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A Model for Analyzing the Strain History of Folded Competent Layers in Deeper Parts of Orogenic Belts

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ABSTRACT

Modern theoretical, experimental, and observational work seems to indicate that the folding of a competent layer under pseudo-viscous conditions can be subdivided into three well-defined phases: A = initial homogeneous deformation ("layer-parallel shortening"); B = permanent buckling; C = subsequent homogeneous deformation ("flattening"). The transition from A to B is supposed to be very sudden ("explosive" folding), but between B and C there is probably considerable overlap. This model is used to consider the strain history of particles situated on the limbs of such folds. The strain suffered by the particles during phase C can be determined from the morphology of the folded layer using a thickness ratio diagram (modified from RAMSAY 1967). A recently published grid (ELLIOTT 1970) enables this strain to be removed from the final strain ellipse. Using a polar graph, the resulting strain ellipse can be tested to determine whether it could have been produced by simple shear during buckling alone, or whether a pre-buckling component of strain (phase A) must be assumed. It is shown that, although the method is two-dimensional, the test is of more general validity.

Introduction

An interesting feature of recent theoretical treatments of folding in layered materials, and one which is potentially of great importance to geology, is the demonstration that under certain conditions significant deformation takes place before the development of folds of finite amplitude (see, for instance, BIOT 1961, RAMBERG 1964, CHAPPLE 1970). If this result is of general application to folded rocks, estimates of sedimentary thicknesses and sizes of sedimentary basins are consistently too high and too low respectively, if these have been made on the basis of fold morphology alone, without detailed study of, or in the absence of, strain markers. It seems, therefore, that one of the immediate tasks of field geologists working in folded regions such as the Alps is to test the results of the theoretical studies against observed relationships. One possible approach to this problem – the direct application of the mathematical treatment to folded rocks – has already been attempted by a number of workers (SHERWIN and CHAPPLE 1968, RAMBERG and GHOSH 1968, JOHNSON 1969, BAYLY 1970, KIRKLAND and ANDERSON 1970, SHERWIN 1970). Another possible line has been intimated by RAMBERG and GHOSH (op. cit.) – the study of the strain distribution and strain history of folded layers – and will be expanded and developed in the following. The aim is to develop a test of the theoretical predictions based solely on measurements of fold morphology and strain, features which do not enter into the mathematico-physical treatment on which the predictions are founded.

The model

All modern theoretical, experimental, and observational work on folding in layered, viscous or pseudo-viscous materials (rocks in the deeper parts of orogenic belts) seem to indicate the following model for the deformation history of a competent[1]) layer in a single folding episode (Fig. 1):

A = initial homogeneous deformation ("layer-parallel shortening"),

B = permanent buckling,

C = subsequent or superimposed homogeneous deformation ("flattening").

The initial phase, in which the layer deforms homogeneously (without the development of folds of finite amplitude), is the one which has hitherto been neglected, although it was recognized in some early experiments (KUENEN and DE SITTER 1938, Fig. 6). Towards the end of this phase, folds of small but finite amplitude develop, the system becomes unstable (the finite amplitude instability of CHAPPLE 1970), and the competent layer starts to deform by buckling. The transition from homogeneous deformation to buckling is predicted to be extremely sharp ("explosive" folding, RAMSAY 1967). Whether the strain during the initial phase is appreciable or not depends on the viscosity contrast between the competent layer and its surroundings. The very low viscosity contrasts obtained by applying BIOT'S formulae to natural folds (SHERWIN and CHAPPLE 1968, RAMBERG and GHOSH 1968) would seem to indicate that this strain must have been appreciable in many natural situations. Theory and experiment indicate that the viscosity contrast must reach values of 2,000 or more before the initial homogeneous strain becomes negligible (e.g. BIOT, ODÉ and ROEVER 1961).

Two well-known features of naturally folded rocks indicate in a qualitative way that initial homogeneous deformation must have been a widespread phenomenum; cleavage refraction and the general lack of the predicted complexity of structure in folded regions. The reason why cleavage refraction can be considered as an indication of initial homogeneous deformation has been given by RAMSAY (1967, Fig. 7, *68*) and RAMBERG and GHOSH (1968). With regard to the complexity of structure in folded regions, FLINN (1962) has pointed out that it is generally less than theoretically expected. He suggested that in many cases the layering must have attained a special position with respect to the strain ellipsoid axes before folding started. It seems that the attainment of such a special orientation could be due to passive rotation of the layering during an initial phase of homogeneous deformation (see FLINN, op. cit., p. 396–402).

After the finite amplitude instability point has been reached, deformation takes place in the competent layer by buckling. Pure buckling, with the layer maintaining a constant thickness on the limbs and hinges of the folds, is dominant at first, but becomes progressively more difficult (DE SITTER 1958, WUNDERLICH 1959, RAMSAY

[1]) The term "competence" has up to now evaded a precise definition in which genetic and geometric aspects are combined. Recent work indicates that a competent layer is one which had a higher effective viscosity than its surroundings during folding, whereby effective viscosity difference depends not only compositional difference but also on the strain rate. From this it seems that the usual geometric criterium for a folded competent layer – that of ideal (1 B) morphology – is too narrow. I suggest that the geometric criteria be extended to include folds of both 1 B and 1 C morphologies (see RAMSAY 1967), with the additional requirement that every fold (both antiform and synform) in the layer show the same morphology. Although individual fold hinges in incompetent layers may show 1 C morphology, the morphology often changes from fold to fold along the layer.

1967, CHAPPLE 1970). Layer-parallel strain becomes progressively more important, with lengthening (and thinning) on the limbs and shortening (and thickening) at the hinges. As the fold tightens, the importance of the active buckling component decreases and the deformation becomes more a homogeneous modification of the previous folded shape (RAMSAY 1962, 1967, MUKHOPADHYAY 1965). For the purposes of geometrical treatment, RAMSAY suggested that the process can be considered as the superimposition of a homogeneous strain upon a pure buckle fold of parallel type (phases B and C, Fig. 1).

Strain history of material on the fold limbs

The strain history of a small planar part of a fold limb, in a two-dimensional section normal to the fold axis, based on the proposed model is shown in Figure 1. During the initial phase (A), an initial circle is transformed to an ellipse ε_s'', where ε is defined as:

$$^1/_2 \ln \text{(long axis/short axis)}.$$

The subscript s indicates that it is a strain ellipse (that the initial shape was exactly circular). The angle between the long axis of the strain ellipse and the bedding trace is Θ''; this angle must be greater than 45° for folds to subsequently develop, and considerably greater for the folds to be preserved, and not unfolded. During the following phase of pure buckling (B), this ellipse is modified by a simple shear (angle of shear ψ) to another ellipse with shape ε_s' and orientation with respect to bedding Θ'. This is then further modified by the subsequent homogeneous strain (C) giving a final ellipse with shape and orientation, ε_s and Θ. If suitable strain markers (ooids, pebbles, etc.) are present in the folded layer, the shape and orientation of the strain ellipse deduced from them is the result of the superimposition of three separate finite homogeneous strains. In order to determine whether the strain involved in phase A was appreciable, a procedure must be set up for estimating the strains involved in phases B and C independent of the strain markers and for removing these strains from the final strain ellipse. The possibility of setting up such a procedure will now be discussed.

Estimation of homogeneous strain superimposed on parallel folded layers

RAMSAY (1967, p. 411–415) has described in detail a method for estimating the amount of homogeneous strain superimposed on parallel folded layers, based on the measurement of thickness variations across the folds. This will now be outlined in a somewhat modified form. The superimposed strain ellipse has a shape given by $\Delta\varepsilon_s$ and is orientated with its long axis parallel to the axial plane trace of the parallel fold. During this deformation, the orthogonal thickness of the fold limb changes from t' to t, and the thickness measured parallel to the axial plane trace from T' to T. At the same time the thickness at the fold hinge changes from A' ($= t'$) to A. By simple geometry it can be shown that (RAMSAY, loc. cit.):

$$t/A = (\cos^2\alpha + e^{-4\Delta\varepsilon s}\sin^2\alpha), \qquad (1)$$

$$T/A = t/A \sec\alpha, \qquad (2)$$

$$T/A = \sec\alpha', \qquad (3)$$

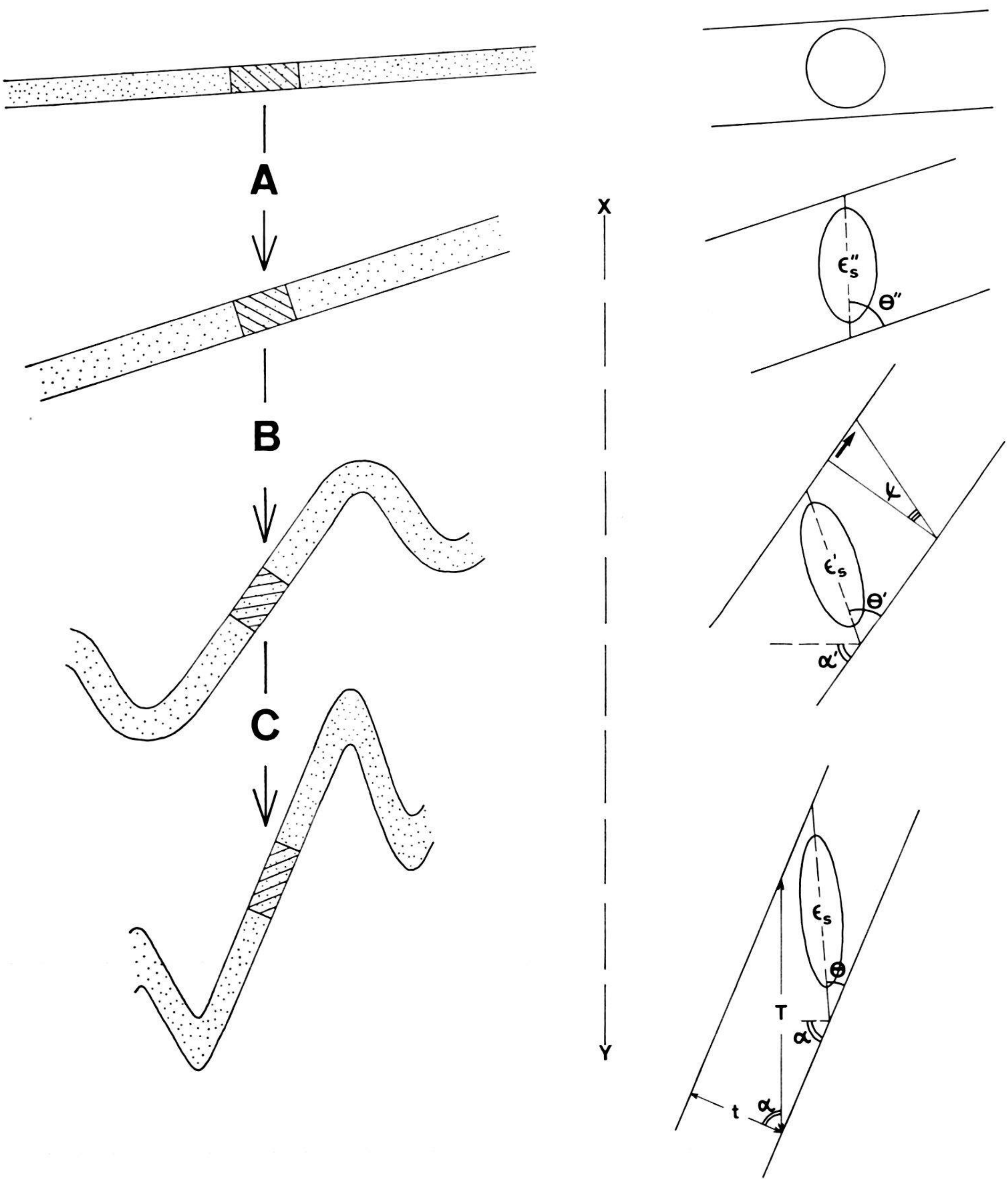

Fig. 1. A model for the deformation history of a competent folded layer, illustrated in the section normal to the fold axis (for explanation, see text).

An enlargement of a small section of the fold limb is shown for each stage to the right, with the strain ellipses and other parameters indicated. The line XY is the trace of the XY plane of the bulk strain ellipsoid (= the axial plane trace of the folds). The bulk strain ellipsoid is taken as irrotational, although the position of the X and Y axes within the XY plane need not be specified and could change relative to the fold axis throughout the deformation (see FLINN 1962). The angles α and α' are measured with respect to a line normal to XY.

where α' and α are the corresponding values of the "limb dip" (the dip of the limb if the axial plane is placed vertical) before and after phase C. Equations (1) and (2) can be used to construct a thickness ratio diagram, carried out logarithmically in Figure 2, with lines of equal superimposed homogeneous strain. Hence the strain involved in phase C of the folding process can be estimated directly from measurements of the relevant thicknesses, t, T, and A in the fold profile by plotting on Figure 2 (see also RAMSAY 1967, Fig. 7, *79*; 7, *80*). The limb dip of the buckle folds before phase C is obtained directly from equation (3).

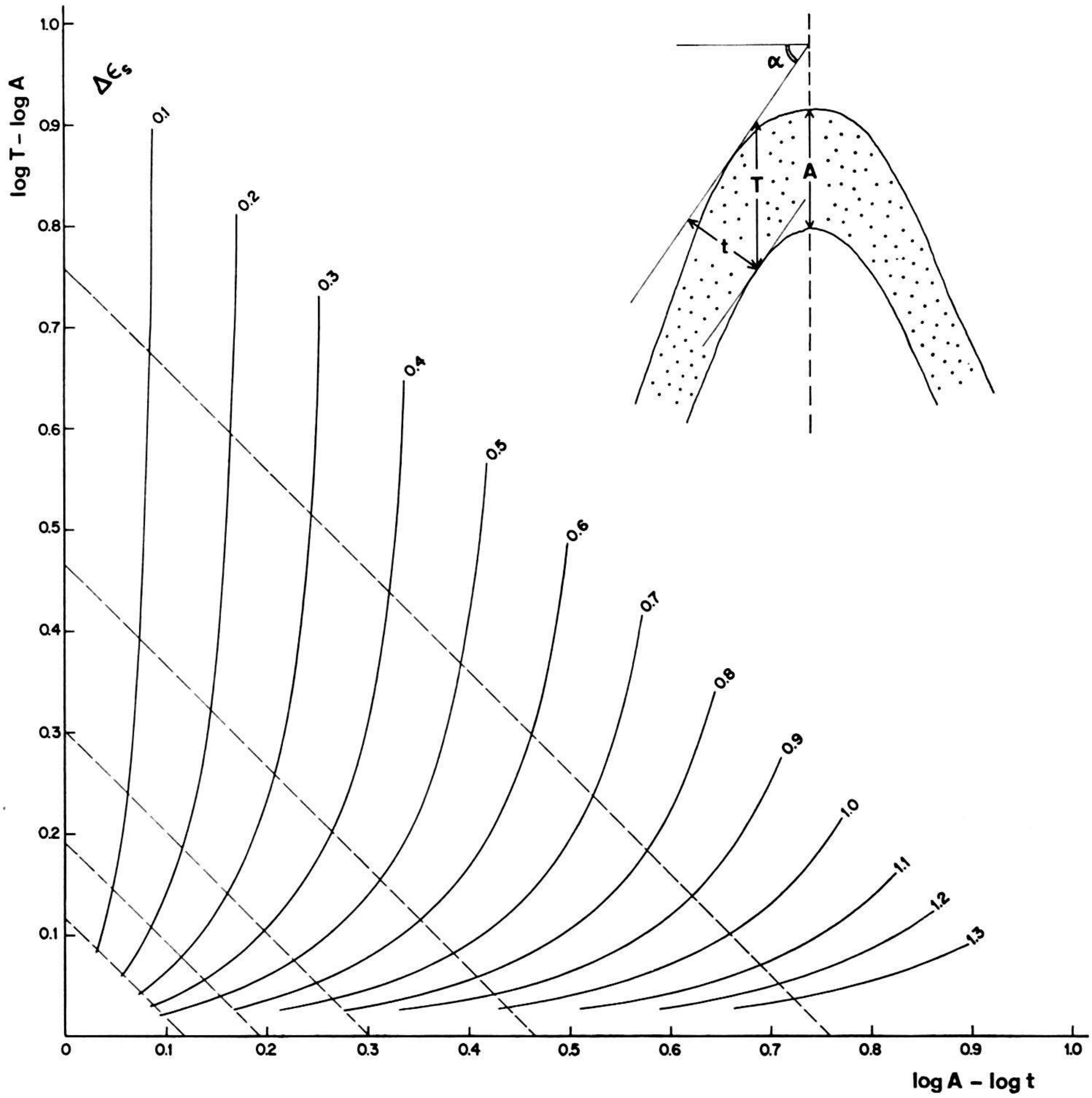

Fig. 2. A logarithmic thickness ratio diagram for parallel folds modified by a superimposed homogeneous strain (after RAMSAY 1967).

The full lines are lines of equal superimposed strain ($\Delta\varepsilon_s$, drawn at intervals of 0.1 between 0 and 1.3), the dashed lines of equal limb dip (α, drawn at intervals of 10° between 40 and 80°). In practice, t and T are measured for various values of α on both fold limbs and a best-fit line constructed which gives directly an average value of $\Delta\ \varepsilon_s$ for that fold.

Having estimated the shape of the phase C strain ellipse ($\Delta\varepsilon_s$), the shape and orientation of the final strain ellipse at the end of phase B (ε_s', Θ') can be determined most easily using the "shape factor grid" recently published by ELLIOTT (1970).

Shear on the limbs of buckle folds

Having removed the effects of the phase C homogeneous deformation, it remains to make an estimate of the strain involved during a pure buckling of the layer (phase B). Assuming that we are dealing with a small *planar* section of a fold limb, we know this strain to have been essentially homogeneous. Since the thickness of the layer remained constant during buckling, any strain must have been a simple shear with shear plane parallel to the layer margins. Since, however, the states of strain within a buckled layer are very complicated, an estimate of the amout of shear involved in the individual case is extremely difficult. All that can be done is to test whether the final strain ellipse could have been produced by simple shear alone, or whether an earlier component of strain must be assumed. This test is best carried out using a polar graph as in Figure 3 (see also ELLIOTT 1970).

The shape and orientation of an ellipse can be represented by plotting on a polar graph, with ε as radius vector and 2Θ as angular coorinate. For representations of strain, it is necessary to chose a reference line (from which Θ is measured) which does not change orientation during the deformation. For simple shear, the reference line is the shear direction and strain ellipses produced solely by simple shear trace out a curve through the origin (actually two symmetrically placed curves starting at the origin, corresponding to the two possible senses of shear). Only if the point (ε_s', Θ') lies on this curve can the ellipse have been produced by simple shear parallel to the layer boundary alone. The condition is even narrower, since it can be shown that the absolute upper limit of the angle of shear is α' (the actual upper limit is less than this, since it is given by the relation: $\tan\psi = \alpha'$ radians, see RAMSAY 1967, p. 440). Hence, to have been produced by simple shear alone, the point must lie at a distance of less than $\gamma = \tan\alpha'$ from the origin (taking into account also the sense of shear).

If the point (ε_s', Θ') does not lie on the strain ellipse curve for simple shear, there are two possibilities:

1. The point lies outside the curve (field 1, Fig. 3). This condition favours the assumption that an initial phase of homogeneous deformation played an appreciable role. This is particularly true if Θ' is greater than 45° (or less than $-45°$) and if the sense of shear would cause the point to move closer to the 90° line on removing the shear strain (Θ'' must be considerably greater than 45° for folding to develop, see above).

2. The point lies inside the curve (field 2, Fig. 3). In this case, it is unlikely that the pre-buckling strain ellipse is due solely to the action of an initial homogeneous deformation, since removal of any amount of shear strain cannot result in Θ'' exceeding 45° (the movement paths of ellipses deformed by simple shear are lines approximately parallel to the strain ellipse path). Points in this field have probably had a more complicated history, i.e. an earlier deformation episode unrelated to the episode of folding under consideration.

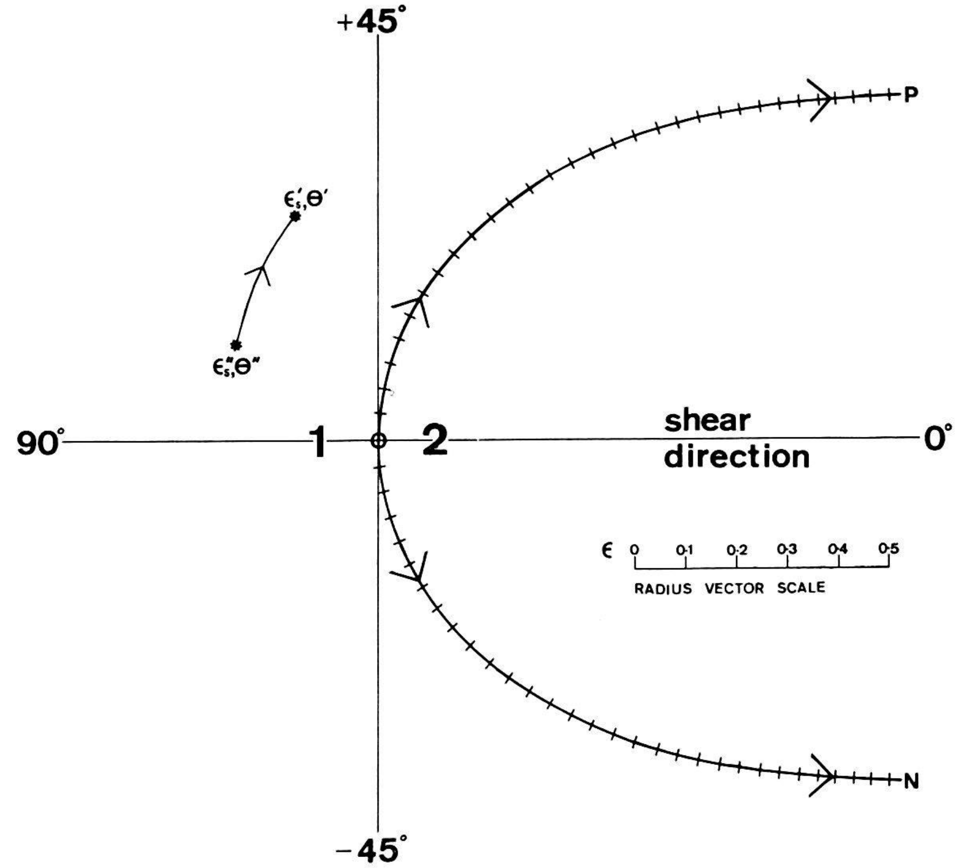

Fig. 3. A polar graph for simple shear deformation showing the locus of all simple shear strain ellipses up to a unit shear of 3.0 (calculated from RAMSAY 1967, equations 3-*67*, 3-*70*).

The radius vector is $\varepsilon = {}^1/_2 \ln \left(\frac{\text{long axis}}{\text{short axis}}\right)$ and the angular coordinate is 2Θ, where Θ is counted as negative when measured clockwise from the shear direction (see ELLIOTT 1970). Progressive simple shear gives a succession of ellipses along curve OP for positive shear and along curve ON for negative shear. Cross marks on these curves are placed at equal unit shear increments of $\Delta\gamma = 0.1$. To remove a given amount of unit shear from a given strain ellipsoid, the point must be moved in the opposite direction to the arrow by the required number of unit shear increments. Deformation of an original ellipse by simple shear causes the point to move along a locus approximately parallel to the strain ellipse locus (for instance, the ellipse [ε_s'', Θ''] from Fig. 1 moves to a new position [ε_s', Θ'] when subjected to the indicated amount of shear, $\psi = \tan^{-1}\gamma$).

Assumptions and difficulties

The procedure outlined above is based on a model of the folding process which according to modern theoretical, experimental and field studies seems to be a good approximation to the actual folding of viscous or pseudo-viscous materials. Its application to rocks is limited to folds which seem to have been developed under such conditions, i.e. conditions under which cohesion was maintained throughout the whole layer volume. It is hoped to use it at a number of places in the Alps where mesoscopic folds of this type in horizons containing favourable strain markers (ooids, radiolarians) are well exposed. The major difficulty will be the accurate reconstruction of the final strain ellipse in the section normal to the fold axis from the available strain markers. Great strides have been made in recent years in refining the techniques of strain analysis (see, for instance, RAMSAY 1967, GAY 1969, ELLIOTT 1970) and it is hoped that this, together with the abundance of unusually favourable material in the Alps, will enable this difficulty to be overcome. Another difficulty is the two-dimensional nature of the procedure. However, it is clear that the limited objective of the procedure, to test for the existence or otherwise of an appreciable component of homogeneous deformation before folding in particular natural situations, is hardly affected by this limitation. This is because the procedure does not assume constant area for the strain ellipses (only the axial ratios come into the calculations), and the chance of the fold profile being orientated so as to give a circular section of the three-dimensional strain ellipsoid in the pre-buckling phase of deformation is extremely small. Hence it is thought that if the practical difficulties of strain analysis can be overcome, work along these lines may in future provide a useful independent test of the predictions of the theoretical and experimental studies.

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