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SHORT NOTE

Strain estimation from flattened buckle folds

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Abstract—A simple and direct method of calculating the post-buckle flattening strain of folds is proposed. Assuming that the folds have Class 1B (parallel) shape before flattening, the stretch of the layer at any position in the flattened fold is inversely proportional to the orthogonal thickness of the layer. A polar graph showing inverse thickness as a function of layer orientation therefore yields directly the shape and orientation of the flattening strain ellipse. The method can be applied to cases where flattening strains have been imposed obliquely to the fold's axial surface.

INTRODUCTION

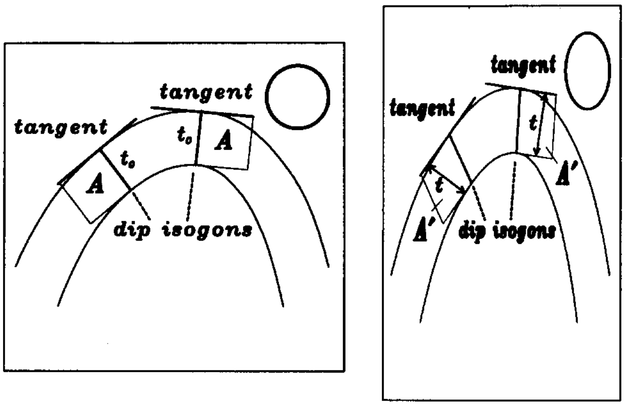
NUMEROUS field observations indicate that folded competent layers undergo progressive modification of geometry as the bulk strain of the layered system increases. Besides bringing about a reduction in the inter-limb angle, increasing strain produces differential layer thickness changes so that fold limbs become attenuated relative to the hinge regions. Using the terminology of Ramsay (1967, pp. 365–367) the progressive strain results in the transformation of Class 1B (parallel) folds into Class 1C folds. These changes in geometry are brought out by graphs representing layer thickness variations and dip isogon patterns (Ramsay 1967, pp. 411–415).

It is customary to attribute these shape modifications to the operation of two processes. Buckling, sometimes referred to as the dynamic component of folding, results from the mechanical instability created by shortening an inhomogeneous system of alternating competent and incompetent layers. Pure buckling would tend to produce folded competent layers of approximately constant orthogonal thickness. Body rotation of the limbs or 'buckling rotation' (Odling 1987), produces increased tightness of the folds. The other contributor to fold development is the kinematic component which produces progressive geometrical changes resulting from the overall straining ('flattening') of the layered system. As with buckling, the effect of this kinematic component is to produce a tightening of the fold but now by a passive, strain-induced rotation of the limbs. The kinematic component brings about differential thinning of parts of the folded layer depending on their orientation in a fashion governed by the geometry of the strain ellipse. These two processes probably operate simultaneously throughout the development of a fold but, especially in the case of folds produced by large strains, an early stage dominated by buckling is succeeded by a 'flattening' stage during which the kinematic component is dominant (Sherwin & Chapple 1968, Hudleston 1973, Hudleston & Stephansson 1973).

For the purpose of estimating the magnitude of flattening strains it is convenient to consider the model in which these two stages are discrete, so that early-formed parallel buckles are modified by later flattening. Using this simple model, Ramsay (1962, 1967, p. 413) proposed a method, the t/α method, by which the amount of flattening can be determined from the way the thickness (t) of a folded layer varies as a function of the limb dip (α). This method including other variants of the technique (Milnes 1971, Hudleston 1973, Gray & Durney 1979) ranks as one of the more frequently applied methods of estimating strain. This note describes a simple alternative to the t/α method.

THE INVERSE THICKNESS METHOD

Consider a true profile of a folded layer which, prior to the imposition of flattening, has a parallel (Class 1B) shape, i.e. has constant orthogonal thickness, t_0 (Fig. 1a). Dip isogons are orthogonal to the layer boundaries at all points around the fold. If squares are constructed with sides parallel to the isogons and tangents to the layer boundaries, these will have the same area at all positions around the fold. After a homogeneous flattening has been imposed on the fold (Fig. 1b), these original squares are transformed to parallelograms with sides still parallel to tangents and dip isogons. Since it is being assumed that any area change will be homogeneous, the areas of all parallelograms around the fold are equal. In turn it follows that the thickness of the layer (t, the perpendicular distance between the tangents for the inner and outer layer boundaries), at any point around



a b

Fig. 1. The geometrical basis of the inverse thickness method. (a) The pre-flattening fold. Squares based on the orthogonal thickness t_0 have the same area (A) at all positions around the fold. (b) After flattening. The original squares are now deformed to parallelograms of the same area (A'). Therefore the orthogonal thickness t at any point is inversely proportional to the stretch of the line parallel to the layer tangent.

the fold is inversely proportional to the stretch (new length/old length) of the side of the parallelogram parallel to the tangent. The strain ellipse is therefore directly constructed by a graph in polar co-ordinates where $1/t$ is plotted as a function of orientation of the layer tangent. The ellipse can either be visually fitted through the points on the inverse thickness graph or a least-squares best-fit ellipse calculated (Erslev & Ge 1990, Kanagawa 1990). Figure 2 shows an application of the method to folds in gneissic bands from Nordland, Norway (from Lisle 1985, p. 47).

DISCUSSION

This new technique for estimating the post-buckle flattening of folds can be seen as complementary to, not replacements for, the existing t/α methods. For example the original t/α method (though not the modification by Gray & Durney 1979) is based on the assumption that the flattening strain ellipse in the fold's profile plane is aligned parallel to the axial trace whereas the method suggested here is free from this limitation.

There is much to be gained by the simultaneous application of a number of techniques for analysing the same strain data. Each technique has its own set of assumptions and therefore discrepancies between the results of the different techniques are often attributable to the violation of one or more of these assumptions. This approach can provide not only sensible estimates of the strain but greater understanding of the development of a particular set of structures.

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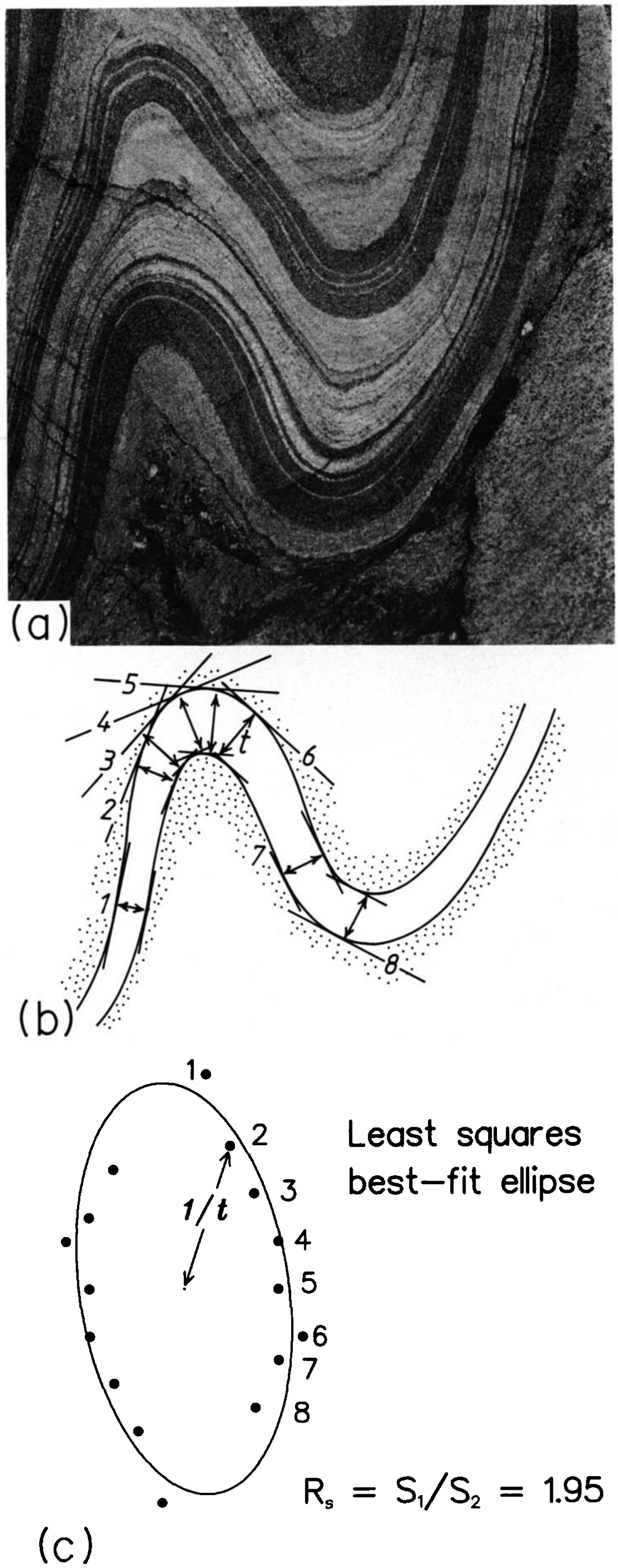

Fig. 2. The application of the inverse thickness method. (a) The measured folds are from Precambrian banded gneisses, Gjeroy Island, Nordland, Norway. (b) Orthogonal thickness measurements perpendicular to tangents 1–8 in folds in the lowest mafic layer in (b). (c) The flattening strain ellipse described by inverse thicknesses ($1/t$) plotted as a function of orientation of tangents 1–8 in (b).