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Superposition of plane strain on an initial sedimentary fabric: an example from Laksefjord, North Norway

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Abstract—Shape fabric determinations in deformed grits, microconglomerates and conglomerates in the Landersfjord region of the Laksefjord Nappe, Finnmark, North Norway, have demonstrated the existence of prolate fabric ellipsoids. The correlation between shape fabric symmetry and the orientation of the principal fabric axes suggests that the fabrics are the result of a tectonic plane strain superimposed roughly coaxially on an initially oblate sedimentary fabric. A plot of the fabric ellipsoids on a three axis diagram allows the effect of the initial fabric to be removed, and the amount of strain to be determined. A contour map of the strain shows it to increase to the north and west. Models are proposed for the origin of the strain.

INTRODUCTION

THE LAKSEFJORD Nappe (Føyn 1960, 1969) is situated in the middle of the tectonic pile making up the Caledonides of Finnmark, North Norway (Gayer & Roberts 1973). The presence of conglomerates within the nappe and the occasional development of high strains have led to several investigations into the distribution and magnitude of tectonic strain (Noake 1974, Williams 1975, Chapman in prep, Chapman *et al.* 1979). These investigations have been undertaken in the lowest stratigraphic unit of the Laksefjord Nappe, the Gozzavarre Member of the Ifjord Formation (Chapman, in prep). However conglomeratic boulder beds are present in the overlying Elvevik Member, while above this the lower part of the Landersfjord Formation contains beds of coarse grit and microconglomerate. The shape fabrics of these rocks, in terms of the mean shape and orientation of the clasts or grains, were determined by the authors at a series of localities at Landersfjord (see Figs. 1 and 2), within the Elvevik Member of the Ifjord Formation and the lower part of the Landersfjord Formation.

The rocks at Landersfjord lie within the steep western limb of a major $D1$ synform. Minor or major folds of either of the two later folding episodes seen elsewhere in the nappe have not been observed at Landersfjord. To the west of the area is a steep fault separating the metasediments from allochthonous basement, while to the south the sequence within the $D1$ fold is truncated by

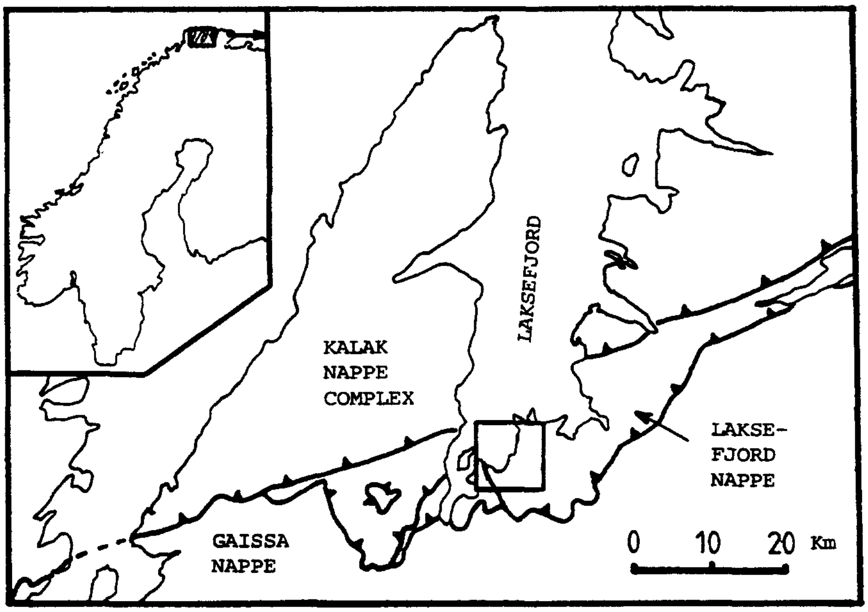

Fig. 1. The Finnmark Caledonides, showing the location of Fig. 2.

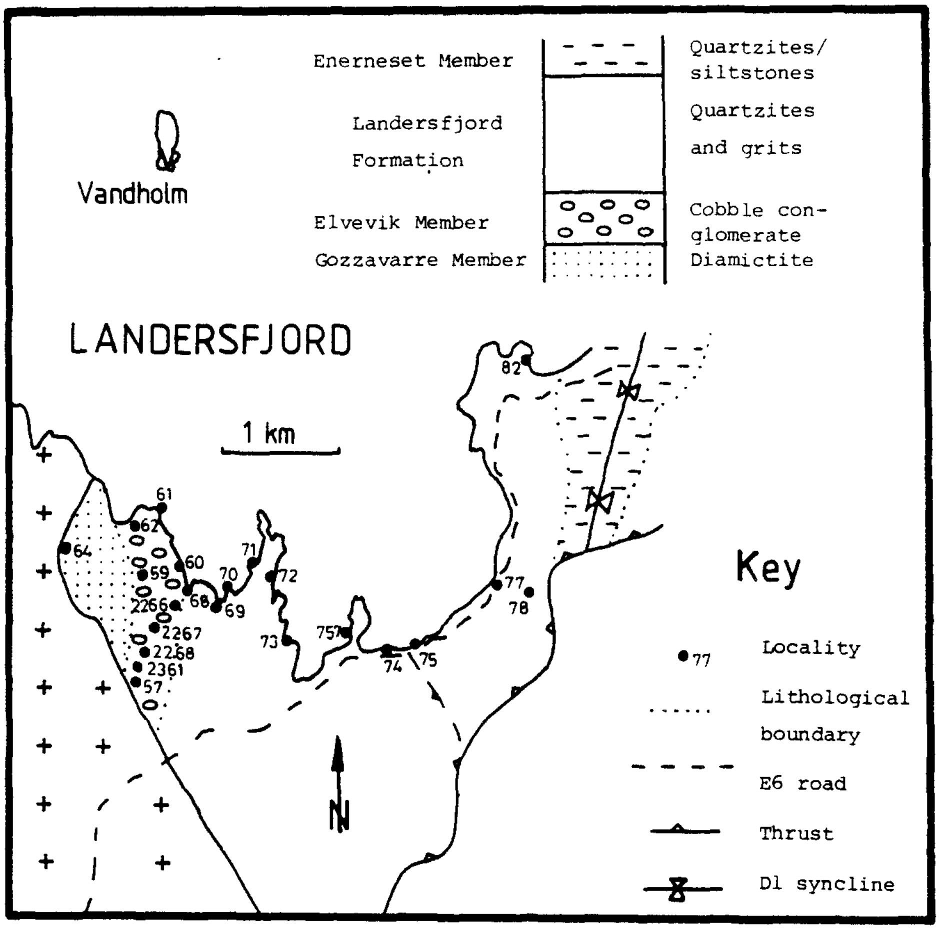

Fig. 2. Geological map of the Landersfjord region, showing the localities at which shape fabrics were determined.

a later minor thrust. To the north of the area, beneath the fjord, lies the Upper Laksefjord Nappe, bounded below by a major thrust fault. The rocks have been metamorphosed to lower greenschist facies. Metamorphic minerals are not abundant owing to the psammitic nature of the lithologies, but epidote is ubiquitous, and tremolite occurs in carbonate rocks on the island of Vandholm. In the fine matrix of the conglomeratic lithologies a foliation and lineation, defined by the orientation of platy minerals and the shape fabric of matrix grains, may locally be developed.

METHODS

A variety of methods were used to determine the shape fabrics at Landersfjord. At locality 2266 the pebbles were extracted from the matrix, and their axial ratios were measured. At localities 2267, 2268 and 2361, pebbles were measured in section on joint faces perpendicular to the local foliation and parallel or perpendicular to the local stretching lineation. As these sections are very probably principal sections of the strain ellipsoid, it was assumed that they were close to principal sections of the fabric ellipsoid. The axial ratios of the fabric ellipsoids were determined using the harmonic mean method of Lisle (1977a) for rapid analysis. At locality 64, clasts were measured on two joint faces whose orientations with respect to the foliation and stretching lineation were known. The fabric ellipsoid was reconstructed from these two sections.

At locality 61 the clasts were measured on three joint faces. For each face the mean elliptical clast shape was determined using Fortran IV program THETA (F), written by C. J. Peach of City of London Polytechnic and based on the Theta curve method of Lisle (1977b) and the Rf/ϕ method (Dunnet 1969). The three ellipses so obtained were combined using Fortran IV program TRISEC (F) (Milton 1980), available at Cardiff, to give the mean ellipsoidal clast shape and orientation. At locality 757, an orientated sample of coarse grit was collected, and three orthogonal thin sections were cut. The mean grain shapes were determined using both the RF/ϕ method and the point-to-point method of Fry (1979) and the fabric ellipsoid was reconstructed using TRISEC (F). Both methods gave similar results, and the Rf/ϕ method was chosen as the more objective.

At the other localities, orientated samples of grit and microconglomerate were collected. On these, three surfaces were cut, polished and etched by immersion in 40% hydrofluoric acid for 8 min, and acetate peels of the surfaces were made. The peels were enlarged optically, and the shapes and orientations of 60 grains were measured from each peel. The mean grain shapes were determined using THETA (F) and the fabric ellipsoid was determined using TRISEC (F). Further data were collected by Noake (1974) on the island of Vandholm, where he measured the axial ratios of deformed clasts on principal strain sections (defined by the local foliation and lineation).

ERRORS

The various techniques used to determine the fabric ellipsoids yield results of varying uncertainty. Where three ellipses were determined using the *Rf/φ* method. and combined to allow for their lack of fit (Milton 1980), the most reliable results were obtained. It is difficult to give a percentage estimate of error, as errors will be present in all five parameters of the derived ellipsoid. A maximum error of less than 10% is estimated for the ellipsoid axial ratios. In the case where the harmonic mean method was used, the strain ellipses were subject to a higher error. Lisle (1977a) has demonstrated that the harmonic mean provides an overestimate of the strain ratio, and his random model suggests that the error may be in the region of 15% at a strain of 1·8; at lower states of strain errors may be much greater than this with a possible error of 50% at 1·2. As only two surfaces were measured in the interests of rapid data collection, there was no check on the amount of error.

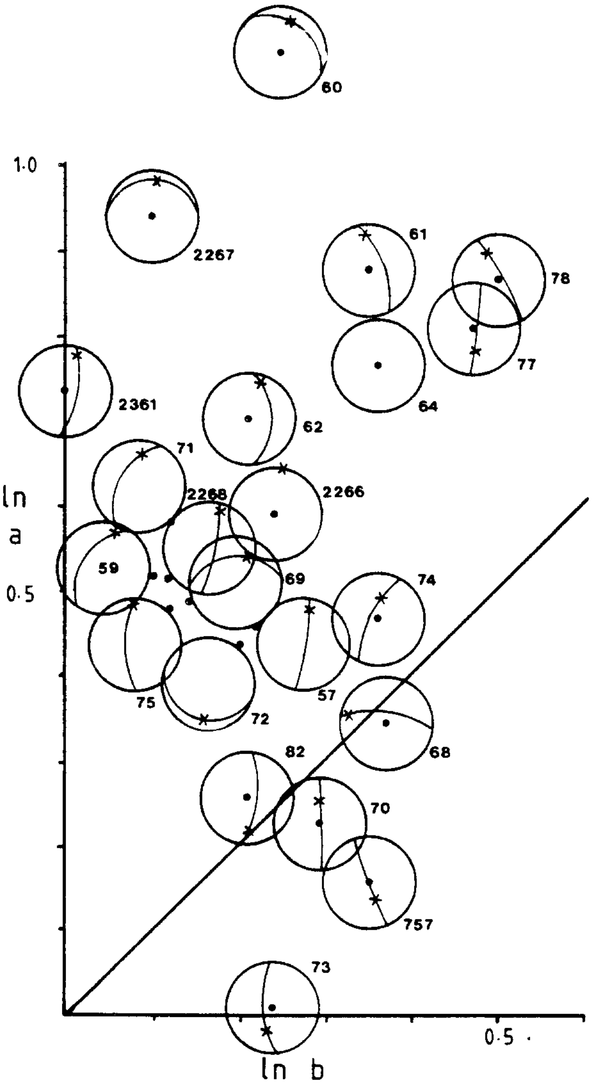

Fig. 3. Flinn plot of the fabric ellipsoids. A stereogram is placed at each point, labelled with the locality number, on which the attitudes of the *XY* plane, as a great circle, and the *X* direction, as a cross, have been marked. Some of the stereograms have been offset from the points for clarity. Locality 64 was not oriented in the field, and the *XY* plane of locality 2266 is horizontal.

RESULTS

Figure 3 shows the shape and orientation of the shape fabric ellipsoids determined at each locality. The ellipsoids lie mostly in the prolate field of the Flinn plot (Flinn 1978), but there is a large range both in the axial ratios (*X/Z* varies from 3.8 to 1.3) and the symmetry (*k* varies from 0.05 to very large) of the fabric (see Notation, below). In most cases the ellipsoid *X* axis trends roughly north–south at a low angle, while the orientation of the *XY* plane is much more variable (see Fig. 4). It may be seen from Figs. 3 and 4 that the localities with lower, more oblate, strains (localities 57, 757, 70, 82 etc.) have steep *XY* planes striking north–south, in an attitude similar to that of the sedimentary bedding, while those with the highest prolate strains (60, 61, 62, 71, 2266, 2267) have shallower to subhorizontal *XY* planes with a more variable, often east–west, strike, close to the tectonic foliation occasionally observed within the Elvevik Member.

It seems likely that the axes of all the ellipsoids have essentially similar orientations, with *X* roughly north–south and the other axes dipping subvertically or subhorizontally perpendicular to *X*, and that the *Y* and *Z* axes of the oblate fabrics interchange with increasing eccentricity of the fabric ellipsoid.

Owens (1974) has shown that this situation is better demonstrated on a three axis plot (after Nadai, 1963, see Fig. 5) than on a Flinn plot. In plotting this diagram, the axes are defined by their orientation rather than by their relative magnitudes. For those localities with subhorizontal *XY* planes (the group in the centre of the

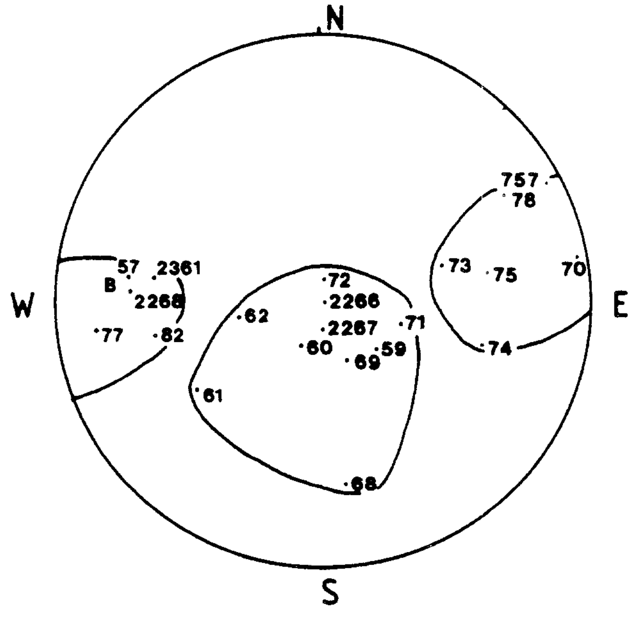

Fig. 4. Stereogram of the poles to the fabric *XY* planes. The poles fall into a rough girdle around the mean fabric *X* axis. The poles within the central area belong to the localities plotting to the right of the ln *X'/R* line of Fig. 6. *B* represents the mean pole to bedding.

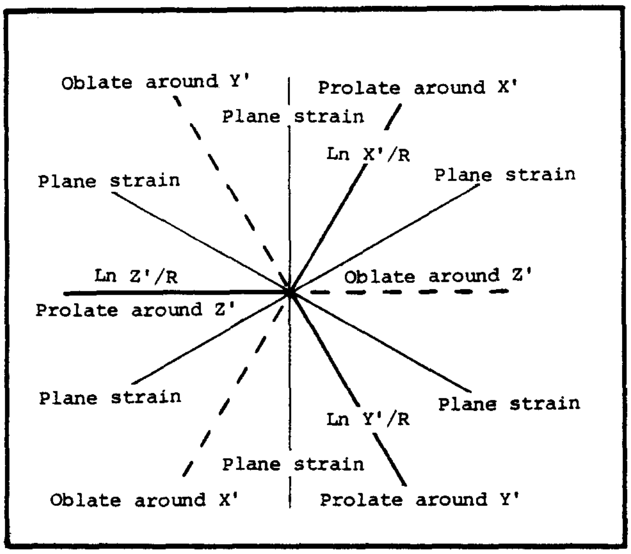

Fig. 5. The three axis plot, showing the various fields (after Owens 1974).

stereogram in Fig. 4), X', Y' and Z' are taken as equivalent to the X, Y and Z fabric ellipsoid axes, while for the others X', Y' and Z' are taken as equivalent to X, Z and Y, so that Y' is always less steep than Z'. R is defined as the radius of the equivalent volume sphere (see Notation) and a three axis plot of $\ln X'/R$, $\ln Y'/R$ and $\ln Z'/R$ may be drawn (see Fig. 6).

It can be seen that most, if not all, of the localities lie within a band parallel to and above the plane strain line bisecting the $\ln X'/R$ and $\ln Z'/R$ axes.

INTERPRETATION

It is proposed that the shape fabrics recorded at Landersfjord are the result of the superposition of a variable tectonic plane strain with a subhorizontal XY plane and a northerly X direction, resulting in the LS fabric occasionally developed within the Gozzavarre and Elvevik Members of the Ifjord Formation, on an initial oblate sedimentary, compactional or earlier tectonic fabric, in which the clast short axes lay perpendicular to the now subvertical bedding.

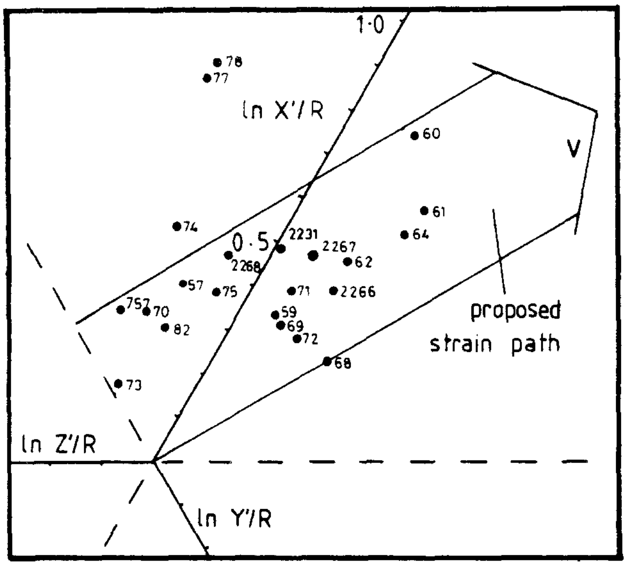

Fig. 6. Three axis plot of the fabric ellipsoids described in the text.

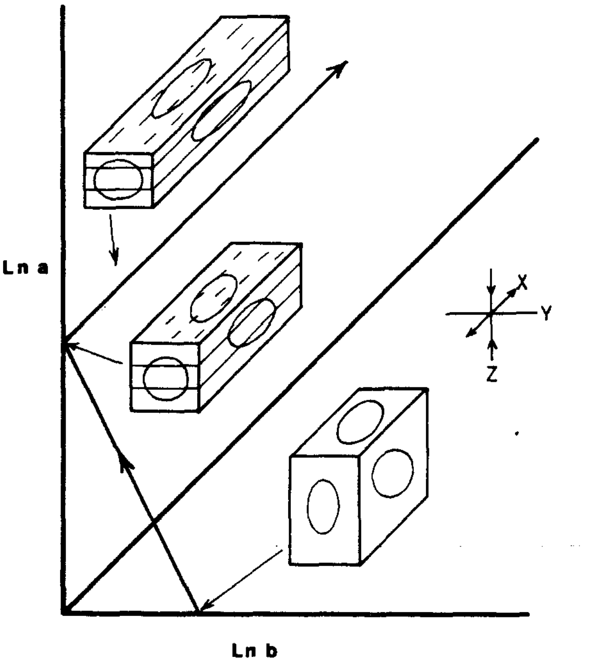

Fig. 7. Flinn plot showing the effect of superposing plane strain on an initial oblate fabric, when the Z axis of the initial fabric is parallel to the Y axis of strain. The development of prolate ellipsoids and a horizontal foliation from an initial vertical fabric mirrors the fabric development at Landersfjord.

Sanderson (1976) has discussed the effect of superposing tectonic plane strain on an oblate compactional fabric, and showed that prolate fabric ellipsoids will develop when the Y direction of strain is parallel to the clast short axes of the initial fabric. The fabric ellipsoid will lie initially on the $\ln a = 0$ line of the Flinn plot (see Fig. 7) and on applying progressive strain will move at 60 degrees to this line until it meets the $\ln b = 0$ line, when the fabric will be completely prolate. It will then move back into the plot, parallel to the plane strain line.

On the three axis plot, however, the path is less complex. The fabric ellipsoid will lie initially on the negative part of the $\ln Y'/R$ axis and will move in a straight line, parallel to the plane strain line, crossing the $\ln X'/R$ axis on the way, as strain is progressively applied. It is proposed that the band in which the localities fall in Fig. 6 represents just such a superposition of tectonic plane strain and initial oblate fabric. The length of the band represents the maximum component of strain recorded at Landersfjord (being highest in Vandholm) while the width of the band represents the range of initial fabrics. One locality (68) lies on the plane strain line, and probably represents a random initial fabric. The maximum eccentricity of initial fabric, represented by the full width of the band, would be equivalent to a fabric ellipsoid with axial ratios 1.5 : 1.5 : 1.0. Three localities (74, 77 and 78) lie outside the band. Two of these lie close above a thrust fault (see Fig. 2) and the third is thought, by field evidence, to lie above a branch of the fault. It is proposed that these localities record another superimposed strain, related to the thrust.

Hutton (1979) has discussed a similar superposition of tectonic strain on an initial sedimentary fabric in rocks close to the Horn Head slide, County Donegal, Ireland. However in the situation he describes, the planar sedimentary fabric lies parallel to the *XY* plane of a prolate strain, and prolate shape fabric ellipsoids are developed from oblate without crossing the ln $b = 0$ line of the Flinn plot.

ESTIMATION OF STRAIN

The amount of strain recorded by the shape fabrics at each locality may be estimated if three assumptions are made.

(1) That the clasts record the same strain as the matrix. This is likely, as the clasts are mostly quartzites or quartz grains and therefore of a similar ductility to the quartzitic matrix, and the concentration of clasts is so high that there can be negligible ductility contrast between the clasts and the clast/matrix system. The clastic grains show good ductile deformation textures, which vary across the area. In specimen 757, the grains show deformation bands though the grain margins are sharp and well defined. In specimen 62 the margins of the deformation bands and the edges of the grains have recrystallised into elongate subgrains, themselves showing undulose extinction, suggesting dynamic recrystallisation. Investigation of quartz *C*-axis distributions in this sample was not very conclusive, but a pole-free area around *X* suggests that deformation was by basal slip. In a specimen collected by Noake on the island of Vandholm, the recrystallised subgrains are more equant in shape, and recrystallisation is more complete.

At localities within the Elvevik and Gozzavarre Members however, the foliation in the matrix is seen to deflect around the more competent clasts, suggesting that the clast shape fabric may not reflect the total strain.

(2) That the initial fabric was truly oblate and that there was no systematic orientation of the clast long axes in the bedding. The Landersfjord quartzites and grits may have been laid down by braided streams (Laird 1972) or by meandering flood plain rivers (Chapman, in prep) so some systematic orientation of clast long axes may have been present in the sedimentary fabric. The two localities closest to the ln $a = 0$ line of Fig. 3 show similar atypical orientations of the ellipsoid *X* axis, which may possibly represent an initial fabric which was not truly oblate. If however the initial fabrics were diagnetic or compactional, they are more likely to have been completely oblate, and the least eccentric locality

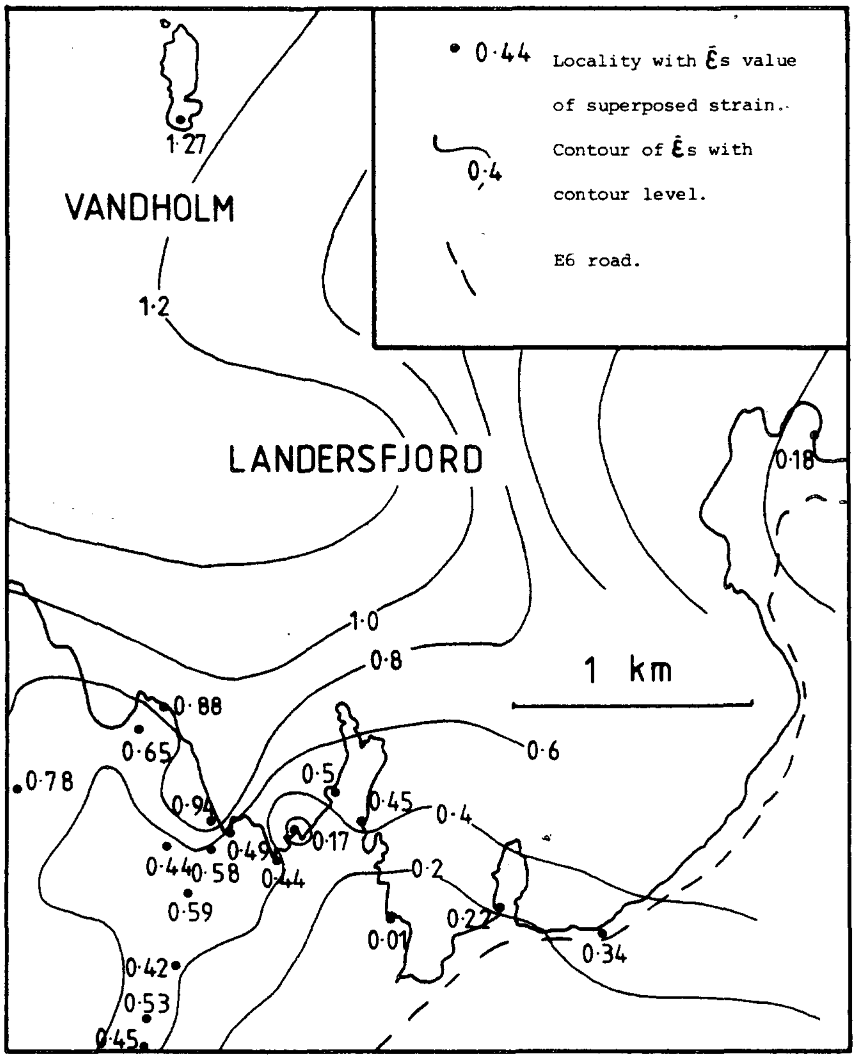

Fig. 8. Contour map of the $\bar{\varepsilon}s$ value of tectonic strain.

(73) lies almost exactly on the $\ln a = 0$ line. In specimen 757, pressure solution can be seen, parallel to the bedding, suggesting that the initial fabric was a compactional, or early tectonic, one.

(3) That the tectonic strain was plane strain. This is suggested by the arrangement of the localities within a band parallel to the plane strain line in Fig. 6.

If these three assumptions are made, then the perpendicular separation of each locality from the $\ln Y'/R$ line on the three axis plot gives a measure of the applied strain. The $\bar{\varepsilon}s$ value of the strain is directly proportional to this separation (see Notation) and a contour map of $\bar{\varepsilon}s$ may be drawn for the Landersfjord region after making a correction for the presumed initial oblate fabric. (Fig. 8). Localities 74, 77 and 78 are not included on this map, for reasons discussed above. Contours of $\bar{\varepsilon}s$ run east–west in much of the region, and north–south in the north-east and south-west corners. The highest $\bar{\varepsilon}s$ value is that recorded on Vandholm by Noake (1974) while the lowest values are found near the E6 road in the south.

ORIGIN OF STRAIN

The rocks on the west side of Landersfjord are on the western limb of a major *D*1 syncline. It is possible that the observed strain and the fold are products of the same deformation episode. Ramsay (1967, p. 220) has suggested that prolate fabric ellipsoids may develop in the hinge of a fold if an initial sedimentary fabric was present. In Landersfjord however, the prolate ellipsoids are developed in the limbs of the fold, and the fold hinge, plunging gently south, parallels the fabric *X* axis, which is not the case as described by Ramsay.

Another possible explanation invokes a second (*D*2 ?) deformation episode post-dating the *D*1 fold. A strain with a subvertical *Z* axis and a north–south *X* axis could be superposed on an initial oblate fabric within the vertical bedding on the limbs of the *D*1 fold to give the observed prolate fabrics. The initial fabric could be a sedimentary or compactional fabric rotated into the vertical on the fold limb, or a *D*1 tectonic fabric associated with the fold. The strain component of the fabric is seen to increase northwards (see Fig. 8) and could be a simple shear strain related to movement on the major thrust situated about 1.5 km north of Vandholm, running east–west. Increasing shear strain upwards, away from a sole thrust and towards a roof thrust, is perhaps unusual. Patterns of strain elsewhere in the nappe (Chapman *et al.* 1979) show the strain to increase downwards towards the basal thrust. At Landersfjord, however, the basal thrust is a late minor structure, while the roof thrust is the basal thrust of the overlying nappe. It is suggested that an inverted metamorphic gradient may have existed below this thrust, increasing the ductility of the rocks, and causing the increase in strain northwards. The increase in strain to the west may be a topographic effect, as the ground rises in this region.

The superposition of *D*1 and *D*2 strains has been proposed by Noake (1974) to explain the presence of prolate fabrics in a region 23 km west of Landersfjord. No *D*2 minor folds are seen at Landersfjord however, and no other evidence is preserved of superimposed deformation episodes in this region.

CONCLUSIONS

(1) Shape fabrics at Landersfjord mostly represent prolate fabric ellipsoids with subhorizontal north–south *X* axes.

(2) The shape fabrics may have been produced by the superposition of a variable tectonic plane strain with $\bar{\varepsilon}s$ of up to 1.27 on an initial oblate sedimentary (or otherwise) fabric where $X : Y : Z \leq 1.5 : 1.5 : 1$.

(3) Three localities close to a thrust fault differ from the overall pattern, and may show the effects of another strain.

(4) The tectonic strain increases to the north and west.

(5) The strain may be related to the development of a major *D*1 fold, or may postdate the fold and be related to a major thrust, situated to the north of the area.

NOTATION

X, Y, Z = axes of the fabric or strain ellipsoid, where $X > Y > Z$.
$\ln a = \ln X/Y$
$\ln b = \ln Y/Z$
$k = \ln a / \ln b$
R = radius of equivalent volume sphere = $(XYZ)^{\frac{1}{3}}$
D = perpendicular separation of each locality from the $\ln Y^1/R$ line on Fig. 6.
$\bar{\varepsilon}s = D\sqrt{2}\cos 30^\circ$
$\bar{\varepsilon}s = (2/3\,[(\ln a)^2 + (\ln b)^2 + (\ln a \times \ln b)^2])^{\frac{1}{2}}$

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