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The determination of progressive deformation histories from antitaxial syntectonic crystal fibres

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Abstract—Antitaxial, syntectonic crystal fibres are modelled here as 'mechanically-passive' features, the fibres representing displacement paths, forming within a homogeneously deforming material. Evidence that many fibres develop in this way is widespread: asymptotic curvature, thinning of fibres, and strained old fibres. A measuring technique is proposed by which the complete deformation history (excluding translation) may be determined. The method involves the iterative unstraining of two complete fibres whose development began and ended simultaneously. A source of error is introduced by assuming that each of the two fibres developed at constant proportional rates, although synthetic examples suggest this error to be minimal. It is suggested that the kinematics of non-passive fibres are unobtainable since the rheologies and boundary conditions of the material involved are relatively unknown, and cannot be determined from geometry alone. Analysis of natural fibres found within the Ordovician slates in New Jersey, U.S.A. indicates that volume losses of up to 50% may occur during the formation of some slates. General constraints concerning the geometrical analysis of syntectonic crystal fibres are briefly discussed, and it is concluded that deformation histories must be interpreted with some modicum of caution.

INTRODUCTION

IN ORDER to fully understand the development and evolution of tectonic features the geologist requires information concerning the final and original geometry, and the path along which the geometry evolved. This much information enables us to place firm constraints on, for example, the potential rheology of the deforming materials, or the validity of cross-sections through mountain belts. In order to realize the original form of a tectonic feature it is desirable to know the deformation state of the feature; that is, the finite strain magnitudes, the rotational components of the deformation, the orientations of the strains, and the variations in volume change. Finite strain studies under particular circumstances may offer viable strain histories (e.g. Graham 1978) but this is the exception rather than the rule. Syntectonic crystal fibres offer the greatest potential for the calculation of incremental and progressive strain histories, and indeed have been used extensively in the determination of the movement history of the Helvetic Alps (Durney & Ramsay 1973), and more recently as indicators of fold kinematics (Beutner & Diegel 1985).

This paper looks at the kinematics of continuously grown antitaxial syntectonic crystal fibres and the possibility of determining the various deformation components from such fibres. I will specifically address fibres found within pressure-shadows adjacent to spherical objects, although the analysis is valid for all continuous, antitaxial, mechanically passive fibres. The first part of the paper will describe the potential kinematics of fibre development and the information which may be extracted from the fibres assuming this model is correct. A measuring technique is proposed, and examples (synthetic and real) are discussed. The second part addresses problems intrinsic to both the proposed technique and those already established. The general limitations associated with any method are reserved for the discussion.

KINEMATICS OF FIBRE DEVELOPMENT

Fibre geometries have been well documented (e.g. Durney & Ramsay 1973, Beutner & Diegel 1985); there can be little doubt that the geometrical development of such fibres is variable. The often pristine and apparently face-controlled fibres shown by Durney & Ramsay (1973) appear to have developed as resilient, if not rigid, objects. However, the fact that the shape of the fibre collection at the distal end is often similar to the shape of the face of the rigid object from which the fibres have developed is not considered unequivocal evidence that the fibres have behaved rigidly. Such a geometry may also be obtained by allowing the fibres to develop within a plane in which no strain occurs perpendicular to the fibre lengths; within, for example, the *XY* plane of a plane-strain ellipsoid. By contrast, the asymptotic curvature and often recrystallized ends of other fibre complexes (Beutner & Diegel 1985, Ellis 1984) are strongly suggestive of a mechanically passive process (Figs. 1 and 6). Unfortunately, it is not yet possible to distinguish, purely from the geometry, the specific kinematics of any fibre complexes. The current state of the art is such that a particular growth model can only be assumed; the 'activity' of fibres remains elusive. It is likely that the spectrum of fibre development is a continuous one varying from 'rigid' through 'partially rigid' to 'mechanically-passive'. The associated mathematics describing the kinematics are, in theory, well known: the simplest mathematical description is that of the 'mechanically-passive' process.

The kinematics of any other fibre behaviour, however, is dependent on the specific rheology of the rigid-object/fibre complex, the rheological contrast between matrix and complex, and the coherence across the various boundaries. If for example, the fibre complex has any coherence with the matrix then it must undergo some rotation. Rosenfeld (1970) showed that, given cohesion between a spherical object and matrix, rotation will occur during a general deformation. Such cohesion allows shear stresses to be transmitted across the matrix–object interface allowing, for example, a growing porphyroblast (such as garnet) to rotate. It seems unlikely that significant shear stresses will be transmitted across a pyrite–matrix boundary; such a boundary is particularly incoherent due to both the high contrast of the phases involved, and the presence of a solution at the interface. For the model proposed here a continuous slip condition is assumed for the object boundary, and the object is not permitted to rotate. This condition is inferred in the stipulation that the fibres must be antitaxial.

With respect to a non-spherical object: due to the incoherence of the interface, shear stresses will virtually vanish, although the uneven distribution of normal stresses will cause the object to rotate. Rotation of the object will cease once the normal stresses are symmetrically disposed about the principal axes of the operating stress system. If the stress system is continually changing then the object will continue to rotate. It is not uncommon to observe fibres adjacent to irregular objects, although whether their geometry reflects the local matrix strain or the rotation of the object is unknown.

Continuous, antitaxial syntectonic fibres commonly show characteristics compatible with formation within a 'mechanically-passive' environment, and it is considered that such a process may well account for the development of most fibre complexes. In particular, concerning the development of quartz fibres, there seems little reason to consider these to have been rigid when one recalls that quartz is a particularly ductile material under even low grade metamorphic conditions. Under conditions in which quartz may not be ductile (e.g. immediately post-diagenesis?) the process of pressure-solution may still effect a potentially passive behaviour of quartz fibres.

The kinematics of a 'mechanically-passive' process are as follows. As two points move apart a crystal fibre will be precipitated such that the fibre directly reflects the displacement path at the time of formation. (Note that no reference is made at this stage to the potential mineralogy of the fibre. The kinetics of the various mineral species involved in this process are relatively unknown, and are not addressed here.) The proposal that *continuously grown* fibres connect points which were once adjacent, and therefore represent displacement paths, seems more realistic than making a direct correlation between fibre orientation and the principal incremental strain directions since the latter do not reflect the motion of particles in a rock but the resultant strain due to these various motions. During the deformation these and all other particles will continue to have their relative distances and orientations changed. For the model, it is assumed that the displacements are homogeneous over the rigid-object/fibre scale. That is, the distal fibres are assumed to deform under the same displacement field as that which simultaneously produces the youngest fibres at the pyrite edge.

The displacement path of one particle relative to another may be calculated in the following manner. Recall that a finite homogeneous deformation (described by the transformation constants in matrix form, D) may be decomposed into a number of infinitesimal deformation increments (Elliott 1972)

$$D_t = D_n\, D_{n-1}\, \ldots\, D_1, \tag{1}$$

where

$$D_i = \begin{bmatrix} a_i & b_i \\ c_i & d_i \end{bmatrix} \equiv \begin{bmatrix} 1 + \dfrac{\partial u}{\partial x} & \dfrac{\partial u}{\partial y} \\ \dfrac{\partial v}{\partial x} & 1 + \dfrac{\partial v}{\partial y} \end{bmatrix}$$

and is known as the deformation gradient tensor, and where u and v are displacements in the x and y directions, respectively.

Note that the rotational component of any deformation increment need not be zero. In addition, none of the increments need be constant-area transformations. Thus, each increment comprises four independent transformation constants.

A point is moved thus:

$$p_1 = Dp_0, \tag{2}$$

where p_0 and p_1 are, respectively, the coordinates of the original and deformed points in vector form. The new point, p_1, may be returned to its original site by the inverse operation

$$p_0 = D^{-1}p_1. \tag{3}$$

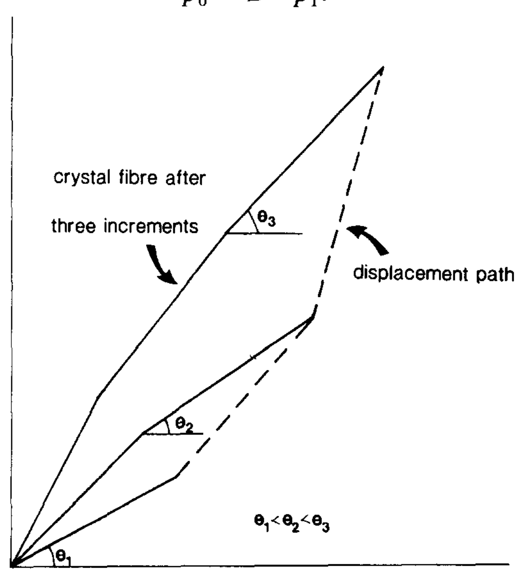


Fig. 2. Development of an antitaxial, mechanically passive, syntectonic crystal fibre, and the displacement path of the most distal particle. Three increments are shown; the incremental principal stretch rotates counter-clockwise. (In order to emphasize the changing lengths and orientations of fibre increments the diagram is highly schematic.)

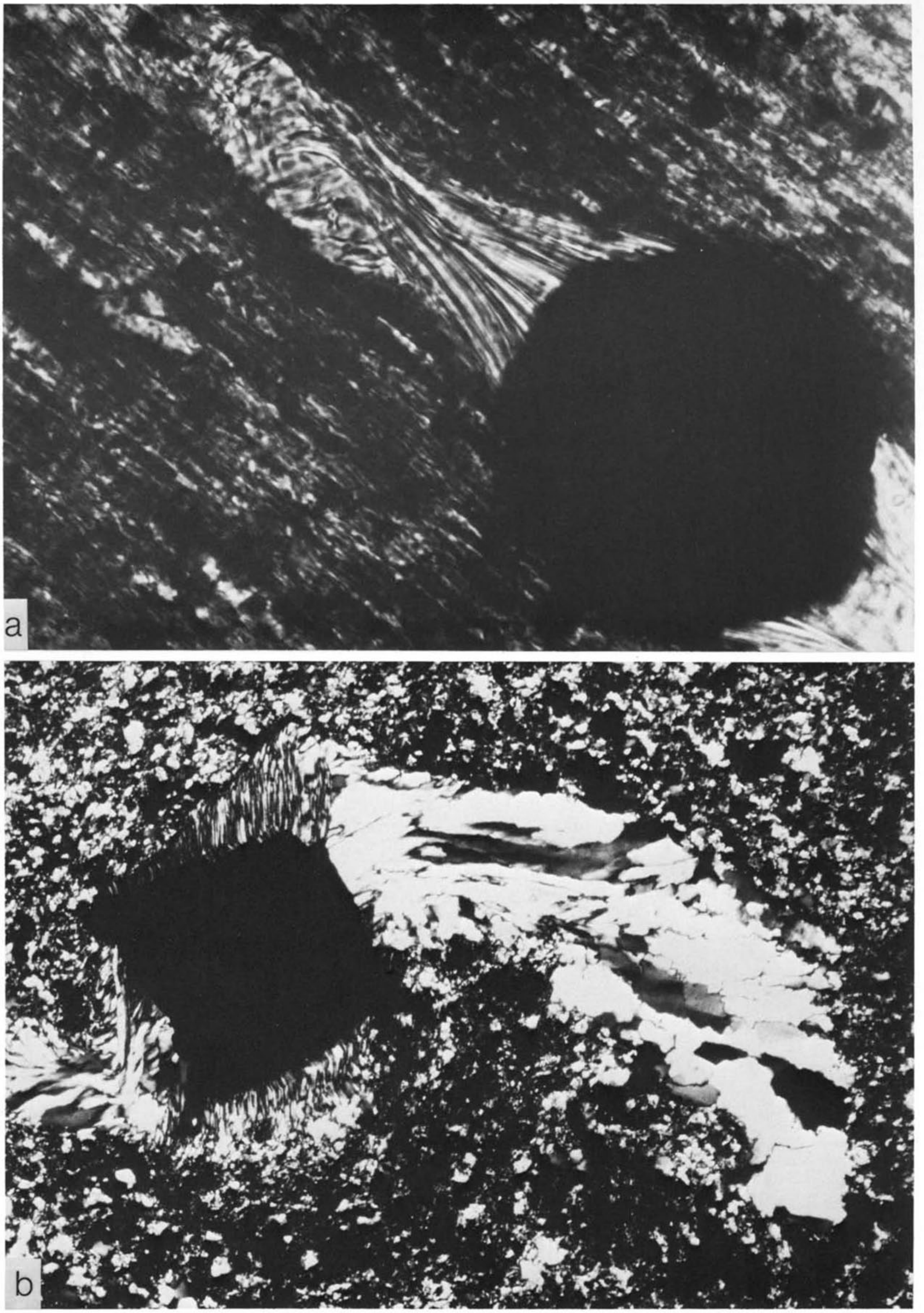
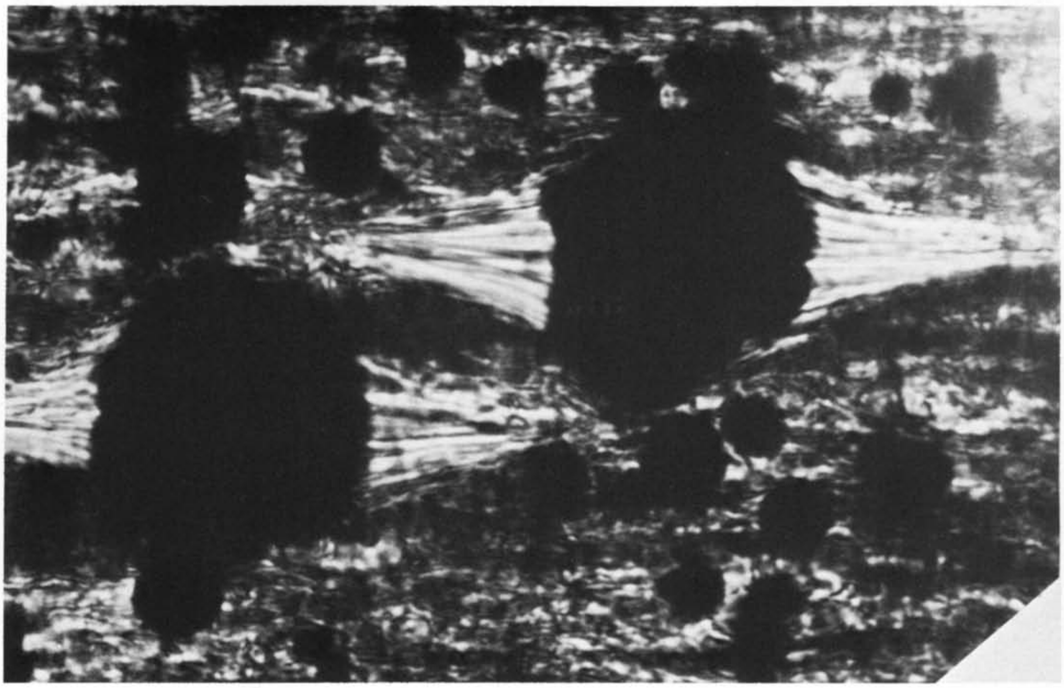


Fig. 1. Antitaxial, syntectonic crystal fibres developed adjacent to rigid objects (pyrites). (a) Quartz and chlorite fibres show an asymptotic curvature and thinning toward the distal end, suggesting a mechanically passive origin. (b) Quartz fibres become progressively recrystallised toward the distal end, showing a non-rigid character. The diameter of each pyrite is approximately 60 μm (photograph (a) by kind permission of Ed Beutner).



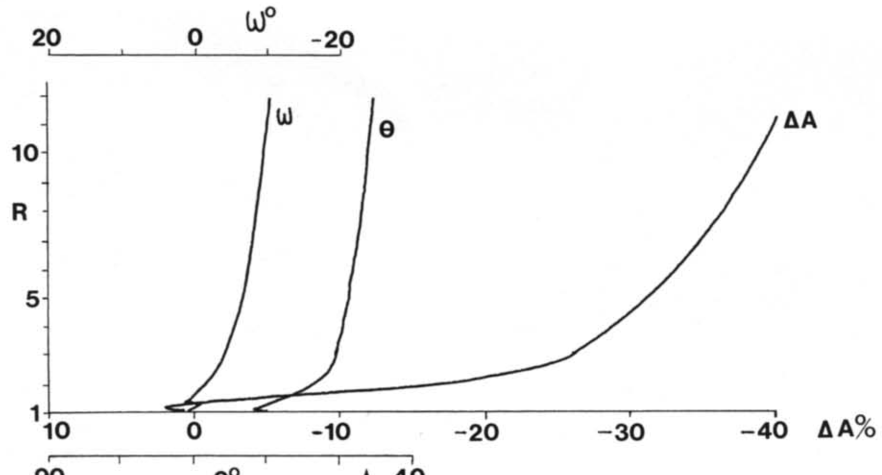


Fig. 6. Natural fibre geometries and associated deformation histories. The orientation of the cleavage trace is indicated on the θ scale. Note the asymptotic curvature of the fibres, suggesting a mechanically passive origin. The fibres are made of a mixture of chlorite, white mica, and quartz. The pyrites are about 25 μm in diameter. (See previous figures for symbols.)

The crystal fibre path is calculated in the following way: the final fibre increment is generated by the particle point at p_0 moving to p_1 via D_n; p_2 is found by moving p_0 via D_{n-1} followed in time by D_n, and so on. In other words

$$\begin{aligned} p_1 &= D_n\, p_0 \\ p_2 &= D_n\, D_{n-1}\, p_0 \\ &\vdots \\ p_n &= D_n\, D_{n-1} \ldots D_1\, p_0. \end{aligned} \tag{4}$$

Figure 2 shows the relationship between the particle displacement path, the crystal fibre, and the incremental (maximum) principal axis.

THE MEASURING TECHNIQUE

Consider again the motion of two points, p_0 and q_0, via any deformation increment. In two dimensions

$$\begin{aligned} p_1 &= D\, p_0 \\ q_1 &= D\, q_0 \end{aligned} \tag{5}$$

(Fig. 3). Now assume that we observe the same points at some later date but in a reference frame rotated θ counter clockwise. Thus

$$\bar{p}_0 = R\, p_0;\ \bar{p}_1 = R\, p_1;\ \bar{q}_0 = R\, q_0; \quad \text{and } \bar{q}_1 = R\, q_1, \tag{6}$$

where

$$R = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}.$$

Since, from eqn (6), $p_0 = R^{-1}\,\bar{p}_0$, $p_1 = R^{-1}\,\bar{p}_1$, etc. substituting in (5) and solving for $\bar{p}_1$, and $\bar{q}_1$

$$\bar{p}_1 = R\, D\, R^{-1}\,\bar{p}_0, \quad \text{and} \quad \bar{q}_1 = R\, D\, R^{-1}\,\bar{q}_0. \tag{7}$$

The quantity $M = R\, D\, R^{-1}$ is now the apparent deformation gradient tensor. (Note that M is defined by these operations to be a second-order tensor.) That is, $\bar{p}_1 = M\,\bar{p}_0$, and $\bar{q}_1 = M\,\bar{q}_0$ giving four equations and four unknowns. The reader should note that the rigid body rotation, R, is *not* the same as the rigid body rotation component of the deformation. The point behind the operations described by eqns (6) and (7) is to emphasize that the frame of reference in which we finally come to examine the fibres is irrelevant. The deformation tensors M and D describe the same quadric, and yield the same relative deformation components since they are related only by a rigid body rotation (Nye 1957). The components of M are easily converted into the type of strain data with which structural geologists are familiar (e.g. Sanderson 1982).

Stated in other words, the method for the determination of the incremental deformation history involves the following steps:

(1) Place the origin of a Cartesian coordinate system over the central point of the circular rigid object (e.g. a framboidal pyrite); the axes should be scaled such that the fibre increments will represent strains of less than about 2% (thus approximating infinitesimal strains). Trial and error is suggested at this point.

(2) Two fibre lengths are chosen and divided into an equal number of increments. The fibres should be chosen such that, as best as may be determined, they both began and ended their development simultaneously, and that the full length of each is preserved. To achieve this, the fibres should be fairly close to each other.

(3) The coordinates of the fibre-increment ends are treated in the following way:

the nearest points (p_1 and q_1) are returned to their points of origin (p_0 and q_0) thus

$$p_0 = M^{-1}\, p_1,\ q_0 = M^{-1}\, q_1. \tag{8}$$

This operation reveals the final deformation increment. The remaining data points are adjusted by M^{-1}. Thus, p_2 now becomes p_1, etc. This third step is repeated until the entire fibre length has been analysed. The incremental deformation history is given by the individual deformation matrices, M_i, the progressive deformation history by their progressive product, eqn (1), and the finite deformation state by the finite product.

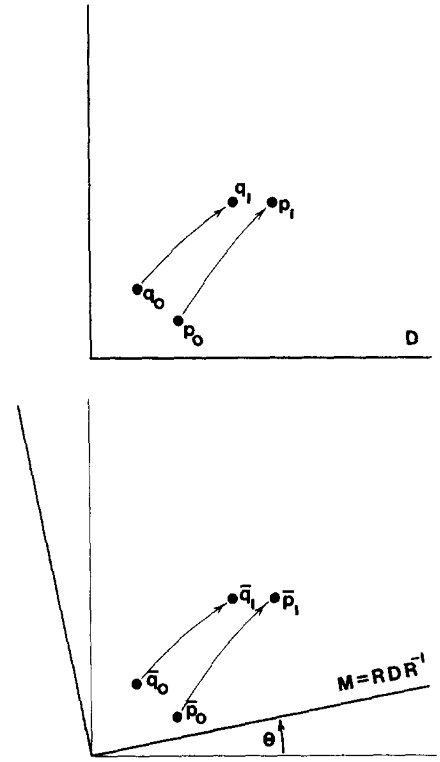


Fig. 3. A view of the relative motion of two particles, viewed in an original framework (top), and one rotated by θ (bottom). See text for details.

The importance of the necessity for homogeneous strain is now apparent: if the strain was not homogeneous (on the scale of the pyrite–fibre complex) then the cycle of adjustments to the gradually decreasing number of fibre increments could not be made, and the strain history becomes indeterminate.

Of particular value is the ability to record the variation of area change. Area change is recorded by the determinant of the deformation matrix which is also an invariant property.

There are two potential sources of error that need to be emphasized. The first is mentioned under point 2 above, and concerns the identification of two fibres which began and ended their development simultaneously. During an increment of infinitesimal strain fibres will have a maximum separation of 90° of arc, and thus may be chosen within this distance in an ideal case. However, during a rotational deformation some of the edge fibres will cease to grow, while new ones begin at the opposite side of the trail. Therefore, in order to ensure the best choice of fibres, they should probably be within about 30–40° of arc to each other, close to the centre of the complex, and away from the side which appears to be progressively falling outside the extension zone.

The second source of error concerns the division of the fibre length into an equal number of increments. Note that increments of any pair will probably not be of the same length. During a rotational deformation history the relative lengths of growth along any two fibres may not be constant, but rather a function of their change in orientation within the displacement field. Based on the examples discussed in a later section, this source of error appears to be minimal. Nevertheless, during parts of the deformation which involve significant rotation this source of error may become more important.

EXAMPLES

In order to demonstrate the technique described here, a set of synthetic examples and a real fibre-trail have been analysed. A computer program, FIBRE, was developed using the equations presented in this paper. The geometry of synthetic crystal fibres was calculated using eqn (2); the co-ordinates of these fibres were then plotted and joined by hand in order to introduce some form of minimal error. New co-ordinates were then produced from a digitizing tablet. In all cases the match between the expected and resultant deformation histories is excellent (Figs. 4 and 5). The analysis of a relatively complex deformation history yielded some 'noise' at the beginning of the history which appeared to settle above a strain ratio of about 1.5 to 1.7 (Fig. 4). This is attributable to the fact that the earliest-formed fibres are, during the analysis, subjected to the most amount of numerical manipulation. For example, one part of the program FIBRE involves the redefinition of the fibre geometry, whereby the fibre is described by a set of co-ordinates which divide the fibre length into an equal number of small increments, each increment approximating an extensional stretch of about 2%. The new co-ordinates are altered by successive unstraining events; the most distal fibres may undergo several hundred redefinitions.

Natural fibre geometries from the Ordovician Martinsburg slate as exposed in the Delaware Water Gap, New Jersey, were analysed using this technique. Results gave what initially appear to be unrealistic deformation

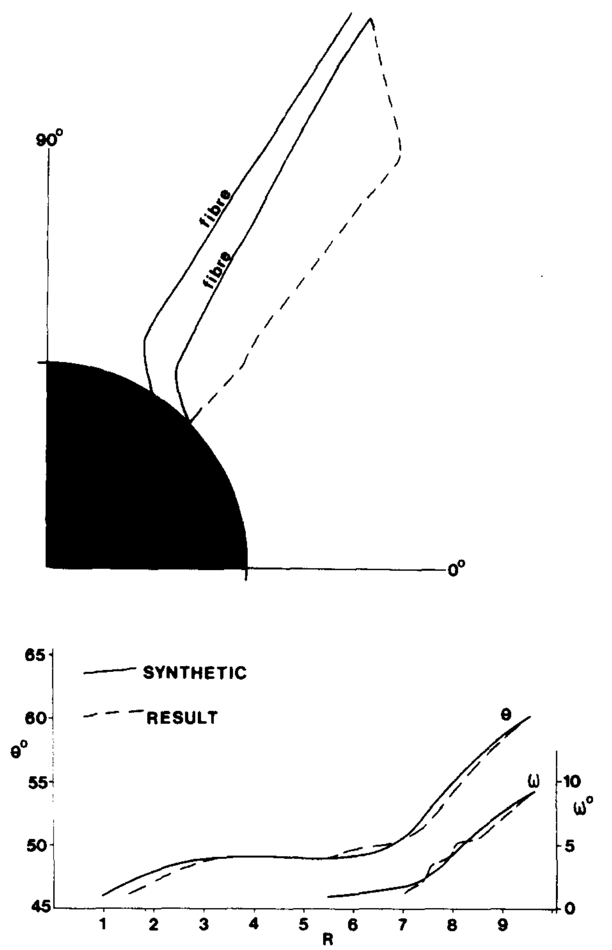


Fig. 4. Top, numerical simulation of the development of an antitaxial, mechanically-passive, syntectonic crystal fibre showing the relationship between the fibre and displacement path of the most distal particle. Bottom, the synthetically produced deformation history and the history determined with the technique described here. Symbols: $R = (1 + e_1)/(1 + e_2)$, θ = orientation of maximum principal stretch, positive angles are counter-clockwise; ω, rigid-body rotation, positive angles indicate counter-clockwise rotation.

histories, particularly with respect to the magnitude of the minor principal strain axis. The example shown in Fig. 6 is apparently associated with an area loss of approximately 40%. This sample was prepared as a thin-section perpendicular to a slaty cleavage and parallel to a moderately developed stretching lineation; it is considered to lie approximately parallel to the finite XZ principal plane. In order to conserve volume during the deformation the product of the principal stretches should equal unity, thus the intermediate stretch for the example shown in Fig. 6 would equal *c.* 1.8. Examination of orthogonal sections shows fibres in the XY principal plane to be relatively straight, indicating a value of stretch in the Y direction of approximately 1. If $Y = 1$ the sample has undergone just over 50% volume loss.

Interpretation

The results obtained from the analysis of natural fibre geometries are significant in that they suggest the possibility of large volume losses which may have occurred

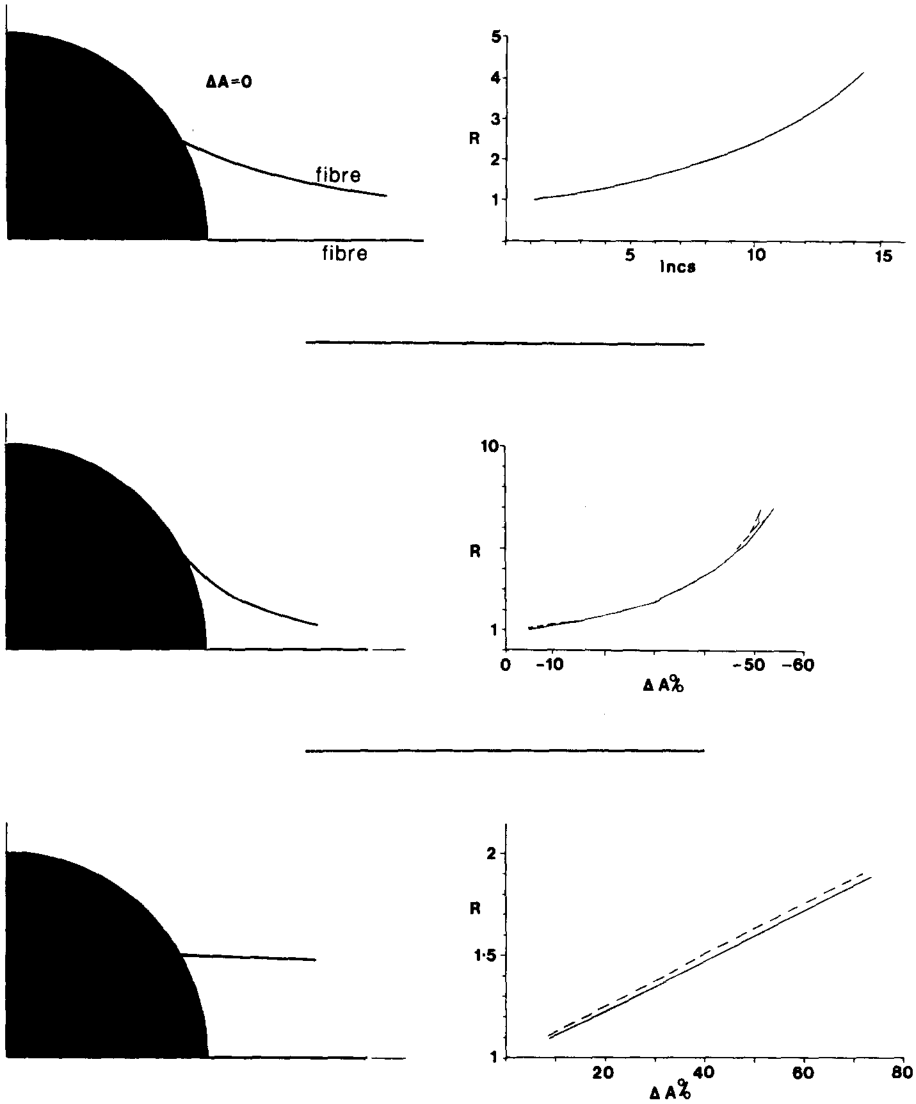


Fig. 5. Examples of synthetic fibre geometries and the correlation between expected and resultant deformation histories. Solid bold lines adjacent to the 'pyrites' represent crystal fibres. Solid lines on graphs represent the synthetic (expected) data; dashed lines the results of analysis with FIBRE. Where lines are indistinguishable only the synthetic line is shown. In all examples the deformation history is coaxial, with the maximum principal stretch horizontal. Symbols: Incs, number of deformation increments; ΔA%, area change; *R*, strain ratio.

during the deformation. Large volume losses are not uncommonly called for, particularly in the formation of slates (see for example Sorby 1853). Similar volume-loss magnitudes have been found in the Martinsburg Formation by Beutner & Charles (in press) and Wright & Platt (1982).

The volume loss described here may of course be confined to the immediate volume about the pyrite–fibre complex, although the homogeneity of the microtexture implies a more pervasive process. A volume loss of such a magnitude implies mass-transfer, and is significant in that theoretical models of deformation are normally constrained to conserve mass. When volume changes occur during the deformation they add to the tectonic part of the strain, and are consequently more significant. The scope of the present paper does not afford a detailed consideration of the results obtained here; further analyses of natural fibre geometries will be presented elsewhere.

COMPARISON WITH OTHER TECHNIQUES

Measuring techniques have been proposed by Durney & Ramsay (1973), Wickham (1973), Casey *et al.* (1983), Ellis (1984), Ramsay & Huber (1984) and Beutner & Diegel (1985). All the methods (including the present one) involve the geometry of at least one complete fibre. The most commonly used method is that proposed by Durney & Ramsay (1973) in which incremental fibre lengths are directly correlated with incremental principal directions, and where the fibres are thought to behave rigidly. This method fails to give correct strain histories for two reasons. First, it neglects to take into account any rotation or potential change of shape which would occur if there existed any coherence between fibres and matrix. Secondly, during a general deformation (i.e. non-coaxial) no single continuous fibre directly reflects the orientation of the principal strain axis.

A more recent technique proposed by Ramsay &

Huber (1983), intended for "deformable fibres", involves a similar iterative unstraining of the fibre length as required in the present method. Each increment of fibre length is again directly correlated with the maximum incremental principal axis, and therefore, as argued for the original method by Durney & Ramsay (1973), may yield incorrect results. Furthermore, the iterative unstraining is performed using a relationship which appears to require *a priori* knowledge of the second principal strain axis (see Ramsay & Huber, eqn D.3, p. 293). Since Ramsay & Huber's method does not include the determination of the minor principal stretch the iterative unstraining is not possible.

Beutner & Diegel (1985) have modified Durney & Ramsay's (1973) 'pyrite' method: the radius term in the latter is replaced by the component of the radius in the incremental extension direction. The method suffers from the same limitations as that of Durney & Ramsay (1973).

Wickham (1973), proposed the same kinematics as are invoked in this study. The measuring technique differs in detail in that Wickham first finds the displacement path of one particle relative to another within a reference frame that is continually rotating with the deformation. In this reference frame, the displacement path is the geometrical inverse of the fibre. This path is then used to calculate the components of the symmetrical part of the deformation gradient tensor

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix},$$

where $S_{ij}\ (i, j = 1, 2)$ are the stretch components, and $S_{ij} = S_{ji}\ (i \neq j)$.

In order to solve the appropriate equations Wickham constrains the deformation to be area constant. That is, det $(S) = 1$. This is a valid and elegant method except that the accuracy of the technique is particularly susceptible to area changes (see error analysis by Wickham 1973). Thus, prior knowledge of the area change is required if the results are to be meaningful. This is obviously not a satisfactory condition; fibres are usually analysed on one of the principal planes of the finite strain ellipsoid, none of which, except the XZ plane of a plane strain state, involve a constant area transformation.

Casey *et al.* (1973) examined fibres which developed within an oblate strain section (or 'chocolate-tablet' section). In such sections the complex array of fibres may develop in a diachronous nature. If synchronously-developed fibres cannot be identified, an unequivocal strain history cannot be determined.

DISCUSSION

Problems intrinsic to the various techniques have been discussed above. There remain several questions, however, involving the interpretation of strain histories deduced from syntectonic crystal fibres. In brief these problems concern the following points.

The extrapolation of measured strain histories to larger scales

It is not sufficient to be comforted by the fact that, within a small rock volume, fibres adjacent to a number of rigid spherical objects present very similar geometries and therefore reflect the general matrix deformation; this may simply be a demonstration of the homogeneity of the individual heterogeneities! A particular example of the potential danger in extrapolation is described below under *size effects*. Nevertheless, various studies of syntectonic fibres (e.g. Durney & Ramsay 1973) do appear to yield results which fit our geological expectations. A particularly elegant model of the kinematic development of overturned folds by Beutner & Diegel (1985) shows that such extrapolation may well be valid.

The origin of curved fibres

Is curvature syn- or post-tectonic? An original curvature (i.e. syntectonic) may be noted when the central fibre at any specific locality does not remain the central fibre (Fisher 1983).

The necessity that fibres remain in one 'flat' plane

Unless non-Euclidean thin-sections can be made, this constraint presents obvious problems. All methods available to date, including the one described in this paper, require fibres to remain in a single plane.

Size effects

Beutner & Diegel (1985) noted considerable strain variation recorded by fibre complexes of different sizes. This was attributed to the heterogeneity of the strain over an area less than that of a thin-section, whereby pyrites greater than 50–70 μm (large enough to encompass many cleavage lamellae) record an average and more consistent strain, and those smaller than about 25 μm (small enough to be encompassed by a cleavage lamella) record a less consistent value.

Total or tectonic strain?

Do fibres represent the total strain, including early compactional deformation, or only the tectonic strain? Ellis & Schriber (1984) recently described fibre complexes and grain shape-fabrics from the same thin-section: the fibres record a significantly greater strain than the shape-fabric. This was attributed to the earlier development of the fibres, and a possible progressive redefinition of the grain texture by dislocation processes. It appears at least from this example that fibres record the total strain.

Chronological comparisons

Whichever method is chosen to graphically portray a deformation history, the result is usually a line varying in orientation between a pair of axes. The chronological development of that particular line, however, is unappreciated. As a consequence, it is not possible to show a time-sequential comparison of deformation histories. The interpretation and comparison of deformation histories must be carried out within the context of the overall structure, which, to some extent, places the structural geologist in a chicken-and-egg situation.

CONCLUSIONS

Continuous syntectonic crystal fibres present structural geologists with the greatest potential for the determination of progressive deformation histories. The technique proposed here is based on a kinematic growth-model whereby fibre increments are formed between mechanically passive particles which are moving apart in a homogeneously deforming material. All the deformation components (excluding translation) can be determined from the geometry of two fibres, provided that they began and ended development simultaneously. A source of error arises from the fact that during a general rotational deformation the relative growth rates along any two fibres will not remain constant. Synthetic examples, however, show this error to be minimal. The iterative unstraining method described here requires the strain increments to have been homogeneous at the scale of the pyrite–fibre complex.

If fibres develop in any other way it may not be possible to determine an accurate deformation history; this arises from the inability to recognize the appropriate rheologies and/or boundary conditions purely from the geometry of fibres.

The results obtained from natural examples suggest that significant volume losses (and possibly mass-transfer) may occur during the formation of a slaty cleavage.

There are a sufficient number of problems intrinsic to any incremental deformation measuring technique, in addition to interpretative questions, that require geologists to treat syntectonic fibres with extreme caution.

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REFERENCES

Beutner, E. C. & Charles, E. G. in press. Large volume loss during cleavage formation, Hamburg sequence, Pennsylvania. *Geology*.

Beutner, E. C. & Diegel, F. A. 1985. Determination of fold kinematics from syntectonic fibers in pressure shadows, Martinsburg Slate, N.J. *Am. J. Sci.* **285**, 16–50.

Casey, M., Dietrich, D. & Ramsay, J. G. 1983. Methods for determining deformation history for chocolate tablet boudinage with fibrous crystals. *Tectonophysics* **92**, 211–239.

Durney, D. W. & Ramsay, J. G. 1973. Incremental strains measured by syntectonic crystal growth. In: *Gravity and Tectonics* (edited by DeJong, K. A. & Scholten, R.) Wiley, New York, 67–96.

Elliott, D. 1972. Deformation paths in structural geology. *Bull. geol. Soc. Am.* **83**, 2621–2638.

Ellis, M. A. 1984. Strain paths and syntectonic fibres. *Abs. with Prog. geol. Soc. Am.* **16**, 14.

Ellis, M. A. & Schriber, C. N. 1984. Strain measures derived from grain shape-fabrics and syntectonic crystal fibres: a comparison. *Abs. with Prog. geol. Soc. Am.* **16**, 501.

Fisher, D. 1983. A deformation history within the Hamburg klippe preserved as syntectonic fibers. Unpublished B.S. thesis, Franklin and Marshall College.

Graham, R. H. 1978. Quantitative deformation studies in the Permian rocks of Alpes Maritimes. *Mém. Bur. Rech. géol. min. Fr.* **91**, 219–238.

Nye, J. F. 1957. *Physical Properties of Crystals*. Oxford University Press, Oxford.

Ramsay, J. G. & Huber, M. 1984. *The Techniques of Modern Structural Geology*. Vol. 1. Academic Press, London.

Rosenfeld, J. L. 1970. Rotated garnets in metamorphic rocks. *Spec. Pap. geol. Soc. Am.* **129**.

Sanderson, D. J. 1982. Models of strain variation in nappes and thrust sheets: a review. *Tectonophysics* **88**, 201–233.

Sorby, H. C. 1853. On the origin of slaty cleavage. *Edinburgh New Phil. J.* **55**, 137–148.

Wickham, J. S. 1973. An estimate of strain increments in a naturally deformed carbonate rock. *Am. J. Sci.* **273**, 23–47.

Wright, T. O. & Platt, L. B. 1982. Pressure dissolution and cleavage in the Martinsburg shale. *Am. J. Sci.* **282**, 122–135.