Journal of Structural Geology, Vol. 7, No. 2, pp. 217 to 223, 1985
Printed in Great Britain

0191-8141/85 $03.00 + 0.00


# Cleavage strain in the Variscan Fold Belt, County Cork, Ireland, estimated from stretched arsenopyrite rosettes

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(*Received* 11 *May* 1984; *accepted in revised form* 9 *July* 1984)

**Abstract**—In south-west Ireland, hydrothermally formed arsenopyrite crystals in a Devonian mudstone have responded to Variscan deformation by brittle extension fracture and fragment separation. The interfragment gaps and terminal extension zones of each crystal are infilled with fibrous quartz. Stretches within the cleavage plane have been calculated by the various methods available, most of which can be modified to incorporate terminal extension zones. The Strain Reversal Method is the most accurate currently available but still gives a minimum estimate of the overall strain. The more direct Hossain method, which gives only slightly lower estimates with this data, is more practical for field use. A strain ellipse can be estimated from each crystal rosette composed of three laths (assuming the original interlimb angles were all 60°) and, because actual rather than relative stretches are estimated, this provides a lower bound to the area increase in the plane of cleavage. Based on the average of our calculated strain ellipses this area increase is at least 114% and implies an average shortening across the cleavage of at least 53%. However, several lines of evidence suggest that the cleavage deformation was more intense and more oblate than that calculated, and we argue that a 300% area increase in the cleavage plane and 75% shortening across the cleavage are more realistic estimates of the true strain. Furthermore, the along-strike elongation indicated is at least 80%, which may be regionally significant. Estimates of orogenic contraction derived from balanced section construction should therefore take into account the possibility of a substantial strike elongation, and tectonic models that can accommodate such elongations need to be developed.

## INTRODUCTION

RIGID inclusions showing pull-apart structure are sometimes found in deformed rocks. They are valuable in palaeostrain analysis because they permit estimation of actual rather than relative extensions and hence estimation of absolute principal strains. Belemnite guards are the most frequently used brittle strain gauges (Daubrée 1876, Heim 1919, Badoux 1963, Ramsay 1967, Beach 1979, Hossain 1979, Ramsay & Huber 1983). Disrupted crinoid stems, some forms of boudinage (Lloyd *et al.* 1982, Ferguson & Lloyd 1982), and deformed rigid–brittle minerals have also been used (Mitra 1976, Freeman 1982, Sanderson & Meneilly 1981).

In this paper we discuss extension analysis using arsenopyrite crystals found on the cleavage planes of a Devonian mudstone in the Variscan orogen of southwest Ireland. The crystals reacted to Variscan deformation by brittle fracturing and separation of the fragments. Interfragment gaps are infilled by fibrous quartz. The crystals also show terminal (and lateral) extension zones, where the mudstone matrix pulled away from the crystal faces. These zones, and the internal gaps, evidently acted as sinks for quartz mobilized during deformation. Crystal extension occurred during the development of a slaty cleavage in the mudstone matrix. Using data from 78 extended arsenopyrite crystals we compare the results given by all the methods currently developed for the calculation of extensional strain.

The strain reversal method (Ferguson 1981, Ferguson & Lloyd 1984) has been modified to take account of terminal extension zones and is used to estimate the strain ellipse and the area increase within the plane of cleavage. From this we estimate the minimum shortening associated with the cleavage-forming deformation. The possible histories of rotation of the interlimb angles affect the ellipse calculations and are discussed.

## GEOLOGICAL SETTING

On Galley Head, County Cork (Fig. 1), the Upper Devonian clastic sequence of fluvial–intertidal origin (Naylor *et al.* 1981) shows evidence of pre-deformation hydrothermal activity. At one coastal locality, Red Strand (W354331), large crystals of arsenopyrite occur in a green mudstone unit of the Toe Head Formation. The crystals have average dimensions of 1 mm × 1 mm × 10 mm and occur as single crystals, cruciform twins and star-shaped trillings (Palache *et al.* 1944, p. 316). Only the latter twin-type has been used in this study (Fig. 2).

In the region, the Upper Palaeozoic sedimentary sequence and the underlying Lower Palaeozoic and Precambrian basement were strongly deformed during the late Variscan orogeny. South of a major thrust zone (shown on Fig. 1) the structure is dominated by large upright folds, faults and thrusts. The dominant trend is

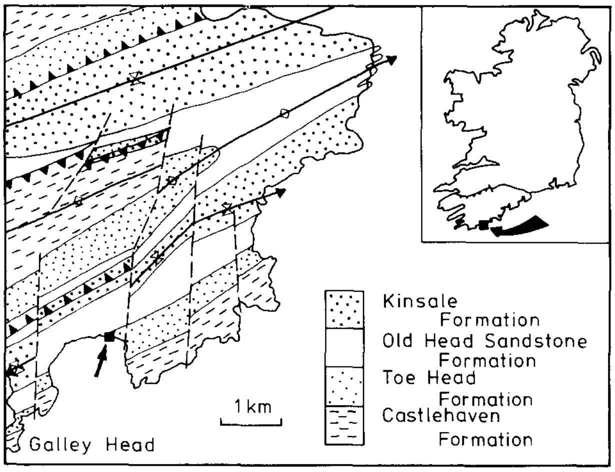



Fig. 1. Map of the geology of the Galley Head area, Co. Cork (the Red Strand locality arrowed) showing stratigraphic formations and major structures. The tight variably plunging folds are cut by both forethrusts and backthrusts. The inset map shows the location of the area within the Variscan orogenic belt, the northern margin of which is indicated.

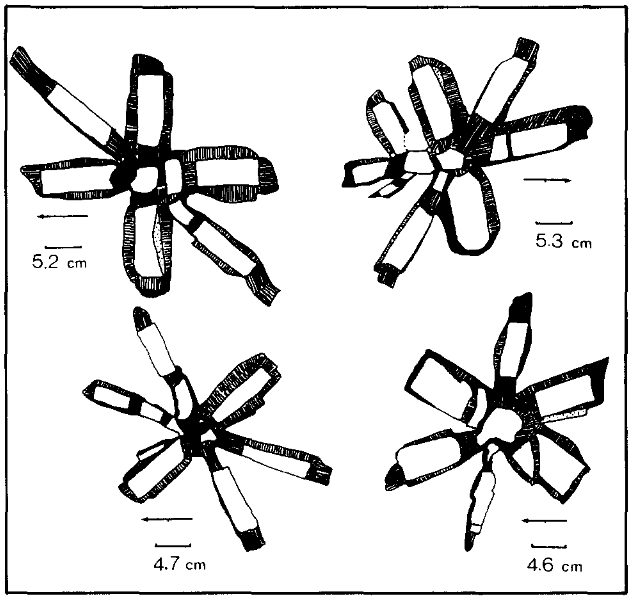



Fig. 2. Four arsenopyrite rosettes as found on the cleavage planes of a mudstone unit at Red Strand, Galley head, showing fragments surrounded by quartz fibres generally at right angles to the crystal faces. The stippled areas represent steeply dipping faces of crystals or of surrounding wall rock. The orientation of each crystal on the cleavage is shown by a cleavage strike arrow pointing 070°, with a downdip tick.

ENE–WSW to E–W. A strong axial-planar cleavage is developed throughout the region. A balanced N–S section (Hossack 1979) for west Cork was constructed by simultaneously drawing a palinspastic restoration using the procedure of Elliott & Johnson (1980). All folds are assumed to be underlain by a décollement surface and the deformation is assumed to be plane strain. The section was balanced by preserving both bed length and area in the plane of section. By comparing the lengths of the deformed and restored sections a 46% shortening across the Variscan belt was estimated (Cooper *et al.* in press). The Red Strand locality is on the southern limb of a tight upright syncline cut by a backthrust (Fig. 1). Cleavage and bedding have the same strike of 070°; the cleavage is vertical and bedding dips 80°N. The cleavage is the dominant fabric in the rock and the arsenopyrite crystals are exposed on cleavage planes along which the rock breaks. By observing sections cut perpendicular to the cleavage we conclude that the crystals grew parallel to bedding planes and were then rotated passively with the bedding by pre-cleavage folding. Judging by the paucity of curved fibres (some of which can be seen in Fig. 2), the crystals deformed in (or very close to) the plane of cleavage during cleavage development. The crystals have responded to deformation by extension fracture and fragment separation, the fractures often following the *c* (001) cleavage or *e* (101) twin plane. Although the arsenopyrite crystals are now extensively altered to pharmacosiderite (Dr. J. Preston, pers. comm.), crystal morphology suggests that, apart from fracture, they are undeformed and responded to deformation as ideal rigid–brittle inclusions.

## METHODS OF ESTIMATING EXTENSIONAL STRAIN

The most commonly used method for estimating extension from 'stretched' rigid inclusions (Ramsay 1967, p. 248) uses the standard engineering definition of elongation or stretch,

$$\sqrt{\lambda} = L_f/L_o, \tag{1}$$

where $L_f$ and $L_o$ are the final and original lengths, respectively (Fig. 3a). We refer to this method as the Ramsay (or *R*) method. A slight modification of this method (Ramsay 1967, p. 249; see our Fig. 3b) was evidently motivated by the need to avoid oversampling the fragment component where the measurements are restricted to a continuous subset taken from a longer train of fragments. Although not intended for use with complete fragmented inclusions, Hossain (1979) chose (without explanation) to use the method, illustrated in Fig. 3(b), in his analysis of stretched belemnites in the Swiss Alps. We will refer to it as the Hossain (or *H*) method. These two methods do not estimate the matrix strain but only that of an embedded rigid inclusion.

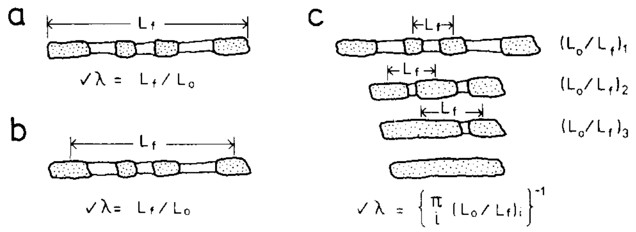
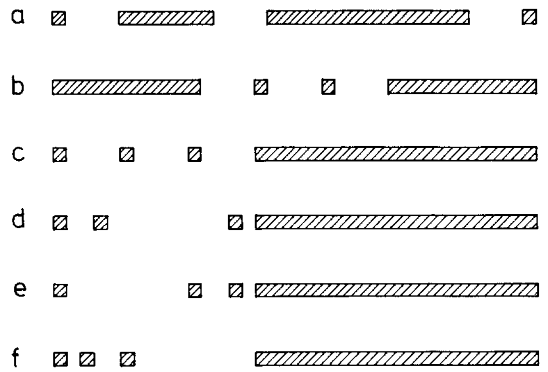



Fig. 3. Methods of calculating stretch using boudinaged rigid inclusions. (a) Ramsay's method; (b) Hossain's method (in both these methods $L_o = L_f - \Sigma g$, where $\Sigma g$ is the sum of the interfragment gap lengths; (c) Ferguson's method where initially the gap requiring the smallest closure strain is selected (this need not be the smallest gap). This first incremental shortening $(L_o/L_f)_1$, is then applied to all segments, thus closing the selected gap and reducing all others. The procedure is repeated until all gaps are closed, and the stretch calculated as shown.




extension estimates (%)

| | Hossain | Ferguson |
|---|---|---|
| a | 52·2 | 58·0 |
| b | 92·3 | 94·4 |
| c | 92·3 | 95·7 |
| d | 92·3 | 96·0 |
| e | 92·3 | 98·6 |
| f | 92·3 | 92·8 |

Fig. 4. History dependence of methods. The fragment trains *a–f* all correspond to a Ramsay extension of 50%; that is $L_f/L_o = 1.5$ ($L_f$ and $L_o$ defined as in Fig. 3a). Hossain-method estimates vary depending only on the sum of the end-of-line fragment lengths; hence *b–f* all yield the same extension. Ferguson's method is sensitive to the full length distributions of fragments and gaps (and their order) and hence yields different extension estimates for all six fragment trains.

A third approach (Ferguson 1981) differs fundamentally from those above. It explicitly recognizes that the object of extension analysis using rigid inclusions is not to record the change in length of the inclusion but to estimate the extension that an identical element in the matrix would have suffered had the inclusion not been there. The method is motivated by the following considerations. Until the first fracture appears a rigid elongate inclusion is unable to record any of the far-field extension suffered by the matrix. Consequently the matrix close to the inclusion must deform inhomogeneously to accommodate the extension which the matrix would have suffered had the inclusion not been there. Similarly, once a single cross-fracture appears, the far-field extension will now be accommodated partly by the separation of the two fragments but also by a continuing inhomogeneous matrix strain. Ferguson's method recognizes that the gaps of a fragmented rigid inclusion record only part of the far-field extension. The method is based on successively closing interfragment gaps until the original inclusion is restored. A full discussion and computer program are given in Ferguson (1981), although in the present study, we have used a computationally much faster algorithm (see Ferguson & Lloyd 1984). The approach is summarized in Fig. 3(c) and we will call this the *F* method.

An important point in comparing the methods outlined above is that Ramsay's method is insensitive to the distributions of fragment and gap lengths which, in turn, are related to the location and timing of fractures within the overall stretch history. Hossain's method is only partially sensitive to the deformation history because the calculated extension depends on the location of those fractures defining the end-of-line fragments. In contrast Ferguson's method is sensitive to the full distribution of fragment and gap lengths and their sequence (that is, to the entire extensional history). This point is made in Fig. 4 and can be made even more forcibly using computer simulations of different stretch histories, all of which lead to the same $L_f/L_o$ value (as defined in Ramsay's method). An example is shown in Fig. 5 and illustrates that extensions calculated by the *H* and *F* methods can be substantially higher than those calculated from the same data using Ramsay's method. It should be pointed out that these curves show the maximum possible variance in $\sqrt{\lambda_F}$ and $\sqrt{\lambda_H}$ for a Ramsay-method stretch of 1.5. The location and timing of fractures in natural pull-apart structures usually will lead to much smaller

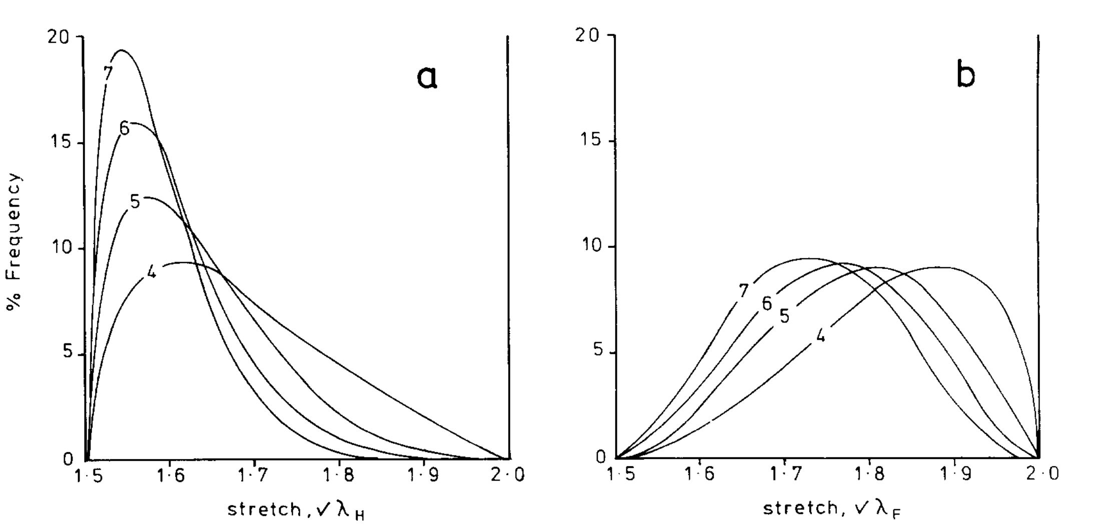



Fig. 5. Stretch distributions of simulated fragment trains calculated by the methods of Hossain (a) and Ferguson (b). Each curve represents the distribution of 10,000 stretches calculated from fragment trains similar to those in Fig. 4 except that both fragment and gap length distributions are random; the only constraint is that $L_f/L_o = 1.5$ (again, as in Fig. 4) so that the Ramsay-method stretch is constant throughout the 40,000 simulations. The different distributions shown represent different numbers of fragments in each train, as labelled on the curves.

variances although the mean stretch, in most cases, will still be substantially larger than the Ramsay stretch. Nevertheless the curves clearly illustrate that the Ramsay approximation gets progressively worse as the number of fragments in a train decreases. They also show that Hossain's method approaches the Ramsay lower bound rather rapidly as the number of fractures increases; this is because its history sensitivity is confined to the end-of-line fragments, which comprise an insignificant fraction of the total length when the number of fragments becomes large. In contrast, Ferguson's method progressively recovers the earlier stages of the pull-apart history and incorporates an estimate of the cryptic (inhomogeneous matrix) strain at each stage. One of us, Ferguson, is further investigating the effect of various parameters on extension calculations by the methods described here using computer simulations.

In general stretches calculated by the three methods ($R$, $H$ and $F$) are related by the inequalities,

$$\sqrt{\lambda_R} < \sqrt{\lambda_H} < \sqrt{\lambda_F}. \qquad (2)$$

While the $F$ method always yields the largest stretch estimate, model boudinage experiments suggest that it still underestimates the far-field strain (Ferguson 1981) even when cross-fractures are already present at the onset of deformation.

*Modifications for terminal extension zones*

We are unaware of any previous attempts to calculate stretches using complete fragmented inclusions with terminal extension zones. Clearly, some modification to the methods described above is called for. We propose that Ramsay's method can be modified very simply by defining the final length as in Fig. 6(a). In effect equation (1) then represents the estimated stretch not of the inclusion but of a line segment joining the two points in the matrix initially in contact with the ends of the inclusion. Of course this method (here called the $R'$ method) yields a larger extension estimate than the $R$ method although it is still history insensitive. Hossain's method does not lend itself to a similar modification although one can argue (by analogy with the $F$ method) that 'extra' (inhomogeneous matrix) strain associated with end-of-line fragments is already incorporated in the stretch calculation.

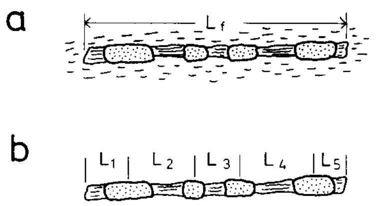



Fig. 6. (a) modified Ramsay ($R'$) method; (b) modified Ferguson ($F'$) method for calculating stretch from boudinaged rigid inclusions with terminal extension zones. In (a) $L_f$ is defined as shown and $L_o$ is the sum of the fragment lengths; stretch is calculated using eq. (1). In (b) the subsystem (L1, L2, L3, L4 or L5) requiring the smallest incremental shortening for closure is selected, and this shortening applied to each subsystem. The procedure is repeated until all vein material (gaps and terminal extension zones) is eliminated (cf. $F$ method, Fig. 3c).

We have modified the $F$ method by assuming notional fragments of zero length at the distal end of each terminal extension zone (Fig. 6b). The effect of this modification (here called the $F'$ method) is that, if a terminal extension zone develops after the first fracture, the $F$ and $F'$ methods will give identical results. This equivalence can be demonstrated formally (although the algebra is tedious) and is entirely consistent with the mechanical considerations outlined in Ferguson (1981). In short Ferguson's method implicitly accounts for extra strain at the extremities of the inclusion whereas the $F'$ method does so explicitly. However, when the matrix pulls away from the end (or ends) of an inclusion before cross-fractures occur, the $F'$ method yields a stretch estimate larger than the $F$ method by an amount proportional to the pre-fracture component of the terminal extension zone.

This modification emphasizes an important general principle for interpreting pull-apart structures, that the far-field extension cannot be judged, even in a relative sense, from the amount of vein material added. For example, although Fig. 7(b) has 87% greater length of 'added' vein material, the two stretched inclusions illustrated in Fig. 7 correspond to identical far-field extensions calculated by Ferguson's method.

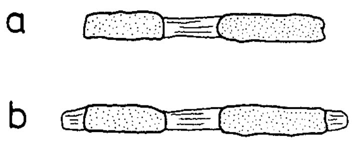



Fig. 7. The $F$ method stretch for *a* is identical to the $F'$ method stretch for *b*. If Ferguson's method is substantially correct, this implies that the terminal extension zones in *b* began to develop after inclusion fracture, and that far-field stretch is the same in both *a* and *b*.

## EXTENSION ANALYSIS OF ARSENOPYRITE ROSETTES

Application of all the above methods is illustrated using 26 arsenopyrite rosettes (78 extended laths). These were collected, keeping all samples oriented, by splitting the rock along cleavage. The rosettes were photographed using extension tubes. The outline of each crystal was clearly drawn on these photographs while observing the actual crystal under a binocular microscope. Examples of the final crystal images from which the measurements were taken are shown in Fig. 2.

Each rosette has three extended laths and can therefore define a strain ellipse. Any three non-contiguous crystal laths could also be used assuming strain homogeneity over a larger area. Although we recognize that the 'contact' stress field close to a rosette is more complex than that close to a single crystal, we treat the three components of the rosette as separate crystals and include the central fragment in each fragment train.

Comparing the stretches calculated for the 78 crystal laths by each of the five methods it is found that, in all cases

$$\lambda_R < \lambda_H < \lambda_F \leq \lambda_{F'}.$$

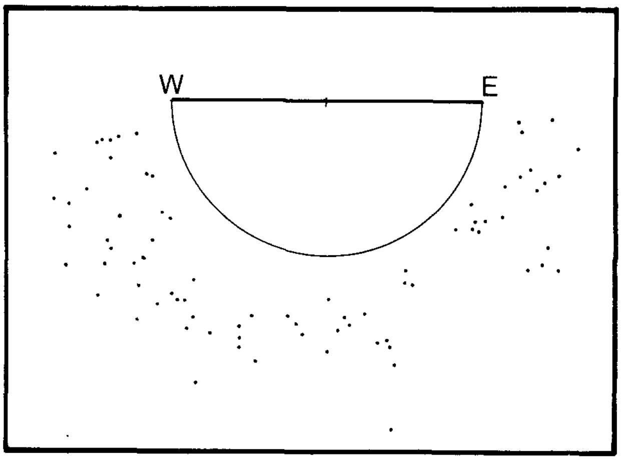



Fig. 8. Pitch and extension of 78 boudinaged arsenopyrite crystals, from the Red Strand locality (Fig. 1), on cleavage. E–W is the strike of cleavage defining the diameter of an undeformed unit circle.

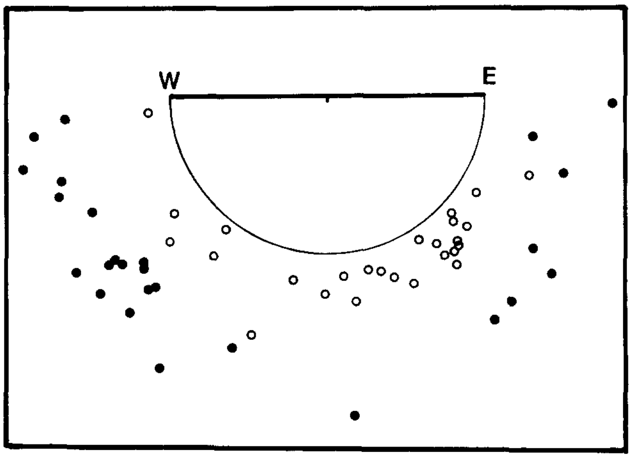



Fig. 9. Pitch and extension of the two principal axes of the 26 cleavage-strain ellipses calculated using the method described in Sanderson (1977).

Most $\lambda_{R'}$ results are closer to $\lambda_F$ than $\lambda_H$ but some are less.

The mean value for the 78 extensions is 50% by the $F'$ method (see Fig. 8), 44.5% by the $R'$ method, 43% by the $F$ method, 40% by the $H$ method and 24% by the $R$ method. The extension values by the $F'$ method are equal to the results of the $F$ method for 30% of the crystals. The terminal extension zones of these samples developed after the first fracture across the inclusion and therefore did not contribute to the overall extension. Both the $H$ method and $R'$ method give results reasonably close to those of the $F'$ method. These two methods are of more practical use in the field since data can be collected more rapidly and no subsequent computer processing is needed. The $H$ method is generally to be preferred because it performs well (relative to the $F$ and $F'$ methods) whether or not terminal extension zones are present.

## ESTIMATION OF CLEAVAGE-STRAIN ELLIPSOID

Three non-colinear stretches within a plane are needed to define a strain ellipse if the orientations of the principal axes of the ellipse are unknown. The observed interlimb angles of the arsenopyrite rosettes often differ from the 60° expected in ideal trillings. However, the laths appear not to have rotated relative to each other during deformation because we have observed neither curved fibres nor en échelon offsets between fragments. Also, the quartz fibres occupying zones where matrix has pulled away from the arsenopyrite laths are almost always normal to the lath margins (Fig. 2), irrespective of orientation. These observations, which are supported by the absence of a stretching lineation on the cleavage planes, imply that the within-cleavage stretches must have been roughly equal in all directions ($\sqrt{\lambda_1} \simeq \sqrt{\lambda_2}$). In the plane perpendicular to cleavage, pressure-solution seams occur against the arsenopyrite crystals, supporting a compressional strain for cleavage formation.

The results of our stretch calculations with the $F'$ method, and the strain ellipses derived using the methods of Sanderson (1977) (which are algebraic equivalents of the familiar Mohr circle constructions), are shown in Figs. 8 and 9. The strain ellipses have been calculated assuming that the original interlath angles are those now observed, and also assuming 60° angles, but for these data the results are very close. Because arsenopyrite rosettes present the awkward additional problem that the calculated stretches underestimate the true stretches by an unknown amount that depends on the timing of the initial fracture and/or matrix detachment, we have checked our solutions using a numerical method. In this the three stretch estimates from a rosette are each represented as a vector ($r$, $\theta$) with respect to some hypothetical maximum stretch direction, $\phi$. The ellipse of minimum area containing the three vectors is computed for this $\phi$, and the global minimum area found by systematic search over all possible $\phi$ values. The ellipses so calculated are only slightly larger than those derived by Sanderson's (1977) method but we have presented results based only on the more conservative (and more familiar) procedure (Fig. 9). Because the calculated principal stretches are minimum estimates of actual rather than relative stretches, they permit lower bound estimates of area increase in the plane of cleavage. These range from 77 to 157% with an average of 114%. Thus, if volume is assumed to be conserved, the shortening across the cleavage can be estimated as 44–61% with an average of 53%. Nevertheless it is important to emphasize that, because the arsenopyrite laths record no cleavage strain at all until the first fracture or matrix detachment occurs, many of the calculated stretches are probably much smaller than the true stretches and will be a poor guide to the bulk strain. Beach (1979) made this point forcibly in his study of stretched belemnites and argued that, on a plot of stretch against orientation, the strain ellipse should be estimated from the envelope bounding the data points. In short, he argued that only the belemnites recording the largest stretch in any given direction should be used to define the strain ellipse. Viewed in this light the strain

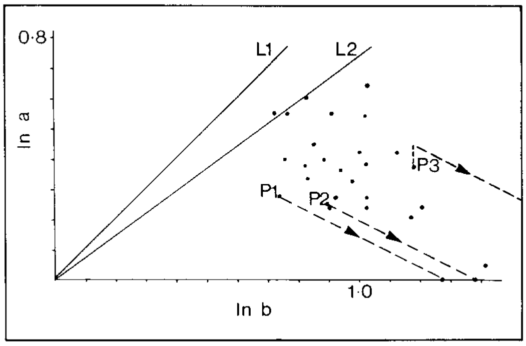



Fig. 10. Logarithmic Flinn plot ($a = \sqrt{\lambda_1/\lambda_2}$, $b = \sqrt{\lambda_2/\lambda_3}$) showing strain ellipsoid shapes derived from data shown in Fig. 8 as described in the text, assuming no volume loss (so that $\sqrt{\lambda_3} = 1/\sqrt{\lambda_1\lambda_2}$). The effect of increasing $\sqrt{\lambda_2}$ to approach the estimated $\sqrt{\lambda_1}$ value is shown for only two ellipsoids, P1 and P2, by the dashed line paths. Since $\sqrt{\lambda_1}$ may be an underestimate, a shift to a larger ln $a$ should precede the displacement towards the $k = 0$ axis. This procedure is followed for one ellipsoid, P3. In addition to the constant volume $k = 1$ line (L1), the $k = 1$ line assuming 3% volume loss per 10% shortening is shown (L2).

implications of our data (Fig. 9) are very different from those outlined above. Note that the largest principal stretch calculated (2.14) is almost vertical (pitch 085° measured east in the vertical cleavage) but ten of the 26 ellipse calculations yield $\sqrt{\lambda_1} > 1.8$ and their pitches range from 001° to 172°. These data strongly support the evidence discussed earlier for a $k \simeq 0$ strain ellipsoid and, bearing in mind that all the calculated stretches are lower bound estimates, $\sqrt{\lambda_1} \simeq \sqrt{\lambda_2} \simeq 2.0$ seems a reasonable estimate. This implies an area increase in the cleavage plane of some 300% and, assuming constant volume, a 75% shortening across the cleavage.

It is instructive to display these implications on a Flinn plot. The calculated strain ellipsoids (Fig. 10) are all oblate and fall within the deformation field of slates from other areas (Ramsay & Wood 1973, fig. 8). Some volume loss is suggested by the deposition of mobilized quartz in the extension zones associated with the arsenopyrite crystals. However, in thin section the slate matrix, composed mainly of very fine grained phyllosilicates with some quartz, exhibits a continuous rather than domainal cleavage with pressure solution seams visible only adjacent to the arsenopyrite crystals. Thus the syntectonic volume loss from the matrix was probably small (say, no more than 15 or 20%) and occurred under very low grade metamorphic conditions. Assuming progressive volume loss during cleavage formation, with about 3% incremental volume loss per 10% incremental shortening, the $k = 1$ line would shift to position L2 on Fig. 10; except for one, all ellipsoids lie in the oblate field. However, in view of the evidence for $\lambda_1 \simeq \lambda_2$ we suggest that the *calculated* cleavage-strain ellipsoids should be displayed on the Flinn plot as indicated by the dashed lines shown in Fig. 10 for two ellipsoids (P1 and P2). Indeed, because calculated values are also lower bound estimates, for many of the ellipsoids a significant (though probably small) shift to a larger $(\lambda_1/\lambda_2)^{1/2}$ value should precede the displacement towards the $k = 0$ axis (e.g. Fig. 10, P3 ellipsoid). In short, it seems that the calculated ellipsoids substantially underestimate both the intensity and the oblateness of the slate deformation.

## CONCLUSIONS

Two-dimensional strain gauges that record extension of the surrounding matrix by fracture and fragment separation enable estimates to be made of actual rather than relative stretches. Therefore they can be used to estimate the shape of the deformation ellipsoid, if volume loss is assumed to be negligible. The stretches calculated from arsenopyrite rosettes in this study are lower-bound estimates of the true stretches. The areas of the derived strain ellipses in the plane of cleavage are therefore minimum estimates, as are the estimated shortenings across the cleavage (average value 53%). Several lines of evidence noted in the preceding section suggest that the true cleavage-strain ellipsoids are probably more oblate than those shown in Fig. 10; better estimates of the shortening across the cleavage may be closer to 75%.

The material lost by the stretching, which occurs in all directions in the cleavage plane of this mudstone unit, must be accommodated elsewhere in the geological framework. The mudstone, interbedded with more competent sandstone units, may be simply thinned out in the vertical plane on the limb of the regional anticline. Detachment surfaces with slickensides are found between sandstone and mudstone units in the area. Mudstone units also thicken in the axial zones of minor folds exposed on coastal sections indicating that this style of folding is typical of the area. However an 80% extension along-strike cannot be successfully explained by this mechanism alone. The arsenopyrite locality is in a zone of culminating fold axes where one would expect to find strike-parallel extension. It could be argued that the observed thinning is accommodated locally by thickening of the mudstone unit along strike, perhaps by lateral imbrication in fold-hinge depressions. Such zones of thickening have not been observed, but the unit cannot be followed for great distances along strike. The surrounding sandstones show a weaker pressure solution cleavage, and limited strike-parallel extension is accommodated along conjugate sets of minor faults and tension gash arrays. Therefore the along-strike extensional strain in the sandstones does not appear to be compatible with that in the mudstone unit, so that the excessive extensions may be confined to the mudstone unit in which it has been measured. Recently, strain heterogeneity on a smaller scale has been measured (Borradaile & Tarling 1984) in Archaean clastic metasediments (greenschist facies) whose component pebbles and quartz and feldspar grains record differing strains according to their rheologies. These strain differences are accommodated in the rock by particulate flow. Dalradian sandstones in Scotland, however, are known to have suffered large deformation without developing obvious tectonic fabrics (unpublished work of B. Freeman; see also Borradaile 1979, 1981) and thus we cannot dismiss the possibility of substantial ductile strike elongation in the sandstones. The strike-parallel extension may therefore be of regional significance, and this suggests that current estimates of regional contraction may need to be revised. Based on across-strike balanced sections (Hossack 1979), assuming plane strain in the plane of section, orogenic contraction across the Variscides in West Cork is estimated at 46% (Cooper *et al.* in press). Neglecting volume loss, our analysis indicates area reduction in the section plane of some 50%, or 44% if we use a conservative within-cleavage strain ellipse with $\sqrt{\lambda_1} \simeq \sqrt{\lambda_2} \simeq 1.8$ (see also fig. 5 in Hossack 1979). As suggested in Hossack (1979), a 10% strike elongation causing a 10% area reduction in geological cross-sections may be more typical for the margins of orogenic belts. The assumption that a 10% strike elongation occurred in the Irish Variscides increases the estimated shortening from 46 to 50% in west Cork. As indicated above, the strike elongation is probably much higher; so there is clearly a need to develop tectonic models that can accommodate large strike extensions, and additional strain analyses are urgently needed to help constrain them.

*Acknowledgements*—We wish to thank Dr. J. Preston of Queen's University, Belfast for initially identifying the arsenopyrite crystals and their alteration products by XRD methods and providing helpful suggestions as to their origin. The identification was confirmed by Dr. R. Nawaz of the Ulster Museum which is also gratefully acknowledged. Our thanks particularly go to Dr. Mark Cooper for his help and encouragement, and for providing valuable discussion along with others in the Cork Geology Department during the writing of this paper. We wish to thank our referees for their useful discussion, which has improved the text. M. Ford acknowledges receipt of a Senior Demonstratorship from University College Cork.

## REFERENCES

Badoux, H. 1963. Les belemnites tronconées de Leytron (Valais). *Bull. Lab. Géol., Mineral. Géophys. Musée Géol. Univ. Lausanne* **138**, 1–7.

Beach, A. 1979. The analysis of deformed belemnites. *J. Struct. Geol.* **1**, 127–135.

Borradaile, G. J. 1979. Strain study of the Caledonides in the Islay region, SW Scotland: implications for strain histories and deformation mechanisms in greenschists. *J. geol. Soc. Lond.* **136**, 77–88.

Borradaile, G. J. 1981. Particulate flow of rocks and the formation of cleavage. *Tectonophysics* **72**, 305–321.

Borradaile, G. J. & Tarling, D. 1984. Strain partitioning and magnetic fabrics in particulate flow. *Can. J. Earth Sci.* **21**, 694–697.

Cooper, M. A., Collins, D., Ford, M., Murphy, F. X. & Trayner, P. M. in press. Structural style, shortening estimates and the thrust front of the Irish Variscides. In: *Variscan Tectonics of the North Atlantic Region* (edited by Hutton, D. H. W. & Sanderson, D. J.). *Spec. Publs geol. Soc. Lond.* **14**, 167–175.

Daubrée, M. 1876. Experiences sur la schistosité des roches et sur les déformations des fossiles etc. *Bull. Serv. Carte. géol. Fr.* 3 *Ser.*, t. iv.

Elliott, D. & Johnson, M. R. W. 1980. Structural evolution in the northern part of the Moine thrust belt, N.W. Scotland. *Trans. R. Soc. Edinb.* **71**, 69–96.

Ferguson, C. C. 1981. A strain reversal method for estimating extension from fragmented rigid inclusions. *Tectonophysics* **79**, T43–52.

Ferguson, C. C. & Lloyd, G. E. 1982. Paleostress and strain estimates from boudinage structure and their bearing on the evolution of a major Variscan fold-thrust complex in south-west England. In: *Strain in Thrust Belts* (edited by Williams, G. D.). *Tectonophysics* **88**, 269–289.

Ferguson, C. C. & Lloyd, G. E. 1984. Extension analysis of stretched belemnites: a comparison of methods. *Tectonophysics* **101**, 196–206.

Freeman, B. 1982. Quartzite deformation mechanisms and deformation mechanism histories. *Mitt. Geol. Inst. ETH Zurich, Neue Folge* **239a**, 103–105.

Heim, A. 1919. Undersuchungen uber den mechanismus der Gebirgsbilung. In: *Geologie der Schweiz*. Tauchwitz, Leipzig.

Hossack, J. R. 1979. The use of balanced sections in the calculation of orogenic contraction: a review. *J. geol. Soc. Lond.* **136**, 705–711.

Hossain, K. M. 1979. Determination of strain from stretched belemnites. *Tectonophysics* **60**, 279–288.

Lloyd, G. E., Ferguson, C. C. & Reading, K. 1982. A stress-transfer model for the development of extension fracture boudinage. *J. Struct. Geol.* **4**, 355–372.

Mitra, S. 1976. A quantitative study of deformation mechanisms and finite strains in quartzite. *Contr. Miner. Petrol.* **59**, 203–226.

Naylor, D., Sevastopulo, G. D., Sleeman, A. G. & Reilly, T. A. 1981. The Variscan Fold Belt in Ireland. In: *The Variscan Orogen in Europe* (edited by Zwart, H. J. & Dornsiepen, U. F.). *Geologie Mijnb.* **60**, 49–66.

Palache, C., Berman, H. & Frondel, C. 1944. *The System of Mineralogy of James Dwight Dana and Edward Salisbury Dana.* 7th Ed. Wiley, New York.

Ramsay, J. G. 1967. *Folding and Fracturing of Rocks*. McGraw-Hill, New York.

Ramsay, J. G. & Wood, D. S. 1973. The geometric effects of volume change during deformation processes. *Tectonophysics* **16**, 263–277.

Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern Structural Geology. Volume 1: Strain Analysis*. Academic Press, London.

Sanderson, D. J. 1977. The algebraic evaluation of two-dimensional finite strain rosettes. *Math. Geol.* **9**, 483–496.

Sanderson, D. J. & Meneilly, A. W. 1981. Analysis of three-dimensional strain modified uniform distributions: andalusite fabrics from a granite aureole. *J. Struct. Geol.* **3**, 109–116.