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Short communication

Strain determination from concentric folds

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Abstract

A new technique to determine flattening strain from initially concentric folds is described in this paper. The proposed method is simple and involves direct measurements on fold profiles. It requires measurement of the distance between the center of the fold to the middle of the layer, and this is plotted as a function of line orientation. The method needs few measurements at fixed angular spacing resulting in quick estimation of strain.

Keywords: Concentric fold; Homogeneous deformation; Flattening strain; Fold profile

1. Introduction

Modification of the shape of folds with progressive increase in bulk strain is common in multi-layered systems consisting of competent and incompetent layers. A competent layer typically takes up concentric fold geometry (class 1B in the terminology of Ramsay, 1967) as a result of shorting. At high amplitudes, further shortening may result in modification of the fold shape by flattening. With progressive increase in strain in the system, the shapes of the folds are modified, resulting in thickening in the fold hinge region, thinning in the limb region, and gradual reduction of the interlimb angle. The increase in strain results in the transformation of fold shape from class 1B to 1C (Ramsay, 1967, p. 365–367). These changes in geometry may be represented by graphs of layer thickness variation and dip isogons patterns (Ramsay, 1967, p. 365–367). The shape modification of folds follows two main processes.

(1) Folding of competent layers produces constant orthogonal thickness in profile section.
(2) Kinematic amplification, in which fold shape changes passively as a result of homogeneous straining of the layered system.

Two previous methods (Ramsay, 1962, 1967; Lisle, 1992, 1997) are available for estimating the magnitude of strain in folds. These methods assume that the folded layers have suffered by flattening and have undergone homogeneous deformation. Based on the thickness of the folded layers, Ramsay (1962,1967, p. 411) proposed the t'_α method [$t' = t_\alpha / t_o$ vs. angle of limb dip (α), where t_α is the orthogonal thickness of the folded layers at different inclinations (α) and t_o is the thickness parallel to the axial surface of the fold], which determines the amount of strain from plots of folded layers where orthogonal thickness (t) and thick-

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ness parallel to the axial surface (T) of folded layers varies as a function of the limb dip (Ramsay, 1967, Figs. 7-79 and 7-80). This method has been used frequently for the determination of strain in flattened folds (Milnes, 1971; Hudleston, 1973; Gray and Durney, 1979).

Lisle (1992) proposed an inverse thickness method on the basis of orthogonal thickness (t) of the folded layers. In this method the thickness of the layer at any point around the fold is inversely proportional to the stretch (length final/length original) of the tangent to the folded layer at the angle of dip at which the thickness is measured. The strain ellipse can be directly constructed by a graph on polar coordinates where $1/t$ is plotted as a function of orientation of the layer tangent. This method is valid only in the folds, which have limb dips of less than $\simeq 65°$. The plotting of data ($1/t$) as shown in Fig. 2b exhibit lack of data points between limb dips of $\simeq 65$ to $90°$, which may lead to different strain ratios during their extrapolation.

The present paper describes an alternative technique to quantify the flattening strain in class 1C or 2 folds (Ramsay, 1967) in single competent layers. These folds are assumed to have formed as concentric folds and were subsequently overprinted by flattening. In the present method, the distance (d) from the folded layer to the center (described in the methodology) is

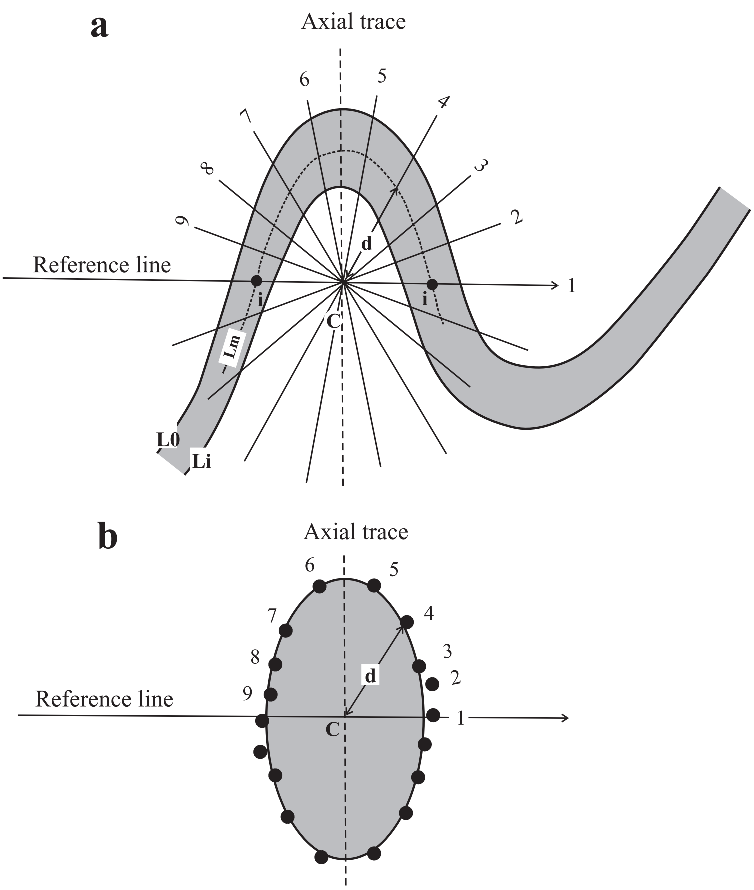

Fig. 1. (a) Sketch of a fold from Precambrian banded gneisses from Nordland, Norway (Lisle, 1985, 1992, p. 47). Lm is the trace of medial surface, Lo is the outer and Li is the inner layer of the fold. C is the center of the fold and i is the inflection points on the medial surface of the folded layer. Lines 1 through 9 (at 20° angular spacing) are the lines of different orientations w.r.t. reference line. (b) The strain ellipse described by the present method. The distance 'd' is plotted on either side of the center as a function of orientation of lines (1–9) in (a).

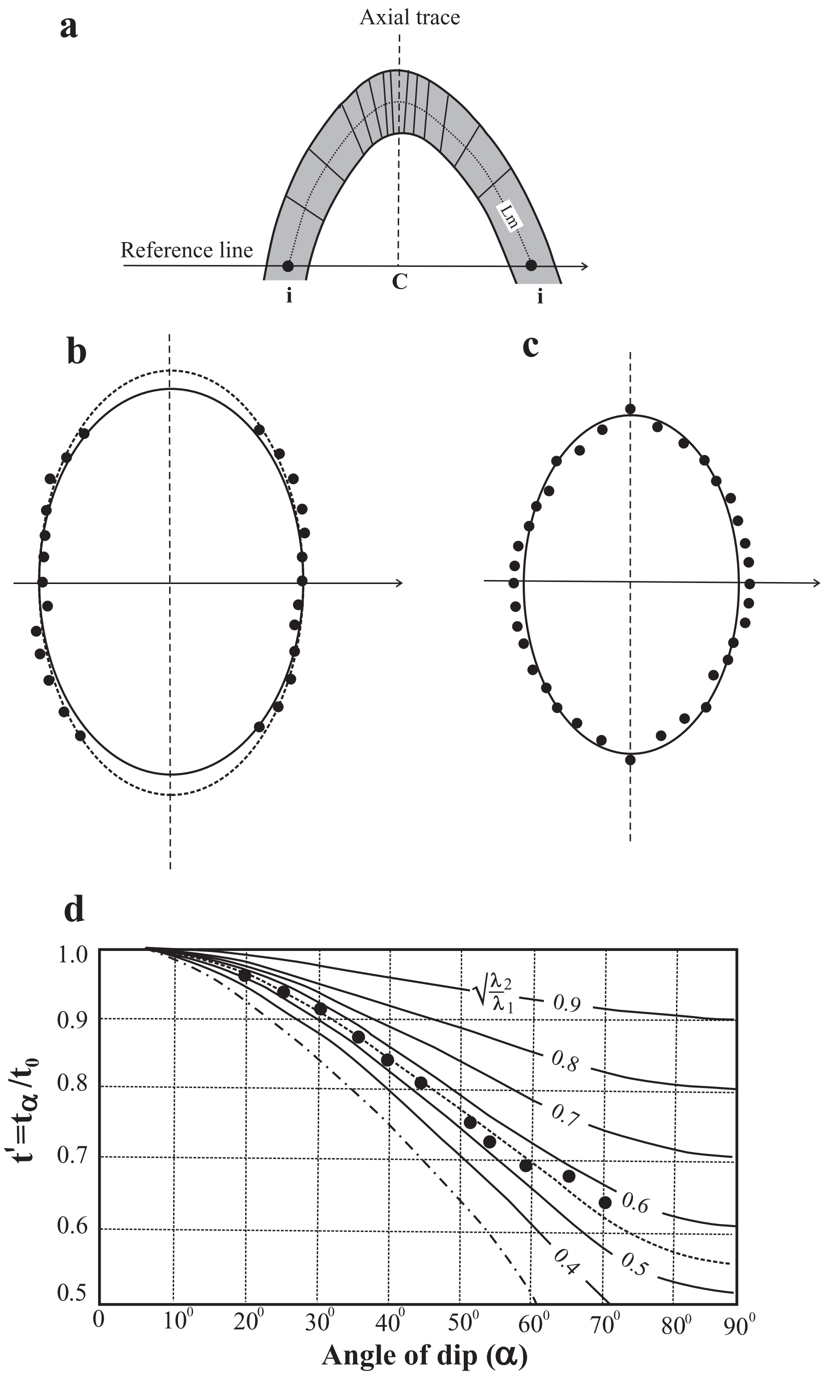

Fig. 2. (a) Traced fold profile from folded specimen collected from the Almora Crystallines of Garhwal Himalaya, India, and cut perpendicular to the hinge of the fold has been used for strain determination. Dip isogons are indicative of class 1C fold (Ramsay, 1967). Lm—trace of median surface, i—inflection points on Lm. (b) Strain ellipse/values obtained from fold (a) by inverse thickness method (Lisle, 1992). The extrapolation of data points gives different strain ratios/ellipses. However, the ellipse made up of continuous line has been considered for comparison. (c) Strain ellipse/values obtained, from (a), by proposed distance method. (d) Strain values obtained, from (a), by the method of Ramsay (1967, Fig. 7.79, p. 413).

plotted in true orientation of that particular line, on either side of the center. The data points are uniform ally distributed for both the fold limbs (Figs. 1b and 2c) and the extrapolation of these points give very precise strain ellipse directly.

The present method is based on the fact that, for folds of approximately concentric shape prior to flattening, the average length in the deformed state in any direction has an aspect ratio comparable to the strain ellipse. The strain ratio is thus simply the ratio of longer axis/shorter axis. It is proposed to measure the distance (*d*) between the median line (Lm) and the center 'C' along lines of different orientations (Fig. 1a). These measured distances are used to construct the strain ellipse (Fig. 1b). Like other methods this method also assumes that the folded layers have suffered flattening strain and have undergone homogeneous deformation.

2. Method

The method is as follows:

1. Make sure that the fold is observed in true profile section (perpendicular to the fold axis).
2. Trace the single layer fold profile either from a field photograph or from the specimen directly, and draw the median line (Lm) passing through the middle of the folded layer.
3. Define the inflection points (*i*) on the median line (Lm) on both the fold limbs and join them by a line-hereafter called the reference line (Figs. 1a and 2a).
4. Draw a line connecting the hinge points of the upper and lower contacts of the layers. This line defines the axial trace of the fold (Fig. 1a).
5. Extend the axial trace up to the reference line. The intersection point is referred to as the center 'C'.
6. Draw lines 1,2,3,4,5... through center 'C' at regular angular spacing (w.r.t. reference line). A minimum of nine lines at intervals of 20° should be drawn (Fig. 1a). In order to obtain more data points and to increase the precision of the method, this angular spacing can be reduced at any convenient angular spacing, e.g. 10° (Fig. 2c) or less.
7. The distance (*d*) from the center 'C' to the middle of the folded layer (Lm) is measured along each line (1–9).

The strain ellipse can be constructed on a polar graph where distance (*d*) is plotted (on either side of the center) as a function of line orientation (Fig. 1b and 2c). The ellipse can be either visually drawn through the points on the graph or calculated using a least squares best fit (Erslev and Ge, 1990; Kanagawa, 1990).

3. Application of the method to natural folds

The present method was applied to two different folds:

Fig. 1a sketch of the fold from Precambrian banded gneisses from Nordland, Norway, previously analyzed using a different method (Fig. 2b; Lisle, 1985, 1992, p. 47), is used to demonstrate the present method of strain determination. A comparison of results is listed in Table 1.

Fig. 2 shows the application of the method to a fold (Fig. 2a) traced from photograph from the Precambrian terrains of the Almora Crystallines of Garhwal Himalaya, India, exhibiting class 1C geometry (Ramsay, 1967) (Fig. 2a). To determine the strain from this fold, different methods have been applied and the results are compared with the present method. Table 2 indicates that there is a small variation in the strain

Table 1
Comparison of two methods of strain determination on the same fold

S. no.	Method	Parameter	Strain ratio
1	Lisle, 1992	Inverse thickness	1.95
2	This paper	Distance	1.91

Table 2
Comparison of three different methods of strain determination on Fig. 2a

S. no.	Method	Parameter	Figure no.	Strain ratio
1	Ramsay, 1967	Thickness	Fig. 2d	1.55
2	Lisle, 1992	Inverse thickness	Fig. 2b	1.44
3	Present method	Distance	Fig. 2c	1.56

ratios obtained by the different methods, which use different parameters.

4. Discussion

The ‘distance method’ presented in this paper is a modified version of existing methods. Instead of using thickness of the folded layer, the distance from the center ‘C’ to the median line (Lm) in different orientations is chosen as the variable to record fold shape. The strain ratio obtained by the method suggested by Lisle (1992) and Ramsay (1967), and that obtained by the present method for two folds (Figs. 1a and 2a) are in close agreement (Tables 1 and 2). The small variation in the result is probably due to the fact that each technique has its own set of assumptions.

Like all other methods, the present method is also based upon the assumption that the folded layers have suffered flattening and have undergone homogeneous deformation. It differs from others in that it assumes a roughly concentric fold shape rather than a parallel-fold geometry. Advantages of this method over others, is that it is precise, very quick and direct.

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