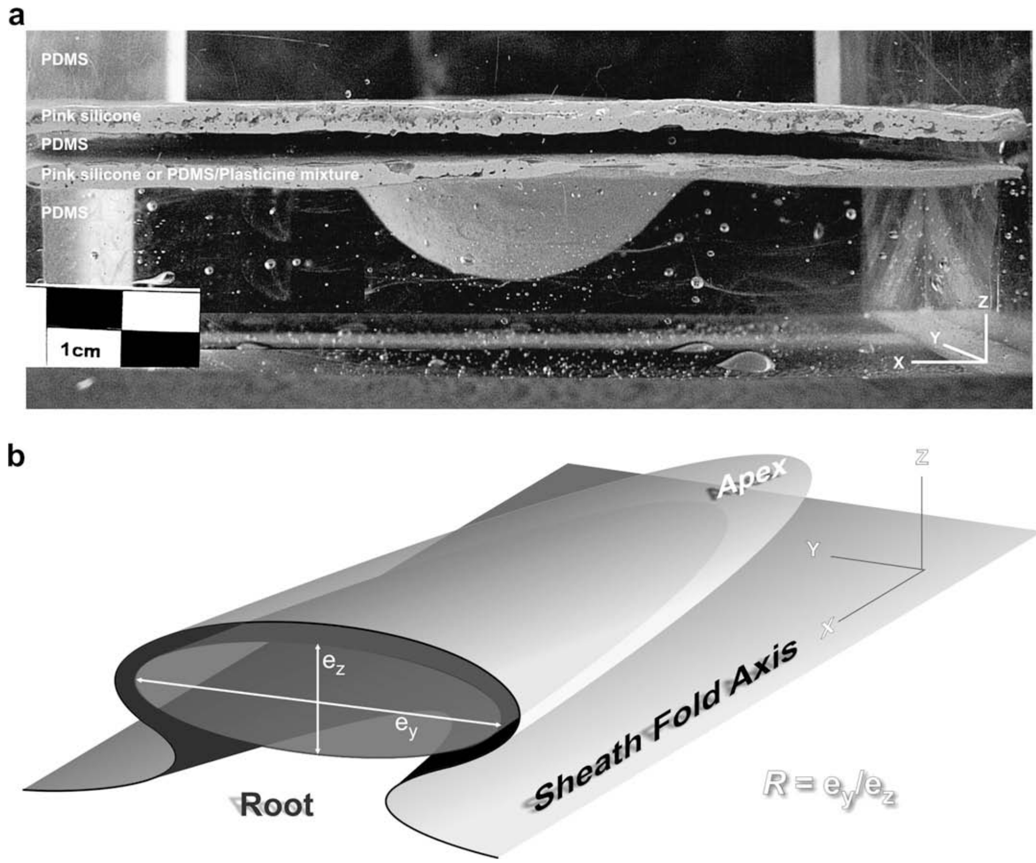

Fig. 4. An initial setup of the experiments. B – sketch of sheath fold and reference frame.

allochthonous unit see Marques et al. (1996). For the purposes of the present study, the relevant information is: (1) after peak PT conditions (eclogite and HP/HT ganulite facies interpreted as recording a subduction stage), the rocks were exhumed and brought on top of the Iberian Terrane through major ductile shear zones under retrogressive amphibolite facies conditions. Mesoscopic features like rolling circular clasts with straight tails defining very high stair stepping (e.g. Bose and Marques, 2004, their Fig. 6a) can only be explained by simple shear flow according to the available experimental and numerical models. This justifies our use of simple shear as the deformation regime. (2) Sheath folding of interlayered marbles and amphibolites shows that, in general, they did not have a great rheological contrast. However, some contrast existed because amphibolite layers sometimes exhibit pinch-and-swell structures (Fig. 1b), indicating that they were stronger than the marbles. This justifies our investigation of the effects of rheological contrast on the formation and evolution of sheath folds.

The studied sheath folds are tubular (Fig. 1) according to Skjernaa's (1989) definition. The hinges are sub-parallel, and parallel to a prominent mineral stretching lineation. The hinges are very long and straight when compared to the very small and highly curved apexes, which are seldom visible. The geometry of the studied folds in terms of the ellipticity ratios is presented in Table 1 and Figs. 2 and 3.

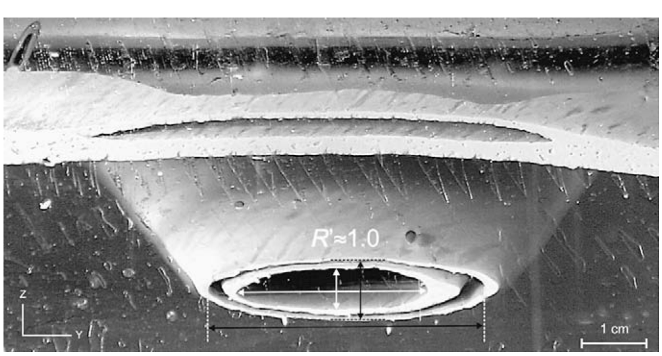

Fig. 5. Image of section perpendicular to sheath fold axis showing the typical nested ellipses. As expected for passive folding in simple shear, $R' = 1.0$. Also note that the sheath fold is not tubular as with rheological contrast (cf. Fig. 4). White or black symbols mark principal axes for determination of ellipticity of internal (R_i) or external (R_e) ellipses, respectively.

3. Experimental procedures

The used apparatus is a modified version of the simple shear apparatus described by Marques and Coelho (2001). The chosen materials are similar to the ones used by all previous authors. Therefore, their suitability as rock analogues will not be discussed here (e.g. Cobbold and Quinquis, 1980; Marques and Cobbold, 1995). The analogue materials used were a polydimethyl-siloxane (PDMS – DC SGM 36) as the transparent linear viscous matrix, a pink silicone putty (Rhodorsil 70009, Rhone-Poulenc) as linear viscous passive marker layer (e.g. Weijermars, 1986; ten Grotenhuis et al., 2002 for silicone putty properties), and commercial plasticine mixed with PDMS in variable proportions to obtain a higher viscosity material. Although "Plasticines" are typically power-law viscous (e.g. Weijermars, 1986), the mixtures we used with PDMS still preserved a Newtonian behaviour as measured in a simple shear apparatus. We ran experiments with viscosity contrast (μ') between 1 and 10, with viscosity of PDMS (matrix) as reference and constant. Therefore, we added Plasticine to PDMS to increase

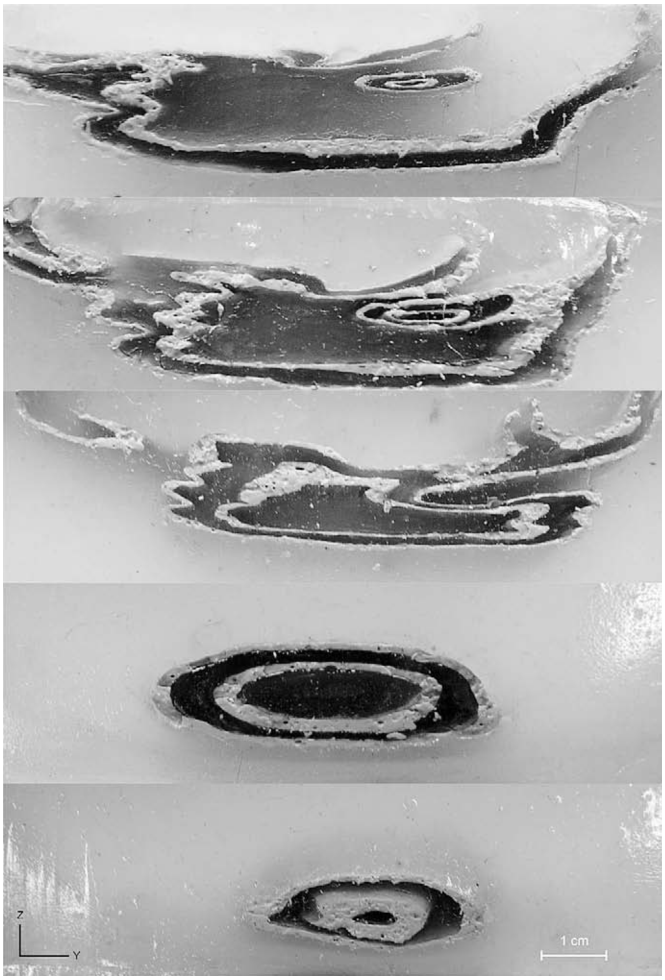

Fig. 6. Photographs of sequential sections along an experimental passive sheath fold, from the root (top) to the apex (bottom). Note similarity with natural folds in Figs. 1 and 2.

viscosity. μ' is the ratio between the viscosities of two layers (e.g. μ_1 and μ_2) defining nested ellipses ($\mu' = \mu_1/\mu_2$, with $\mu_1 > \mu_2$).

The models were 500 mm long, 120 mm wide, and 80–100 mm high. The silicone adhered to the walls that drove planar Couette flow, and slipped against side and end walls. The applied strain rate was $5E^{-4}\,s^{-1}$, therefore, within the linear viscous domain of PDMS (e.g. ten Grotenhuis et al., 2002). Before deformation, the model comprised a convex downwards hemispherical deflection (Fig. 4a). The deflection was deliberately exaggerated so that measurements and visualization of main features were obvious. Clearly, sheath folds develop from any deflection on the marker layer, no matter how small the deflection, as shown in Fig. 7a. The experiments were arrested at $\gamma \approx 6$.

The parameter R' of Alsop and Holdsworth (2006) is used here to characterize geometrical relationships observed in cross-sections of sheath folds. R' is the ratio between ellipticities of external (R_e) and internal (R_i) ellipses, respectively ($R' = R_e/R_i$). Skjernaa's (1989) definition is used to discriminate between sheath and tubular folds.

4. Experimental results

In the used experimental configuration, there are two possibilities regarding distribution of the different viscosity layers: (1) the higher viscosity layer capping the lower viscosity layer, or (2) vice-versa. This latter setup is not favourable for evaluation of axial ratios of nested ellipses, at least for the used strain, because for significant viscosity contrast there is no section with nested

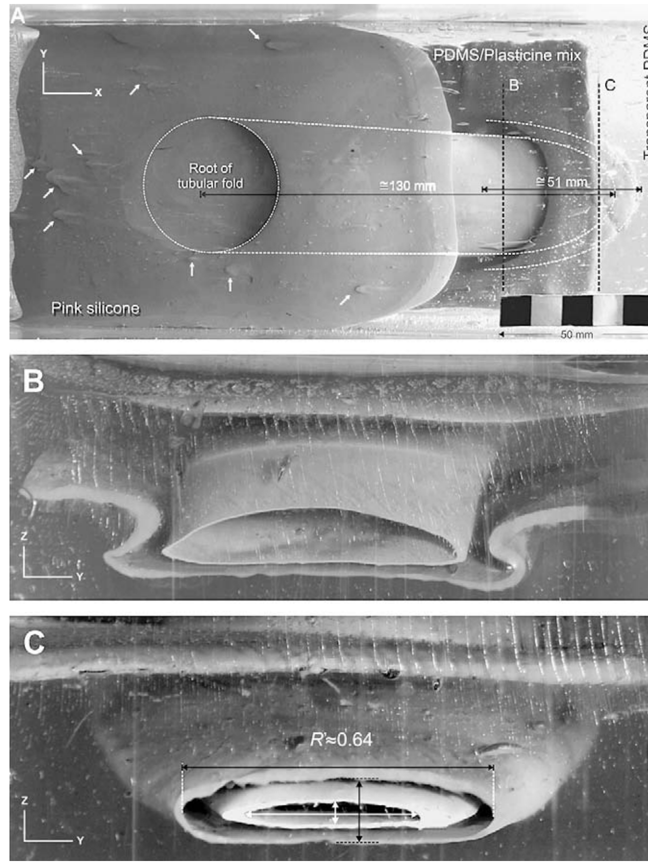

Fig. 7. An Image taken along Z to show the 3D geometry of a sheath fold s.l. formed with rheological contrast between layers. Note the conspicuous tubular shape of the internal fold capped at the apex by a higher viscosity, less developed sheath fold. Comparison of b and c shows that the tube shape becomes a sheath shape in the portion of the tubular fold inside the capping sheath.

ellipses. Therefore, we restrict the results presented here to the case where the high viscosity layer caps the low viscosity layer. Marques and Cobbold (1995) studied sheath fold development with the lower viscosity layer capping the high viscosity deflection, and showed the great effect of such configuration and initial deflection shape on sheath fold development and geometry. The results for $\mu' \approx 1$ (passive folding, Model 1) and $\mu' \approx 7.5$ (Model 2) are presented. For $\mu' \approx 10$, the more viscous layer does not strain.

4.1. Model 1 – passive folding (Figs. 5 and 6)

A reference experiment was run to show most relevant geometrical relationships of sheath folds developed passively. Fig. 5 shows a fold with the typical characteristics of a sheath fold developed from a precursor hemispherical deflection: angle between limbs less than 90° (corresponding to a fully developed sheath fold), nested ellipses in cross-section, and $R' \approx 1$. Polyharmonic folding as observed in Figs. 1a, 2 and 3 can easily be obtained experimentally by making a major deflection with minor deflections on its surface (Fig. 6).

4.2. Model 2 – folding with rheological contrast (Fig. 7)

The overall shape of the experimental fold is that of a well-developed inner tubular fold, capped by a much less developed, though well-defined, outer sheath *s.s.* As shown in Fig. 7, the length of the sheath is much smaller than the length of the tube. The sheath shape of the tubular fold is only preserved closer to the apex, in the portion of the tube contained within the capping sheath fold (cf. Fig. 7b and c). The shape of the inner fold, tubular by definition, is in great contrast with the sheath fold developed passively for a similar amount of shear strain in Model 1 (cf. Fig. 5).

Regarding the R' value measured in cross-section as in Fig. 7c, it is around 0.6, in great contrast to the $R' \approx 1$ for passive folding of an initial hemispherical deflection.

5. Discussion and conclusions

The experiments with no viscosity contrast between layers ($\mu' = 1$, Model 1) confirm the geometrical features known from theory of passive sheath folding, and show that parasitic folding (as observed in nature, e.g. Figs. 1a, 2 and 3) can be the result of different dimension of precursor non-cylindrical deflections (Fig. 6).

The experiments with viscosity contrast (Model 2) show that, for a similar amount of shear strain, the non-passive sheath is much less developed (strained) than the passive sheath. This indicates that the higher viscosity, less strained sheath fold underwent mixed "rigid" body translation and strain. When $\mu' > 10$, the higher viscosity deflection behaves as an effectively rigid body that undergoes translation and no strain. Comparison between tubular shape of non-passive fold and sheath shape of passive fold suggests that translation of the capping higher viscosity deflection sucked/dragged the inner lower viscosity deflection and stretched it into a flattened tubular fold. This is our interpretation, in the absence of 3D flow markers. As a result of differential development of higher and lower viscosity folds, R' cannot be equal to one. Because the higher viscosity sheath is less developed (therefore, less flattened), its ellipticity is smaller than the ellipticity of the lower viscosity, highly stretched and flattened sheath. Therefore, R' increasingly departs from one as the viscosity contrast increases. Model 2 can explain $R' \neq 1$ in simple shear (in great contrast to passive sheath folding), and also the flattened tubular shape of most folds in the studied occurrence. However, it still cannot explain the low ellipticity eyes inside high ellipticity eyes as observed in the studied occurrence (Fig. 1). Therefore, one still has to justify the low ellipticity eyes with the shape and orientation of the precursor deflection (Skjernaa, 1989; Mies, 1993; Marques and Cobbold, 1995).

Sheath fold development and geometry depend in great part on precursor shape, orientation and timing, on flow type, and on rheology contrast. Cobbold and Quinquis (1980), Marques and Cobbold (1995), and Rosas et al. (2001, 2002) have shown experimentally that sheath folds can easily amplify from non-cylindrical deflections in bulk simple shear. Jiang and Williams (1999) showed that sheath folds do not form under certain types of flow, and Ez (2000) argued that sheath folds, so commonly associated with simple shear in the literature, can form in pure shear, with or without associated constriction. We used bulk simple shear because the structural association in the studied rocks indicates that they deformed under (mainly) simple shear.

The influence of the shape and orientation of the initial non-cylindrical deflection was further investigated by Skjernaa (1989), Mies (1993) and Marques and Cobbold (1995), who have shown that those two variables could account for most of the observed geometric features of sheath folds. The present study re-enforces this idea, and further shows that rheological contrast can also account for some of the geometrical features observed in sheath folds. Carreras et al. (2005) distinguished sheath folds based on the relative age of the folded surface, which can be pre- or syn-shearing. Therefore, sheath folds can develop from pre-existing folds or from instabilities in the shear related foliation. The complex tectonometamorphic history of the studied rocks does not allow such distinction; therefore, we used a non-cylindrical deflection prior to deformation (similarly to Marques and Cobbold, 1995).

Ghosh and Sengupta (1984) concluded, from the study of natural shear zones, that sheath folds can initiate as active folds by the creation of a buckling instability on newly developed foliation surfaces. Further development into a sheath fold could be explained by rheological contrast and heterogeneous strain. Carreras et al. (2005), from the study of natural shear zones, also suggest that sheath folds can develop from combined buckling and shear-induced flattening, with or without rheological contrast or mechanical anisotropy. The present work shows experimentally that non-passive sheath folding is possible, in simple shear, and indicates that a viscosity contrast of 10 is the limit to generate a sheath fold in the higher viscosity layer containing a precursor non-cylindrical deflection.

Alsop and Holdsworth (2006) argued that bulk strain type can be assessed from sheath fold geometry. Alsop and Holdsworth (2006) support their study on measurements of mostly ellipticity (R'). However, previous experimental and theoretical modelling, and the present experimental work, show that the initial shape of the deflection and viscosity contrast greatly control R'. As an exercise to verify if R' can be used to deduce deformation regime, we took a ca. 1 m^2 slab of interlayered marble and amphibolite (Fig. 2) and one sheath fold (Fig. 3) from the studied quarry. Aspect ratios of 13 nested ellipses were measured in Figs. 2 and 4 in Fig. 3, and the respective R' were calculated (see Table 1 and Fig. 3). It is clear from the data that sheath folds in 1 sq m, or even in one isolated fold, span the entire range of eye fold types. R' values can be as high as 4.7 or as low as 0.48 (Table 1), through values close to 1. In Fig. 3, it is noteworthy that the aspect ratios of the ellipses gradually decrease inward. The observed patterns can be explained by heterogeneity of initial deflections and rheological contrast. Multiple orders of folding as observed in Fig. 2 can easily be obtained experimentally by making a major deflection with minor deflections on its surface (Fig. 6). In passive sheath folding there is no influence of section location or layer thickness on the determination of R'. Conversely, in non-passive sheath folding, location of the section where R' is to be determined should be carefully evaluated because the relative position of layers with contrasting viscosity makes a difference. For example, the present experiments show that if the higher viscosity layer caps the lower viscosity layer, then $R' < 1$. If the layer distribution is the opposite, then $R' > 1$.

To summarize, the present experimental results with viscosity contrast show that: (1) the viscosity contrast between layers should be lower than one order of magnitude ($\mu' < 10$) to generate a sheath fold in both higher and lower viscosity layers. Otherwise the high viscosity layer undergoes but translation. It behaves as effectively rigid. (2) The lower viscosity layer develops into a tubular fold, dragged by the higher viscosity layer that undergoes mixed strain and shear plane parallel translation. For a similar amount of shear strain, a passive sheath is much longer than the non-passive sheath. (3) R' of non-passive folds departs from 1 when the viscosity contrast is significantly different from 1, despite the hemispherical shape of the precursor deflection. This is in great contrast with sheath folds developed passively from a hemispherical precursor deflection in simple shear, for which $R' = 1$. These conclusions hold for the experimental conditions used in the present investigation.

From the present experimental study and previous work investigating other variables, we conclude that the R' parameter should be used cautiously, and that extraction of kinematical information from sheath fold geometry alone can be erroneous.

Acknowledgments

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