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Discussion of Sheath fold development with viscosity contrast: analogue experiments in bulk simple shear by Marques, F.O., Guerreiro, S.M., Fernandes, A.R.

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We thank Marques et al. (2008) for adding to the experimental database concerning the generation of sheath folds. Marques et al. (2008) present the results of two experiments, one in which there is only limited viscosity contrast between layers which therefore effectively behave in a passive way, and a second experiment in which the viscosity contrast between layers is greater. Both experiments took place under bulk simple shear deformation. However, we wish to take this opportunity to correct some misconceptions and possible errors presented by Marques et al. (2008) which directly concern our work (Alsop and Holdsworth, 2006).

Before discussing these points in detail, we feel it useful to reiterate and summarise the major points of our model (Alsop and Holdsworth, 2006). Sheath folds are best described with reference to a simple Cartesian reference frame. An *x* axis can be defined lying along the length of the tube or tongue, whilst cross sections normal to the *x* axis display elliptical eye-folds whose long and short axes lie parallel to the *y* and short *z* axes, respectively (Fig. 1a). Nested closures defining eye-folds may display consistent differences in ellipticity from the outer- (R_{yz}) to the inner-most ($R_{y'z'}$) eye-shaped rings of individual sheath folds (Fig. 1a) (Alsop and Holdsworth, 2006; Alsop et al., 2007). The outer-most ellipse (R_{yz}) may be defined as the largest complete elliptical ring which is observed. It is normally bounded on the outer margin by a surface which displays incomplete elliptical closures characterised by double-vergence geometries. The inner-most elliptical ring ($R_{y'z'}$) forms the smallest observed elliptical pattern situated within the outer-most ellipse. The variation in overall aspect ratios from outer to inner rings of eye-folds is defined as R' (where $R' = R_{yz}/R_{y'z'}$) and may display Type A or analogous-eye-fold ($R' = 1$), Type B or bulls-eye-fold ($R' > 1$) or Type C and cats-eye-fold ($R' < 1$) geometries (Fig. 1b). An analysis of these parameters in natural sheath folds has led Alsop and Holdsworth (2006) and Alsop et al. (2007) to suggest that cats-eye-fold patterns ($R' < 1$) are typically produced during simple shear or general shear (where a component of flattening has been involved), whilst bulls-eye-fold patterns ($R' > 1$) are generated during constrictional deformation. We now discuss in detail the several issues raised by Marques et al. (2008) which concern our interpretations and analysis.

1) As noted above, R' as defined by Alsop and Holdsworth (2006) is a comparison of the inner-most and outer-most ellipse values from individual sheath folds. Marques et al. (2008) have incorrectly calculated the R' parameter by comparing *individual* ellipses contained within the outer-most ellipse (R_{yz}) to generate a range of R' values for single folds (e.g. Marques et al. 2008, their Table 1, Fig. 3). In addition, they do not measure the outer-most ellipse of their experimental sheaths (e.g. Figs. 5, 7). The range of R' values noted by Marques et al. (2008) (their Table 1) is partially a consequence of incorrect calculation and should therefore be viewed with extreme caution.
2) The 2D slab shown by Marques et al. (2008) (their Fig. 2) displays beautiful closures on the polished surface. However the folds are in such close proximity to one another that they clearly interfere with adjacent folds to create local refolding and interference structure e.g. closure 6 on their Fig. 2. Clearly the results of any elliptical analysis associated with refolding and reworking should therefore be treated with caution. As we have specifically noted when examining elliptical values "polyphase folding are excluded from our dataset" (Alsop et al. 2007:p. 1587.)
3) As specifically highlighted by Marques et al. (2008), their experiment involving simple shear deformation of layers with rheological contrast generates sheath folds with cats-eye-fold patterns ($R' < 1$). Correct calculation of elliptical values (see point 1 above) indicates $R' = 0.69$. This is similar to mean values of $R' = 0.691$ calculated from 160 sheath folds generated during

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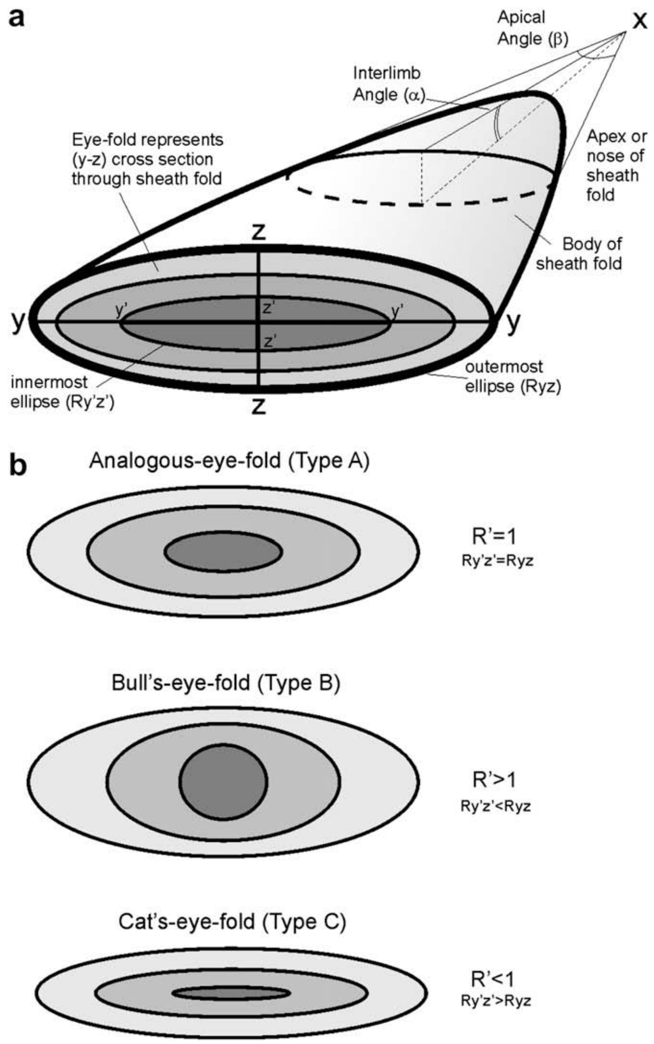

Fig. 1. a) Schematic diagram illustrating the *x*, *y* and *z* axes of a sheath fold together with the inter-limb angle (α) and apical angle (β) of the curvilinear fold hinge-line. Elliptical ratios of the outer-most ring (R_{yz}) and inner-most ring ($R_{y'z'}$) are also given. *Y–Z* orientated cross sections across the sheath fold result in eye-fold geometries. Elliptical ratios of the outer-most ring (R_{yz}) and inner-most ring ($R_{y'z'}$) are also given. b) Schematic diagram illustrating the variation in elliptical ratios (R') within Type A, analogous-eye-fold ($R'=1$), Type B, bulls-eye-fold ($R'>1$) and Type C, cats-eye-fold ($R'<1$).

simple shear deformation of multi-layered rocks (Alsop and Holdsworth, 2006:Table 1). The experiment of Marques et al. (2008) therefore strongly supports our interpretation that cats-eye-fold patterns ($R'<1$) are indeed generated during simple shear deformation.

4) Marques et al. (2008) state that "In passive sheath folding there is no influence of section location or layer thickness on the determination of R'. However, the serial sections they display through the passive model (Fig. 5) do in fact show a variation in R' with different slices. Some variation is to be expected (see Alsop et al. 2007). Whilst some sections are close to $R'=1$ others are less and display cats-eye-fold patterns ($R'=0.8$) (Fig. 6). Thus, while viscosity contrasts and passive/non-passive layering may influence the precise R' value, the typical cats-eye-fold patterns generated during experimental simple shear deformation once again support our original interpretation.
5) Marques et al. (2008) suggest that sheath folds that form within passive layering during simple shear deformation will display $R'=1$ patterns. Entirely passive folded layering is probably uncommon within shear zones, with many pre-cursors to sheath folds displaying buckle fold geometries consistent with buckling instabilities. (e.g. Ghosh and Sengupta, 1984; see also Alsop and Carreras, 2007). However, surficial environments such as sedimentary slumps and ignimbrite flows also generate sheath folds where layering may indeed behave more passively. Analysis of elliptical ratios in these settings by Alsop et al. (2007) reveals that both flow types display cats-eye-fold patterns (mean $R'=0.71$) and no evidence of $R'=1$ or $R'>1$ bulls-eye-fold patterns.
6) Marques et al. (2008) admit that their models "still cannot explain the low ellipticity eyes inside the high ellipticity eyes" i.e. Bulls-eye-folds marked by $R'>1$. They suggest that this has to be justified by the shape and orientation of the pre-cursor deflection. This mechanism has been specifically addressed at length by Alsop et al. (2007:p. 1597) and Alsop and Holdsworth (2006:p. 1602) who suggest that "one of the contributing factors in the development of bulls-eye and cats-eye-folds may be the orientation of the pre-cursor fold relative to the later shearing". However, we feel that variation in bulk strain, together with local variation in strain type associated with perturbations in flow (e.g. Alsop & Holdsworth 2004a,b,c, 2005, 2006, 2007) may represent a major influence.
7) Marques et al. (2008) suggest that if the higher viscosity layer caps the lower viscosity layer then $R'<1$ and cats-eye-folds are produced. They also state that if the layer distribution is the opposite (i.e. a lower viscosity layer capping a higher viscosity layer) then $R'>1$ and bulls-eye-folds will be produced. Unfortunately this assertion was not tested in the present experiments. In addition, photographs of natural sheath folds shown by Marques et al. (2008) do not support this statement! The geometry of eye-folds developed in more viscous dark amphibolite and lighter less-viscous marble (Fig. 2) do not vary with layer distribution. Many natural sheath folds consist of folded multilayers with obvious viscosity contrasts. Natural sheath folds most typically display a sequential and systematic variation in elliptical ratios from the outer- to the inner-most layers i.e. ratios either progressively increase or decrease towards the centre (e.g. Alsop et al. 2007:p. 1600). In summary, natural sheath folds clearly do not display alternating R_{yz} values to coincide with the alternating multilayers!

To conclude, the experiments of Marques et al. (2008) were generated during simple shear deformation and typically create sheath folds with $R'<1$ cats-eye-folds. These results are entirely consistent with our analysis of more than 1800 elliptical patterns from natural sheath folds. The admission by Marques et al. (2008) that the simple shear experiments "still cannot explain the low ellipticity eyes inside high ellipticity eyes" (bulls-eye-fold patterns) leads us to encourage the authors to undertake experiments involving constrictional deformation in order to further constrain the geometry of sheath folds in such settings.

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