Journal of Structural Geology, Vol. 2, No. 1/2, pp. 111 to 117.
Pergamon Press Ltd. 1980. Printed in Great Britain.

0191-8141/80/0601-0111 $02.00/0

Strain profile of a boundary within a large ductile shear zone

J. GROCOTT

Geologisch Instituut, Universiteit van Amsterdam, Nieuwe Prinsengracht 130, 1018 VZ Amsterdam, The Netherlands

and

J. WATTERSON

Geology Department, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, England

(*Received* 17 *May* 1979; *accepted in revised form* 27 *October* 1979)

Abstract—A 13 km continuous strain profile across an internal boundary of the Ikertôq shear belt is presented. Rocks were classified according to strain intensity, five levels of intensity being recognised on the basis of field criteria. The shear strain for each level has been estimated from a plot of fold inter-limb angle against shear strain. The shear strain coordinate for each fold is determined from a knowledge of the plunge, and of the initial plunge to within 20°.

The data plotted in this way have a form similar to theoretical curves which relate variation in inter-limb angle to strain, assuming passive differential rotation of fold limbs. An appropriate theoretical curve is selected, by comparison with the plot of field data, to calibrate the strain profile.

The total transcurrent displacement within the profile section is estimated as 47.6 km. Some significant differences between large and small scale shear zones are reviewed.

INTRODUCTION

LARGE scale shear zones have been studied mainly from the point of view of their significance in Precambrian history and tectonics. Future work is likely to emphasise their significance in two other respects: (i) as the tectonically deeper expression of major faults and thrusts, both intraplate and interplate, as an improved knowledge of both the geometry and mechanics of shear zones is necessary for the reconstruction of vertical sections through major displacement zones; (ii) as the products of large scale ductile deformation processes at amphibolite and granulite facies. Advances in both these fields require a knowledge of strain profiles across shear zones and of the progressive development of strain profiles from the time of initiation. In some respects small shear zones, which are much more easily studied, can provide information directly applicable to the larger examples. In respect of strain profiles however, there appear to be recurrent and systematic differences between shear zones on different scales. Boundary regions, where strain gradients are particularly steep, occupy a decreasingly smaller proportion of the width of shear zones as their overall width increases. A further difference is that small shear zones characteristically have simple strain profiles, the regularity of which suggests that they are the products of a single displacement event, albeit one which took a long time to complete. Small shear zones with profiles of the type illustrated by Ramsay & Graham (1970) and Watterson (1979) could develop, although they have not necessarily done so, with a constant strain rate profile. The largest shear zone which we know to be of this type is less than 1 km wide. Larger shear zones characteristically have complex profiles which suggest that the strain rate profile varied with time. The problem is complicated by the fact that the present outcrops of large shear zones appear to record displacements which took place at different tectonic levels, and to this extent their greater complexity is the result of a longer history rather than a feature of rheological or mechanical significance. It may be that the complexities due to a longer displacement history obscure original profiles of a simplicity comparable to that of smaller shear zones.

With these problems in mind we have attempted to measure the strain profile across the boundary of a large shear zone.

METHODS OF INVESTIGATION

Strain profiles in small shear zones can be constructed from strain values determined from the angle between the shear zone boundary and the XY plane of the shape fabric (Ramsay & Graham 1970), but only in rocks which had either an isotropic or a known shape fabric before the shear zone formed. Alternatively the change in attitude of lithological banding passing through a shear zone can be used. Neither of these methods can be used in large shear zones: not only is the orientation of the shear zone boundary difficult to determine with sufficient precision, but the progressively smaller angles between fabric and boundary cannot be determined with sufficient accuracy when they are hundreds or thousands of metres apart. None of the large shear zones known to us has lithological banding sufficiently persistent for this to be of use in strain determination.

Methods which have been used to determine large scale shear strains include the reorientation of regional dyke swarms (Escher *et al.* 1975) and the statistical realignment of fold axial planes and axes (Bak *et al.* 1975). Neither of these methods is appropriate to continuous strain profiling, and each requires some special circumstances rather than being of general application. Analyses of vein orientations and behaviour can be used in some circumstances but cannot be applied generally. The only methods we know of which could be used in our study are based on (i) interlimb angles of folds and (ii) direct measurement of strains from shape fabrics in suitable rocks. Both these methods have been used in Ikertôq and the results of the fold measurement method are reported here. Some method based on random particle distribution, such as the dvα method of Ramsay (1967), might be made practicable in due course. In addition to a method for measuring strain this work also requires a suitably exposed shear zone: although not ideal in many respects the Ikertôq shear belt was chosen for logistical reasons.

The early Proterozoic Ikertôq shear belt (Fig. 1, inset) is an approximately 45 km wide zone of mainly transcurrent dextral displacement (Watterson 1975, Bak *et al.* 1976), striking E–W and at a high angle to the outer coastline of West Greenland. Although extending 150 km from the Labrador Sea to the Inland Ice the shear zone is not known in any detail further than about 40 km from the outer coast, this distance corresponding to the length of the longest of the several fjords which are subparallel to its strike. Neither of the external boundaries is suitable for work aimed at constructing a continuous strain profile. The northern boundary region is overprinted by large scale ductile overthrusting deformation (Grocott 1979) which post-dates the transcurrent displacement. The southern boundary is incompletely exposed due to the presence of Itivdleq Fjord. Within the coastal region however, augen of less deformed rocks occur on all scales within the highly deformed rocks of the shear belt. The largest of these, the Kingaq augen, is about 10 km wide, its central part is only slightly deformed, and the rocks are similar in appearance to those outside the shear belt. The transition from the Kingaq augen southwards into the highly deformed

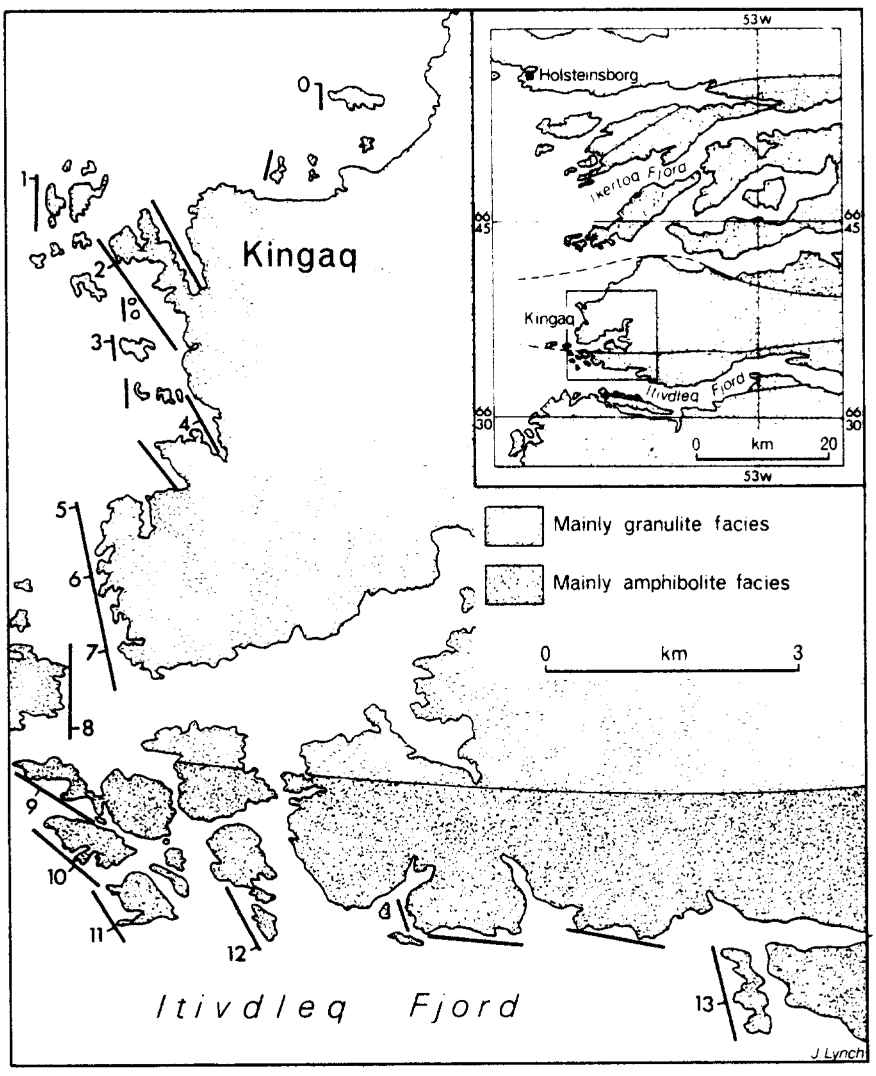

Fig. 1. The Ikertôq shear belt as defined by facies boundaries (inset) and the traverse area showing traverse lines with distances along the section shown in km.

rocks of the shear belt in Itivdleq Fjord is sufficiently well exposed, on the mainland and on the islands of the archipelago in the vicinity of Itivdleq settlement, for an almost complete section to be examined on coastal outcrop, of an internal boundary of the shear belt. It is probable that the strain profile across an internal boundary of this type will be unlike that of an external boundary because of the strain concentration which is likely to occur adjacent to the augen; this qualification should be borne in mind when the significance of the strain profile is considered.

Method

A traverse was made (see Fig. 1) of coastal outcrops giving almost complete cover of a composite section extending 13 km normal to the strike of the shear zone fabric. The rocks were classified according to the degree of deformation in the commonest rock composition; that is tonalitic gneiss. Changes were mapped on the smallest scale which could be recorded on a 1 : 20 000 map; that is zones less than 20 m wide were recorded but not represented on the map, although some of the more important ones are represented in the profile (Fig. 2). Five classes of deformation intensity were recognised and defined as follows.

Class 5 (very low deformation): Only the planar *mineral* fabrics relate to the shear zone deformation. Shape fabrics are almost entirely the product of pre-shear zone strain (i.e. Archaean). Few folds of shear zone age occur. The rocks are of granulite facies.

Class 4 (low deformation): Banding and fabrics are commonly at high angles to one another. The shape fabrics are significantly modified by the shear zone deformation. Pre-shear minor folds are easily distinguished, and form small scale interference patterns with folds of shear zone age. The rocks commonly retain a granulite facies mineralogy.

Class 3 (moderate deformation): Banding and fabrics are not everywhere parallel; the shear zone component of shape fabrics is well defined and the rocks have a slab-like appearance. The rocks are of amphibolite facies.

Class 2 (high deformation): Platy, banding and fabrics are parallel except in folds. The rocks are of amphibolite facies.

Class 1 (intense deformation): Extremely platy and relatively fine grained. The rocks are of amphibolite facies.

Measurements were made of fold orientations and interlimb angles, and planar and linear elements of both shape fabric and mineral fabric (where not parallel to the shape fabric). Folds of shear zone age have axes parallel to the linear element of the shape fabric, which is a resultant fabric because of the existence of pre-shear shape fabrics.

A qualitative strain profile was constructed using the five-fold strain classification, and fold data were separated according to strain class. A simple shear model is used for reasons and with the qualifications given previously (Escher & Watterson 1974). The validity of such a model is strongly dependent on scale.

CALIBRATION OF THE QUALITATIVE STRAIN PROFILE

Fold measurements

During a progressive simple shear deformation fold inter-limb angles will change and fold axes will rotate towards the X axis of the strain ellipsoid. Within the traverse described fold axes are progressively reorientated from a steep to a gentle plunge as inter-limb angle decreases, and we are concerned with quantifying this variation. The absence of folds having gentle plunges and wide inter-limb angles suggests that opening of folds has not occurred in this case. However, in other areas initial limb orientations may be such that this possibility is realised.

In areas of low strain, steep E – W shear zone fabrics are seen to form at a high angle to the dominant N – S steeply dipping banding of the granulite facies gneisses. This banding commonly defines folds of pre-shear zone

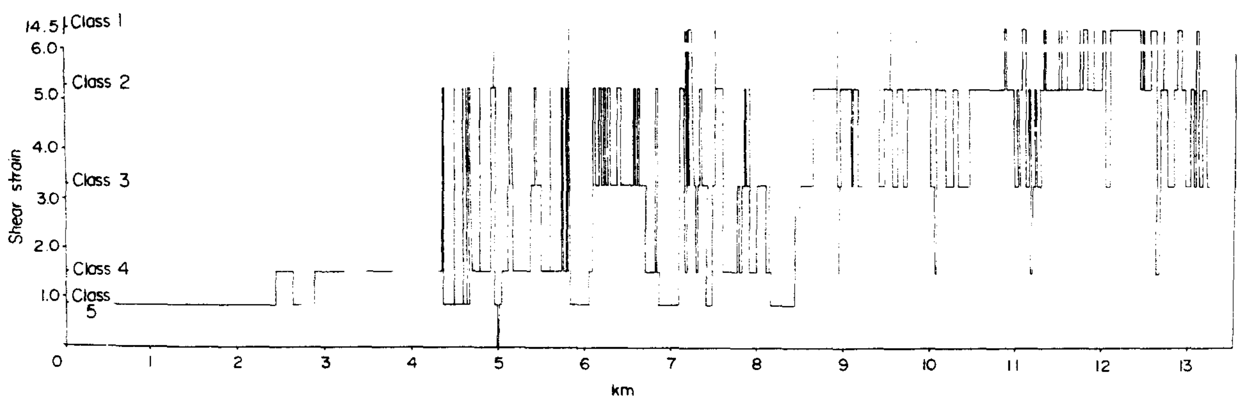

Fig. 2. Quantitative strain profile. The ordinate is calibrated using values for shear strain quoted in Table 1. The km scale refers to distance south along the profile shown on Fig. 1.

age (Archaean). Folds with axial planes parallel to the shear zone fabric, and believed to be of shear zone age, plunge steeply west parallel to the intersection between banding and shear zone fabric, and are easily distinguished from the earlier folds. The earlier folds have generally steep but variable plunges.

In areas of higher strain the two ages of folds are not distinguishable from one another as both sets have been reorientated and tightened. The reorientation and tightening of these folds suggested that a systematic relationship might be found between strain and fold orientation and tightness. Fold measurements were made with this in mind and the results are shown in Fig. 3.

Objectivity test

These data can be used to test the objectivity of the qualitative strain classification. Each observer traversed independently, noting strain intensity according to agreed criteria summarised above. Fold measurements by the two observers are shown separately in Fig. 3, and show a high degree of consistency which is expressed in

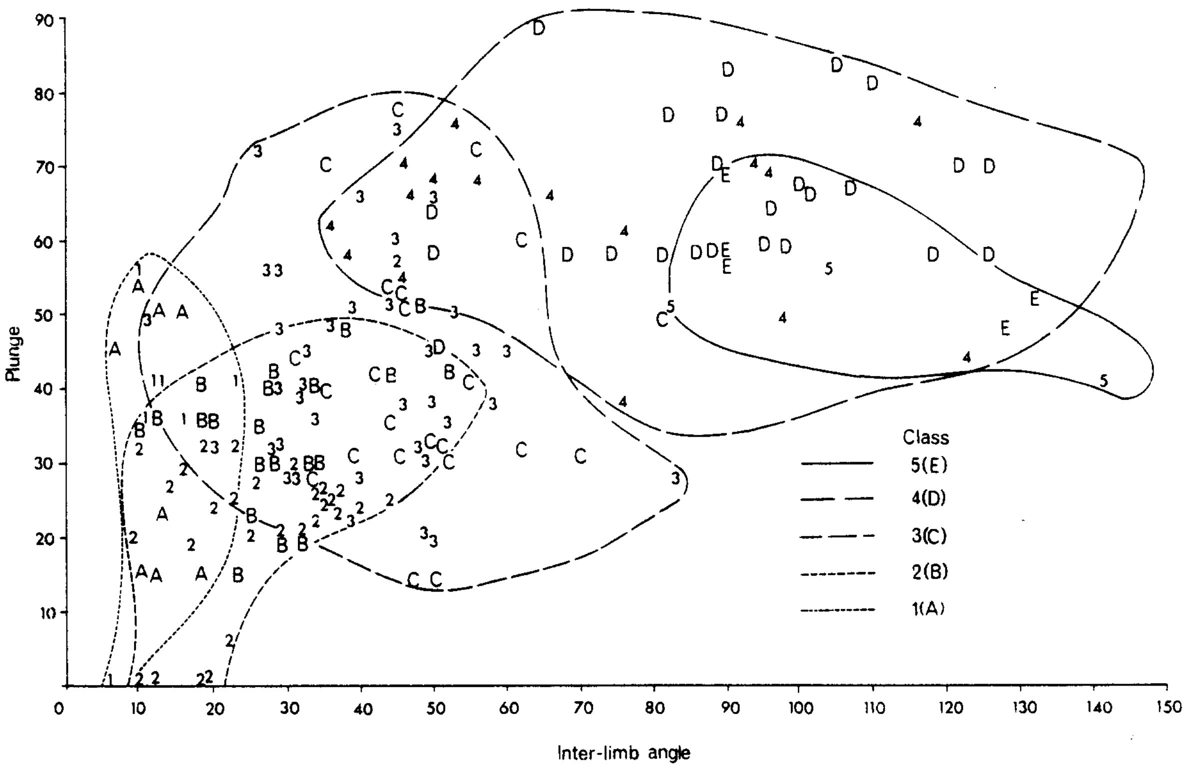

Fig. 3. Plot of fold axis plunge against inter-limb angle for 187 folds measured in the profile section. Fields occupied by folds measured in gneisses of each qualitative strain class are outlined. Folds measured by J. W. are marked by a letter, those measured by J. G. are marked by a number.

Table 1. Mean inter-limb angles of west plunging folds in each qualitative strain class.

No. OF FOLDS J.G.	J.W.	CLASS	MEAN I.L.A.	C.R.	t at P=0.01	MEAN PLUNGE	C.R.	t at P=0.01	MEAN I.L.A. ON XZ	γ (150°)
10	6	1	15.00°	1.03	2.95	9.10°	-	-	2°	14.50
25	17	2	29.00°	1.88	2.71	28.00°	3.25	2.71	15°	5.25
28	21	3	45.50°	1.92	2.71	39.70°	0.14	2.68	32°	3.30
16	24	4	86.00°	3.04	2.71	66.70°	0.22	2.71	78°	1.45
7		5	109.70°	-	-	70.00°	-	-	105°	0.85
154										

Where the critical ratio is less than the Student's t-value at $P = 0.01$ the difference between the means of data collected by each observer is not significant at this level of confidence. The numbers in the mean inter-limb angle and mean plunge columns are derived from the combined means of data from both observers. The shear strain is obtained from Fig. 4 (150° curve) using the mean values for each qualitative strain class corrected to the XZ plane using the mean value for the plunge, as described in the text.

Table 1. It is emphasised that fold measurements were made after the strain intensity had been evaluated on criteria which did not include fold characteristics.

Figure 3 shows some data points in areas of class 1 strain with higher angles of plunge than expected. These folds occur in narrow zones which have undergone a strong, later superimposed strain. The movement direction of the later deformation plunges steeply east, and the horizontal component is sinistral. Such displacements reorientate previously sub-horizontal fold axes, and impart a steeper plunge to some folds in areas of class 1 strain.

Relationship between inter-limb angles and shear strain

To relate variation in inter-limb angle to shear strain a folding model must be proposed. The model adopted is simple, and relies on the belief that passive differential rotation of fold limbs is an important agent in tightening folds in rocks deforming under upper amphibolite facies conditions. Although use of this model requires selection of an initial inter-limb angle, it is not implied that the fold generating mechanism, whether heterogeneous shear or buckling, no longer operated beyond this angle but that it had relatively little effect on the further progressive development of the folds. For the purposes of the model, it is assumed that passive differential rotation becomes dominant at one of a range of angles greater than 120°. Figure 4 shows how folds passively tighten due to differential rotation of the limbs for initial inter-limb angles in the range of 120–170°. Each curve on Fig. 4 is derived by considering the effect of simple shear deformation on folds of a particular inter-limb angle with varying orientations relative to the shear plane. All angles are referred to their projection onto the *XZ* plane of the deformation ellipsoid, and the change in angle with shear strain plotted for each initial orientation. Each curve on Fig. 4 is then a bounding line to the field containing all data points which lie above and to the right of the line. The curves therefore represent a minimum shear strain for a particular inter-limb angle. In fact most data points for folds which are tightening plot close to the boundary curves so that if the above assumption of mechanism is realistic, one of the curves on Fig. 4 should allow the strain corresponding to a particular inter-limb angle to be determined, and then used to calibrate the qualitative strain profile.

The fold inter-limb angle/plunge data have now to be presented in a way which allows comparison with these theoretical curves. This should permit a particular curve to be selected in order to calibrate the profile, and incidently provide a test of the assumption that passive differential rotation of fold limbs was the dominant fold tightening mechanism in these rocks.

Figure 5 is a stereonet showing the orientation of the measured folds. It is clear from this figure that west plunging fold axes rotate with increasing strain, towards the *X* axis of the strain ellipsoid consistent with transcurrent E – W shearing, that is horizontal E – W. It is also apparent from Fig. 5 that the initial plunge of west

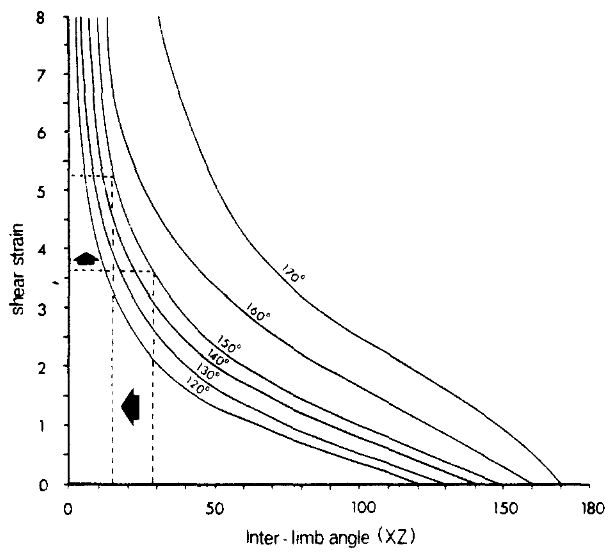

Fig. 4. Graph showing curves of minimum inter-limb angle against shear strain for folds tightened by passive differential rotation of fold limbs. Curves for initial inter-limb angles of 120°, 130°, 140°, 150°, 160°, and 170° are shown. All possible combinations of inter-limb angle and shear strain for a given initial inter-limb angle plot above the relevant curve, which thus gives a minimum shear strain for a given inter-limb angle. See text for details. As an example of how strain for each class is derived from this figure dotted lines show the derivation of shear strain for class 2 using the 150° curve. Dotted lines parallel to the ordinate show measured and *XZ* plane projected values for inter-limb angles of folds in areas of class 2 strain. Those parallel to the abscissa show corresponding uncorrected and corrected values for the shear strain (see also Table 1).

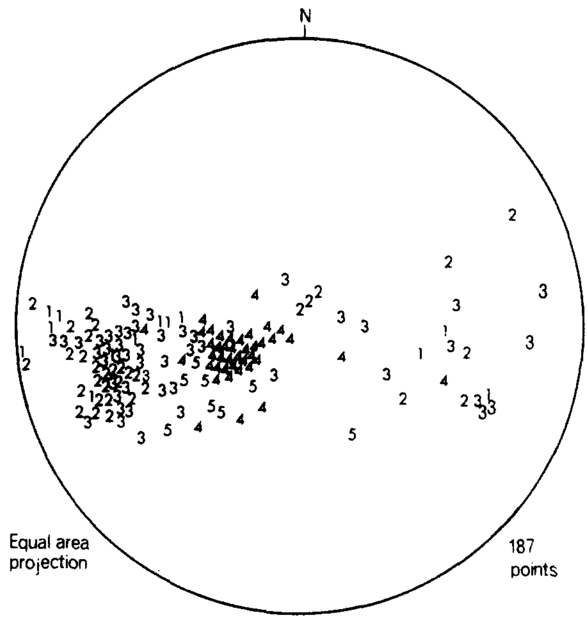

Fig. 5. Stereogram of fold axes. The strain class of gneisses in which each fold was measured is indicated by a number, 1–5.

plunging folds was between 70° and 85°: since the mean plunge of folds in areas of class 4 strain is 67° (Table 1) their original plunge must have exceeded 70°, however it is unlikely to have exceeded 85° as this would require an unreasonably high strain for class 4. Because of the clockwise change in azimuth of the *XY* plane during dextral transcurrent shear, fold axes initially parallel to the intersection of the *XY* plane and a steep west dipping banding will initially have a southwest component of plunge, which will decrease with increasing deformation. The distribution of fold axes shown in Fig. 5 is consistent with the expected progressive change in plunge direction.

Using the reasonable assumption that all west plunging folds in Fig. 5 had an original plunge between 70° and 85°, a range in shear strain can be determined for each measured fold within which must lie the actual value of shear strain undergone by the fold. The minimum and maximum values of shear strain derived from the plunge data for each fold are plotted against inter-limb angle in Fig. 6. This figure can be compared with Fig. 4 to select the most suitable curve with which to calibrate the strain profile.

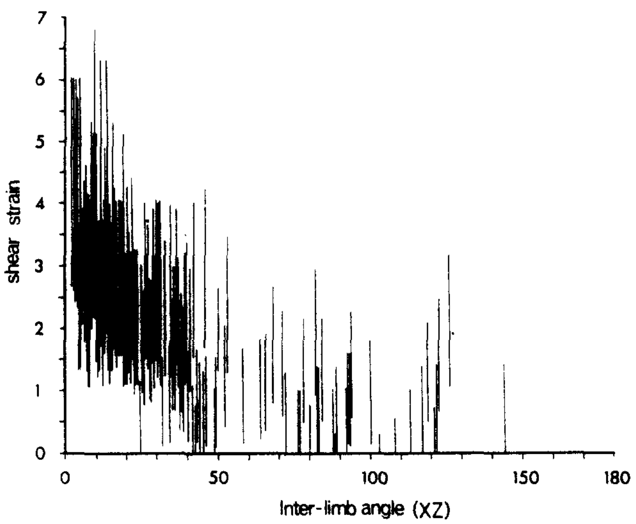

Fig. 6. Plot of the possible range of shear strain undergone by each measured fold. Each bar on the graph related to one fold with a particular inter-limb angle. The maximum point of each bar assumes an initial plunge west of 85°, the minimum point a plunge of 70°. The inter-limb angles plotted have been corrected to the *XZ* plane as described in the text.

Figure 6 embodies an important correction to the measured inter-limb angle data. The method as outlined refers to the inter-limb angles of folds as measured in the *XZ* plane of the strain ellipsoid, whereas the inter-limb angles we have measured and plotted in Fig. 3 are true inter-limb angles, that is measured normal to the fold axis. If measured inter-limb angles were to be plotted in Fig. 6 and comparison made with Fig. 4 a systematic error would be introduced because true inter-limb angles are greater than those which would be seen in *XZ* section. The inter-limb angles plotted in Fig. 6 have been corrected to take this factor into account, and are plotted as they would appear on the *XZ* plane, which is horizontal for transcurrent displacement.

Comparison of Figs. 4 and 6 reveals an encouraging similarity between the theoretical fold behaviour and the actual behaviour of the measured fold. This supports the suggestion that passive differential rotation of fold limbs is the dominant agent in fold development in these rocks.

Figure 7 is redrawn from Fig. 6 to show the maximum and minimum shear strain data points for each fold. Superimposed on Fig. 7 are the theoretical curves of fold behaviour assuming initial fold inter-limb angles of 120° and 150°. The 120° curve is close to the curve which would be drawn through the mean of the maximum/minimum strain points for each fold. However for three reasons which are outlined below it is suggested that the 150° curve, which lies close to the best fit of the maximum data points in Fig. 7, is more suitable for calibration of the strain profile.

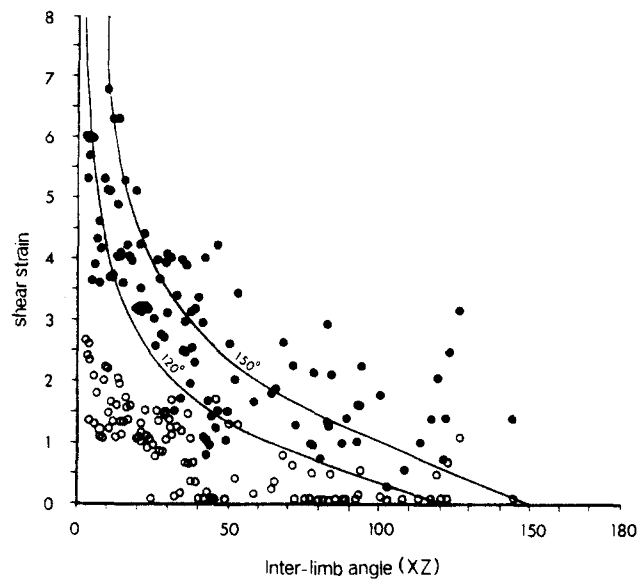

Fig. 7. Redrawn Fig. 6 to show maximum and minimum data points only. Superimposed on these data points are the 120° and 150° theoretical curves of fold behaviour redrawn from Fig. 4.

The 120° curve although lying close to the mean of the maximum/minimum data points will yield a low value for the strain for the following reasons.

1. At higher strains Archaean folds have not been distinguished from folds of shear zone age. These folds will be tighter than expected after a given shear zone strain. Some of the folds plotted in Fig. 6 at higher strains are probably Archaean, and will bias the mean towards lower inter-limb angles at a given strain.

2. The assumed range in plunge is probably too wide. In particular since the mean plunge in areas of class 4 strain is only about 67°, and the lowest assumed original plunge is only 3° steeper, the minimum shear strain points are probably too low.

3. In many localities the movement direction has a slight plunge west, whereas we have assumed a horizontal movement direction throughout. Any departure from a horizontal movement direction to a west plunge, will reduce the correction for profile incorporated in Fig. 6, with the effect of moving maximum/minimum data point pairs to the right.

These factors would be difficult to quantify, but they suggest that the 150° curve of Fig. 4 which closely corresponds to the best fit curve for the maximum data points in Fig. 6, is most suitable to quantify the strain profile.

Figure 6 shows that the dominant mechanism of fold tightening is passive rotation of fold limbs. However, at low inter-limb angles and high strains the correspondence of the theoretical curves with our data decreases (Fig. 7), that is the inter-limb angles are smaller than predicted for the shear strains determined from the fold plunges. This could be because the movement direction has a plunge west rather than being horizontal. The error due to this would be most significant in folds with gentle plunges, that is those with smallest inter-limb angles, and would mean that shear strains are systematically underestimated. It is also possible that the fold generating mechanism, whether heterogeneous shear or buckling, continues to actively reduce inter-limb angles even at high strains. A more detailed study of the folds could lead to a better understanding of the relative significance of generating mechanisms and passive rotation in determining fold morphology.

The quantitative profile

Using Fig. 4 (150° curve), mean inter-limb angles obtained earlier for each qualitative strain class can be used to give a mean value of shear strain for each class. The mean inter-limb angle of each strain class is corrected, as for individual folds, to the *XZ* plane by an amount dependent on the mean plunge of folds in each class (Table 1). This corrected value for the inter-limb angle is then used to obtain the shear strain for each class from the 150° curve on Fig. 4. The values for shear strain found in this way are shown in Table 1. Figure 2 is a strain profile constructed using these results. This profile provides a quantitative picture of strain variation across the section, and corresponds to a displacement of 47.6 km. Due to the small number of strain intensity classes used in the construction of the profile, the important distinction between gradual and abrupt changes in intensity is not shown. The profile is consequently misleadingly angular and future work should attempt to distinguish between gradual and abrupt changes.

CONCLUSIONS

A method has been described which allows continuous strain profiling of large shear zones. The profile presented is very irregular and, based on minimum strain estimates, corresponds to a displacement of about 47.6 km and a mean shear strain of about 3.6. The internal boundary between shear zone and augen is distinct and does not coincide with the facies boundary, that is the shear zone extends 3 km into rocks dominantly of granulite facies. The 9 km traversed within dominantly amphibolite facies rocks has a mean shear strain of 4.9: if applied to the full width of the shear zone (46 km less 10 km augen) this shear strain would correspond to a total transcurrent displacement of 176 km. This estimate is lower than a previous estimate of 200 km (Bak *et al.* 1976) and is still only an approximate value.

A principal deficiency of the profile is the lack of time control. Although all the strain recorded in the profile took place under amphibolite facies conditions, it is not known for how long these conditions prevailed. More importantly, the strain rate profile is not known at any stage in the displacement history. The only indication of timing is the observation, also made in other shear zones, that low or moderate strains appear not to be superimposed on higher strains, and broad zones of strain do not appear ever to be superimposed on earlier narrow zones. The extent to which large shear zones are, or, are not, comprised of numerous smaller zones is not evident from the information presented, although this marginal zone does include a large number of small zones which are largely responsible for the irregular profile. We believe, but cannot demonstrate, that the external boundaries of the Ikertoq belt would show a more regular increase in strain, and that parts of the interior of the belt would show a more constant strain than that shown in the profile. The extreme irregularity of this profile may be a result of a more complex strain history which might be expected on the margin of a large augen. The relationship between strain and the considerable grain size changes which occur will be described elsewhere together with strain measurements on a hand-specimen scale.

The restricted range of gneiss banding before the shear zone formation has given rise to a correspondingly restricted range of orientation of initial fold axes. Although this restricted range has been essential in validation of the method it is not a necessary condition for application of the method elsewhere. It is however important that the initial plunge of individual folds is known to within 20°, and this may prove a limitation to the application of the method.

Acknowledgements—This work was carried out as part of the Liverpool Precambrian Boundary Programme, supported by the Natural Environment Research Council grant GR/1785, and carried out with the cooperation of the Geological Survey of Greenland.

REFERENCES

Bak, J., Korstgård, J. A. & Sørensen, K. 1975. A major shear zone in the Nagssugtoqidian of west Greenland. *Tectonophysics* **27**, 191–209.

Bak, J., Grocott, J., Korstgård, J. A., Sørensen, K., Nash, D. F. & Watterson, J. 1976. Tectonic implications of Precambrian shear belts in western Greenland. *Nature, Lond.* **254**, 566–569.

Escher, A. & Watterson, J. 1974. Stretching fabrics, folds, and crustal shortening. *Tectonophysics* **22**, 223–231.

Escher, A., Escher, J. & Watterson, J. 1975. The reorientation of the Kangâmuit dyke swarm, west Greenland. *Can. Jl Earth Sci.* **12**, 158–173.

Grocott, J. 1979. Shape fabrics and superimposed simple shear strain in a Precambrian shear belt, west Greenland. *J. geol. Soc. Lond.* **136**, 471–488.

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

Ramsay, J. G., & Graham, R. H. 1970. Strain variations in shear belts. *Can. Jl Earth Sci.* **7**, 786–813.

Watterson, J. 1975. Mechanism for the persistence of tectonic lineaments. *Nature, Lond.* **253**, 520–522.

Watterson, J. 1979. Strain and strain rate gradients at the ductile levels of fault displacements. *Proc. Conf. Analysis of Actual Fault Zones in Bedrock.* U.S. Geol. Surv. Office of Earthquake Studies, 235–257.