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Tittel
The structural history of the Leipikvatnet Nappe, central Scandinavian Caledonides, in the region of the Joma sulphide deposit, Nord-Trøndelag, Norway.

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The Leipikvatnet Nappe in the Joma area is composed of the stratigraphicsequence; greenstone, quartzitic phyllite, graphitic phyllite, tectonically repeated by thrusting and local overturned in the area of the Joma sulphide deposit. D1 and D2 deformations are associated with movements on the major and internal thrust planes, whereas D3 and D4 post-date them. D3 deformation is suggested, from lineation distributions and finite strain results, to have resulted from late movement of the Børgefjell Massive. Subhorisontally orientated F4 folds are suggested to have formed in response to overburden pressure when horizontal stress was reduced over the crest of the rising massive. The Røyrvik reenstones are composed of massive and pillowed lava fows, overlain volcaniclastic deposits and are thought to represent the remnants of a basaltic aceanic island.

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Arve Haugen
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7th July 1988

Dear Arve,

I have, at last, written a paper on my work on the structural geology of the Joma area and enclose a copy for your information. If you can find the time to read it, I would also be greatful for your comments before I submitt it, probably to N.G.T. I have also sent copies to Frank Vokes, Arne Reinsbakken and Mike Stephens for their comments.

I hope all is going well at Joma. Hope to hear from you soon,

Best Wishes,

Noelle Odling.

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The structural history of the Leipikvattnet Nappe, central Scandinavian Caledonides, in the region of the Joma sulphide deposit, Nord Trøndelag, Norway.

Noelle E. Odling

Abstract

The Leipikvattnet Nappe in the Joma area is composed of the stratigraphic sequence; greenstone, quartzitic phyllite, graphitic phyllite, tectonically repeated by thrusting and locally overturned in the area of the Joma sulphide deposit. D1 and D2 deformations are associated with movements on the major and internal thrust planes, whereas D3 and D4 post-date them. D3 deformation is suggested, from lineation distributions and finite strain results, to have resulted from late movement of the Bjørgefjell Massive. Subhorizontally oriented F4 folds are suggested to have formed in response to overburden pressure when horizontal stress was reduced over the crest of the rising massive. The Røyrvik greenstones are composed of massive and pillowed lava flows, overlain by volcaniclastic deposits and are thought to represent the remnants of a basaltic oceanic island.

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Introduction

The Leipikvattnet Nappe, one of the Köli nappes of the Upper Allochthon of the Scandinavian Caledonides, outcrops over a distance of approximately 120km, trending northeast from the Grong-Olden culmination to north of the Bjørgefjell Massive (FIG.1). The nappe contains the Joma massive sulphide deposit, situated 16km east of the village of Røyrvik, in Limingen, Nord Trøndelag, (FIG.2) which is hosted by the Røyrvik Group greenstones and has been mined for Cu and Zn by Grong Gruber A/S since 1972. The present paper is based on a study of the structural history of the area immediately surrounding this massive sulphide occurrence.

In the vicinity of the Joma deposit, the Leipikvattnet Nappe is composed of intercalated greenstone, quartz phyllite and graphitic phyllite units (FIG.2). The rocks show evidence of four deformation phases. The dominant phase (D2) has resulted in a largely penetrative cleavage subparallel to the lithological layering, and is associated with the major movements on thrust planes. Evidence of an earlier phase, largely overprinted by D2 deformation, is occasionally preserved in quartzitic phyllites. The penetrative cleavage and thrust planes are folded by the third phase of deformation, to which the major, northeast trending, Joma synform belongs, giving the characteristic arcuate form to the outcrop pattern. A fourth phase of deformation, comprising minor folds and kinks, is weakly developed in the south of the area adjacent to the upper bounding thrust of the Leipikvattnet Nappe. This sequence of deformation is in agreement with the general scheme of deformation present throughout the Upper Allochthon.

The Geology of the Joma area.

The rocks of the Joma area comprise the structural sequence: (from base upwards) greenstone, quartz phyllite and graphitic phyllite which is repeated twice, with a third greenstone outcropping adjacent to the upper bounding thrust contact with the Gjersvik Nappe (FIG.2). Although there is a gross similarity between these three units, the greenstones in particular (termed the outer, middle and inner greenstones from north to south) show individual characteristics.

The Outer Greenstone.

The outer greenstone is composed of pillow lavas and massive greenstones which are interpreted as massive flows and shallow level intrusions. The pillow lavas show well preserved pillow structures with dark, fine grained rims and paler cores with abundant fractures filled largely by carbonate. The pillows are closely packed with sparse interstitial deposits. Adjacent to the upper contact of the outer greenstone with quartzitic phyllites, the pillows contain variolitic structures comprising spherical to ellipsoidal particles from 2mm to 4cm long. These show internal concentrical layering and are mineralogically similar to the host greenstone but contain higher proportions of clinozoisite.

The pillowed greenstones are dominant in the east and pass westwards, through a complexly interfingered zone (FIG.2), into a massive greenstone of varying grain size which, in the coarsest examples, displays relict ophitic textures. Grain size of this massive greenstone was found to be independent of deformation intensity and the variation is therefore thought to be an original feature. The massive greenstones have sharp or gradational contacts with pillow lavas and, where gradational, pass into pillow lavas through a breccia composed of pillow fragments. The relict ophitic textures indicate an igneous origin for the massive greenstone and they are interpreted as representing massive flows and shallow level intrusions. Associated with the massive greenstones are thin lenses of black graphitic and quartzitic phyllite which often show an en echelon arrangement. These closely resemble the phyllites occurring between the three greenstone units and are associated with breccias containing greenstone fragments and impure marbles. They are interpreted as sediments of mixed biological/chemical and volcanogenic origin.

The Middle Greenstone.

The pillow lavas of the middle greenstone closely resemble those of the outer greenstone, except that no variolitic structures were found and interstitial deposits are more abundant. They show a generally lower state of preservation than the pillow lavas of the outer greenstone and were identified largely by the presence of elongate lenses of intense fracturing. These weather to give a characteristic appearance and are preserved when all signs of pillow margins have been destroyed.

The pillow lavas were found to form a elongate wedge-shaped outcrop in the centre of the middle greenstone (FIG.2) which is flanked by massive to finely laminated greenstones. This laminated greenstone, which resembles the interstitial deposits between pillows, is composed of light and dark laminae formed by varying proportions of plagioclase, actinolite and clinozoisite, which are the constituent minerals of the greenstone, and is interpreted as a volcaniclastic deposit. Intercalated with laminated greenstones are more massive units which show only faint layering. Due to the presence of layering, their concordance with laminated greenstone and the lack of any igneous textures, these are also thought to be of volcaniclastic origin.

The Inner Greenstone.

The inner greenstone forms discontinuous layers adjacent to the upper bounding thrust to the Leipikvattnet Nappe. It is composed of medium to fine grained, massive to laminated greenstones which closely resembles the volcaniclastic deposits of the middle greenstone. This, together with the lack of any relict igneous features, is thought to indicate that these greenstones represent volcaniclastic deposits, similar to those of the middle greenstone.

The Phyllites

Quartzitic phyllites are concentrated in the areas adjacent to the structurally upper contacts of the outer and middle greenstone units. They show gradational contacts with graphitic phyllites, and the name 'quartzitic phyllite' was arbitrarily applied by Kollung (1979) to phyllites with more than about 50% quartz. The quartzitic phyllites are composed of alternating quartz rich and mica rich layers. The quartz rich layers range from a few mm to 10cm thick and show a complete gradation from laterally continuous, parallel layers of even thickness and separation to anastomosing, discontinuous layers down to a few mm thick. As the earliest fold structures were found in quartz phyllites with regular layering it is thought likely that this type of layering is an original feature from which the irregular, anastomosing layering is developed by deformation. The competence contrast between graphitic and quartz rich layers renders the rock susceptible to folding and this rock type is the most sensitive indicator of the deformation history in the area. In contrast to the quartzitic phyllites which are resistance to erosion and form high standing ground, the graphitic phyllites are susceptible to weathering and are badly exposed. They resemble the mica rich layers within the quartzitic phyllites.

The Deformation history of the Leipikvattnet Nappe.

Main phase deformation - D2

The main penetrative cleavage and mineral lineation developed in the area belongs to the second identifiable phase of deformation. S2 cleavage dips southwest to northwest (due to later folding), forming a distribution that approximates a great circle about the major F3 fold axis (FIG.3a). Mineral lineations in the graphitic phyllites and greenstones and rodding lineations on quartz layers surfaces within quartzitic phyllites dip gently northwest through north to east (FIG.3b). F2 folding is best developed in the quartzitic phyllites where it is commonly refolded by F3 folds. However, where F3 folding is gentle, it was possible to determine the vergence of F2 folds. In the quartzitic phyllites overlying both the outer and middle greenstones, this generally sinistral looking eastwards along the F2 axes, i.e., they indicate the possible presence of a major synform to the south and antiform to the north.

In the greenstone units, F2 folding is rarely developed and the intensity of D2 deformation is expressed as S2 cleavage development. The relative intensities of S2 cleavage, mapped in the middle greenstone, showed that S2 is most strongly developed adjacent to the lower contact and weakest in the centre of the greenstone unit (FIG.4). At rare exposures of the structurally lower contacts of the middle and inner greenstone units, S2 cleavage within the greenstone was seen to be slightly oblique to the contact and to increase in intensity and swing into parallelism approaching the contact. Layering in quartzitic phyllites is occasionally observed to be truncated by the contact and, at the lower contact of the inner greenstone unit, many thin intercalated slivers of greenstone and phyllite were observed. These features are thought to indicate that these contacts are tectonic in origin and that they mark the locations of secondary thrusts within the Leipikvattnet Nappe. The distribution of S2 cleavage intensity within the outer greenstone shows a rather different pattern to that of the middle greenstone, being most strongly developed in the thin western limb and decreasing in intensity eastwards. The lower contact was nowhere found exposed and it is therefore uncertain whether it also marks the location of a thrust. However, the similarity in outcrop pattern with the middle greenstone suggest that it may also be of tectonic nature.

The repeated sequence of greenstone, quartzitic phyllite, graphitic phyllite is thus interpreted as a structural repetition resulting from movement along thrusts internal to the Leipikvattnet nappe which are located at the structural bases of the middle and upper greenstones and possibly also the outer greenstone. The relationship between S2 cleavage and the lower greenstone contacts indicates that the movement is associated with D2 deformation and therefore coeval with movement along the major thrusts bounding the Leipikvattnet Nappe.

The area of low D2 deformation in the middle greenstone coincides approximately with the distribution of pillowed greenstone which forms an thin, elongate wedge, parallel to the trace of S2 cleavage (FIG.4). This, with the similarity of the volcaniclastic greenstones on either side, suggests the presence of a major F2 fold whose trace passes through the outcrop of pillowed greenstone. Further evidence of this fold was found from lithological logging of drill cores located along an east-west profile by A. Reinsbakken (1986). Three major lithological types were identified by Reinsbakken; two types of pillowed greenstone and volcaniclastic greenstone. Their distribution shows a repeated sequence reflected about the location of the proposed F2 fold trace, which is cut at depth by the thrust at the base of the middle greenstone (FIG.5). Both the F2 fold trace and thrust at the base of the middle greenstone are refolded by the F3 Joma synform.

The outcrop pattern implies that the Joma massive sulphide deposit occurs in the structurally lower limb of this structure and this is consistent with the vergence of F2 folds found in the ore body (Odling, in press) which are opposite to those of the quartzitic phyllites. This pattern of F2 fold vergence implies that the fold is antiformal. Previous studies of stratigraphy and chemistry of the sulphides and surrounding greenstones have indicated that the ore body is inverted (Olsen 1980, Reinsbakken 1986). This sense of younging thus implies that the stratigraphy is locally inverted in the region of the ore body and that the upper portion of the middle greenstone is the correct way up. As there is no indication of further major F2 folds between the thrusts at the base of the middle and inner greenstones, this therefore suggests that the structurally repeated sequence; greenstone, quartzitic phyllite, graphitic phyllite, represents a stratigraphic sequence.

The presence of other major F2 fold traces within the outer and inner greenstone units could have resulted in the inversion of that other portions of the Leipikvattnet Nappe but several features indicate this to be unlikely. The outcrop pattern of the outer greenstone shows pillowed greenstones in the east, passing westwards through a zone of complex interfingering (FIG.2) into massive greenstones and therefore has a superficially similar pattern to that observed in the middle greenstone. However, due to the lack of any relationship between D2 deformation intensity and shape of the outcrop patterns and of F2 folds in marker horizons such as black phyllites zones, this interfingering is thought to be an original feature. Thus, it is thought unlikely that any major F2 fold exists within the outer greenstone. The inner greenstone forms a thin strip adjacent to upper bounding thrust of the Leipikvattnet Nappe. As this greenstone is generally well cleaved and lacks marker horizons, it is possible that it contains a major F2 fold trace. However, if, as suggested here, the inner greenstone lower contact represents a thrust, any F2 folds within this greenstone unit would affect the younging direction of only a small portion of the Leipikvattnet Nappe, adjacent to the upper bounding thrust with the Gjersvik Nappe. It is therefore unlikely that any other major F2 folds, with which inverted stratigraphy could be associated, exist in the Joma region. The stratigraphic nature of the sequence greenstone, quartzitic phyllite, graphitic phyllite thus implies that the rocks of the Leipikvattnet Nappe in the Joma area are generally the right way up except where locally overturned by F2 folding in the area of the Joma sulphide deposit.

Early Deformation - D1

F1 folds were identified in thin sections and occasional outcrops of quartzitic phyllite. They appear as small scale folds, with an axial planar penetrative cleavage in the mica rich layers, which is strongly crenulated by S2 and more gently folded by F3 folds (Plate I). The interference fold pattern styles and lineations on quartz layer surfaces suggests that F1 and F2 folds are coaxial. Further evidence of existence of deformation prior to the main phase D2 was seen in the Joma sulphide deposit. Tectonic contacts between greenstone and sulphide were observed to be folded around large F2 fold hinges implying that at least some of these contacts must have developed prior to D2 (Odling, in press). This deformation is correlated with the D1 deformation phase identified in the quartzitic phyllites.

Within the greenstone units, no indication was found of deformation earlier than D2. Where the S2 cleavage is weakly developed, the original features of the greenstone (pillows, breccia fragments) can be identified and S2 is nowhere observed as a crenulation of an earlier cleavage. This, together with the probability that F1 and F2 folds in the quartzitic phyllites are coaxial, suggests that D1 and D2 deformation are represent essentially early and late structures within the same deformation phase. The difference between the quartzitic phyllites and greenstones in recording the early deformation can be explained in terms of the mechanical properties of these two rock types. The high competency contrast between quartzitic and phyllitic layers in the quartzitic phyllites results in the early development of folds which can be refolded at a later stage in the deformation. In the greenstones, which lack layering of contrasting competency, the effect of further deformation an on early developed cleavage is simply to strengthen it so that and early and late deformation are indistinguishable.

D3 deformation - the Joma Synform

Thrust planes of D2 age and S2 cleavage are folded by the major, northeast trending, D3 Joma synform which gives the arcuate outcrop pattern characteristic of the Joma region (FIG.2). This synform, which plunges gently southwest to northeast, has a steeply, west to northwest dipping eastern limb and a gently southeast to steeply northwest dipping western limb. The dip of the western limb flattens southwards producing a increase in the Joma synform interlimb angle, so that this fold dies out in the south of the region, and is replaced by another synform to the northwest which trends southwestwards through the overlying Gjersvik Nappe (FIG.2).

D3 deformation intensity, highly variable throughout the region, is most strongly developed around the inner arcs of the outer and middle greenstones in the Joma Synform hinge zone, the steeply dipping eastern limb, and the steeply northwest dipping part of the western limb. F3 folds are open to tight, frequently showing a tendency towards chevron style to which S3 forms an axial planar, crenulation cleavage, rarely penetrative. Small scale F3 folds, as the major Joma synform, are commonly discontinuous along their traces and tend to occur in groups forming zones of F3 folds which are distributed in *en echelon* or relay patterns. F3 folds trend at approximately right angles to F2 fold hinges, thus developing characteristic dome and basin interference fold patterns in the quartzitic phyllites.

S3 crenulation cleavage and F3 fold axial planes dip moderately northwestwards and are slightly steeper on the eastern limb of the Joma Synform, reflecting a slight fanning around the major fold hinge (FIG.6). F3 fold hinges and L3 intersection lineations vary in plunge from gently southwest to gently northwest forming northwest trending zones of L3 plunge direction (FIG.7). Southwest plunges occur in the southwest and northeast of the area (zones A and B, FIG.8) and are separated by a zone of northeast plunges in the region of the middle greenstone (zone B, FIG.8). Possible causes of this variation in L3 plunge are, post-D3 deformation, variable intensity of D3 deformation or a variation in the pre-D3 surface (S2 and lithological layering). As D4 structures are very weakly developed in the area, it is unlikely that later deformation could have significantly affected the L3 plunge. Although D3 deformation is variable in intensity, areas of strong F3 folding and well developed S3 cleavage trend northeast rather than northwest (FIG.7) and cut across zone B of northwest L3 plunges. It is thought most probable, therefore, that the variation in L3 plunge is due to variation in the orientation of S2 cleavage and lithlogical layering prior to D3 deformation.

The F3 Joma synform has folded the northwest trending L2 lineations. Folded lineation distributions are dependent on the deformation type active during folding and thus these L2 distributions can be used to give information on the D3 folding mechanism by comparing simple theoretical models with the observed distributions. The possible theoretical patterns shown by folded lineations can be represented by those formed by two end member folding mechanisms; concentric and simple shear folding. Concentric folding results in small circle distributions about the fold axis and shear folding results in great circle distributions containing the original lineation orientation and the shear direction (Ramsay 1967, chapter 8). The original orientation of L2 is unknown, but was estimated from the hinge zones in 'box-shaped' F3 folds in the quartzitic phyllites, where the original orientation of L2 is thought to be least disturbed. This gives a shallowly northwest plunging lineation direction as the pre-D3, L2 lineation orientation. Assuming that L2 parallels the D2 shear direction, this is in agreement with the overall gentle westerly plunge of the nappes of the Upper Allochthon. The shear direction appropriate to D3 is unknown so the shear folding model was constructed using the best fit great circle to the L2 distributions for zones A, B and C, that passes through the estimated original orientation of L2 (FIG.9). For the concentric folding model, the best fit small circles about the F3 fold hinge, determined from the maxima of L3 orientations, were constructed (FIG.9).

Plots of L2 distribution for these three zones A, B and C (FIG.9) show that there is no significant variation in the L2 patterns across the region. The theoretical distributions derived from the models, show similar patterns for zones A and C, but are significantly different for zone B where the simple shear model shows the best fit to the data. The concentric folding model could be modified to provide a better fit to the observed data by additional pure shear deformation in which the maximum compression is orientated perpendicular to the fold axial plane and the minimum compression steeply plunging. This would rotate the lineations towards a great circle distribution in better agreement with the distribution shown by L2 lineations. However, this would also tend to rotate the F3 fold hinges and, as these have remained at a high angle to the L2 trend, it seems unlikely that significant pure shear deformation of this orientation can have taken place. Thus, the distribution of L2 lineations indicates that F3 folding probably developed by a dominantly simple shear mechanism.

D4 Deformation

Late phase D4 deformation within the Leipikvattnet Nappe in the Joma area is expressed as conjugate sets of minor kink folds which occur sporadically but are concentrated in the southwest, adjacent to the thrust contact with the Gjersvik nappe. Axial plane orientations are highly variable (FIG.10) but conjugate set intersections consistently plunge subhorizontally with northeast and southwest trends (FIG.10). Their geometry indicates an overall moderate to steep northwest plunging direction of maximum compression.

In the region around the Joma area, D3 and D4 structures were found to show a complementary spacial relationship. Approaching the upper bounding thrust of the Leipikvattnet Nappe, D3 deformation becomes less intense while D4 structures become more wide spread. In the overlying Gjersvik nappe, no F3 folds were identified and the shallowly dipping member of F4 conjugate set becomes dominant. Where both F3 and F4 structures occur, F4 postdate F3 folds, but the spatial relationship between the two phases of deformation suggests a close relationship and it is thought that D4 deformation probably followed D3 within a narrow time interval.

Strain Analysis.

Estimation of finite strain was carried out to aid in the interpretation of the mechanisms that gave rise to the various deformation phases identified from the analysis of minor structures. Possible strain markers in the Joma region include pillows and variolitic structures within the pillow lavas. The large size of outcrop required for reliable strain measurement and their restricted distribution in a sufficiently good state of preservation made the pillow lavas unsuitable for strain analysis. Thus the variolitic structures which occur widely throughout the outer greenstone, and for which relatively small samples were required, were chosen as strain markers.

The variolitic structures found in the outer greenstones occur in groups of subspherical to ellipsoidal particles (Plate II). The variolites are 1 to 10cm in length, and are composed of concentric layers rich in actinolite, plagioclase, clinozoisite and sphene. They may be either paler or darker than their matrix, depending on the relative concentrations of clinozoisite and sphene. The origin of these structures is unknown, but their location within pillows, the observation that the groups do not cross pillow margins, and the correspondence between their elongation and intensity of S2 cleavage, suggests that they are an origin feature of the pillowed greenstone. The similarity of shape shown by variolites from the same locality suggests that they were originally approximately spherical and the near spherical shapes of specimens from areas of low D2 deformation supports this.

The method

Each specimen was cut along three, mutually perpendicular planes, chosen so that one of the planes coincided with the S2 cleavage, and a second, perpendicular to S2 containing the L2 lineation. These planes were thought to approximate the principal planes of the D2 (the most intense deformation phase) strain ellipsoid and were chosen as measurement on the principal planes improves the accuracy of the results. Each face was enlarged photographically (magification of up to 10X) so that individual variolites were a minimum of 1cm across. The long axis orientation of each variolite was estimated by eye and measured to the nearest degree. Long and short axes were measured to within 0.01mm (after magnification), from which the axial ratio was calculated.

The shape of an initially spherical particle after deformation defines the finite strain ellipsoid. Thus an estimate of finite strain can be obtained from a group of initially subspherical particles by arithmetically averaging their axial ratios. However, if the initial shape of the particles significantly departed from spherical, this leads to overestimation of the axial ratios (Lisle 1977) and a method which takes the initial variation in long axis orientation into consideration is required. Shimamoto and Ikeda (1976) has shown that, if the long axis of initially elliptical particles are randomly oriented, the strain ellipse can be obtained from the deformed sample by averaging the components of the 2X2 matrices each of which represents the shape and orientation of an elliptical particle.

For a test specimen of the variolitic greenstone, finite strain was estimated for each of the three faces using the two methods described above. The first method assumes that the particles were initially spherical and involves calculation of the arithmetic average of particle long axis orientations and axial ratios. 95% confidence limits were calculated on the axial ratios (assuming a normal distribution) and long axis orientations (assuming a Von Mises distribution, method after Cheeney 1983). The second method (Shimamoto and Ikeda 1976) assumes that the particles were initially non-spherical and of random orientation. Each method was applied to 20, 30, 40 and 50 particles per face to test for the number of particles needed to give a satisfactorily reproducible result. The results of the two methods, shown in Table 1, agree to within the 95% confidence limits for the arithmetic method for both long axis orientations and axial ratios. There is, therefore, little error in assuming that the particles were initially spherical in shape. Most of the results for 20, 30, 40 and 50 particles show agreement within the 95% confidence limits for the arithmetic method, although an improvement in consistency was found if 30 or more particles were measured.

The arithmetic average of long axis orientations and axial ratios for a minimum of 30 (?) particles was calculated for each of the three faces from ten specimens of pillowed greenstone containing variolitic structures. Specimen 10 contains highly elongate variolites which have been folded by D3. In order to measure finite strain from this specimen, the lengths of the variolites were measured around F3 folds and their orientation assumed to be that of F3 fold long limbs. The finite strain result from this specimen therefore indicates largely D2 strain, the effects of F3 folding having been removed. The two dimensional results were then combined using a method and computer programme developed by Gendzwill and Stauffer (1981) to obtain the three dimensional finite strain ellipsoid. In this method, the two dimensional results are adjusted until a fit to a three dimensional ellipsoid is obtained. The adjustments applied were found to lie within the 95% confidence limits on the two dimensional data.

Finite strain analysis results

The results from the finite strain analysis of 10 specimens are listed in Table 2 and plotted in FIG.11. A logarithmic plot of the axial ratio, a (maximum/intermediate) versus b, (intermediate/minimum) is shown in FIG.11(a). All specimens show close to plane strain (k=1) and lie consistently on the flattening side of the k=1 line, with a wide range in intensity values. The maximum and minimum axes orientations are plotted on a lower hemisphere Lambert Equal area projection in FIG.11(b) and show a wide scatter due to later F3 folding. The maximum axes show an arcuate trend similar to that for L2 lineations, which indicates that L2 lineations parallel the D2 strain maximum.

The lowest strains, specimens 3 and 4, come from the central part of the eastern Joma Synform limb whereas the highest strains, specimens 9 and 10, come from the western limb. This shows agreement with the qualitative estimations of S2 and S3 cleavage intensity throughout the outer greenstone. The finite strains measured (except for specimen 10) reflect the total strain experienced by the rock, i.e., the results of D1, D2 and D3 deformation phases. It has been suggested from fold interference patterns in the quarztitic phyllites, that D1 and D2 deformations are coaxial and therefore equivalent to a single deformation from the point of view of strain. The specimens show varying degrees of S3 cleavage development (reflecting D3 deformation intensity) and is most intense in specimens 5, 8, 9 and 10. However, the finite strain results from these specimens do not depart significantly from the plane strain trend shown by specimens with low S3 cleavage development and this supports the suggestion that D3 deformation is coaxial with D1 and D2 deformation.

The near plane strain results for the finite strain analysis are consistent with a dominantly simple shear deformation mechanism for the main deformation (D1 and D2) with a northwest/southeast trending shear direction. This is also consistent with the distributions of folded L2 lineations around the Joma Synform which have been shown to imply a dominantly simple shear deformation mechanism during D3. The asymmetry of the Joma synform indicates a southeasterly directed shear sense during D3 deformation, which is in agreement with the generally supposed direction of nappe movement during D1/D2 deformation phases. This suggests that D1, D2 and D3 deformations are not only coaxial but also shared the same shear sense.

Discussion and Conclusions.

Correlation of deformation phases of the Joma area with the rest of the central Scandinavian Caledonides.
Four phases of deformation have been recognized in the Joma area of which the first and second comprise the deformation associated with movement on the major and internal thrust planes. Within the central Scandinavian Caledonides in general, three to five deformation phases are recognized, indicating the heterogeneity of deformation on this scale. The Joma Synform (F3 in this study) belongs to a major set of upright folds (Zachrisson 1969) which can be traced throughout the central Scandinavian Caledonides (FIG. 12). These folds trend north to northeast, plunge shallowly north or south and are associated with a variably developed crenulation cleavage, locally penetrative. In detail, these major folds are composed of a series of *en echelon*

smaller folds which are characteristically impersistent along strike, examples of which are described from the Marsfjällen area (Trouw 1973), the Western Synform (Zachrisson 1969) and the Joma Synform (this study). These major fold trends can, however, be traced for distances of several hundreds of kms and they can therefore be used to correlate the deformation sequences of different areas within the central Scandinavian Caledonides.

The pre-D3 deformation sequence: Between one and three phases are recognized as pre-dating the major, northeast trending F3 folds. Throughout most of the area two phases are recognized, as in the Joma area, but in the Gjersvik Nappe only one has been found (Roberts 1979, Lutro 1979, Halls et al. 1977) and in the Tärna-Björkvattnet and Kvarnsbergsvattnet areas (Stephens 1977, Sjöstrand 1978) three phases are identified. These deformation phases are associated with a penetrative and crenulation cleavages subparallel to the major thrust planes and it is generally agreed that they are associated with major movement on these planes. Mineral and rodding lineations and pebble elongations (Lisle 1984 and others mentioned in the text above, after restoration to pre-D3 orientations) trend east-west to northwest-southeast (FIG.12) and are thought to reflect the movement direction of the nappe sequence.

Fold axes generally trend parallel to these lineations where associated with a penetrative cleavage, but show oblique trends where associated with a crenulation cleavage, e.g. in the Marsfjällen area (Trouw 1973). This is thought to reflect the rotation of fold axes during progressive simple shear, from perpendicular to parallel to the shear direction. In some areas, the crenulation cleavage can be traced laterally into a penetrative cleavage (Trouw 1973, Sandwall 1981). Early phases of deformation, predating the local penetrative cleavage, are preserved in garnet cores (Trouw 1973, Sjöstrand 1978, Lutro 1979) and as small scale folds (Stephens 1977, this study).

These phases of deformation can be interpreted as representing a repeated deformation cycle occurring within the same deformation event, in a similar way to that recorded in shear zones (Escher & Watterson 1974, Bell 1978, Platt 1983). The cycle begins with the development of folds with hinges at right angles to the shear direction with which a crenulation cleavage, initiated at 45^o to the shear plane, is associated. As deformation proceeds the crenulation cleavage rotates towards the shear plane and becomes penetrative. At the same time, fold hinges are rotated into the shear direction. At a later stage this cleavage is itself folded and a second crenulation cleavage develops, marking another deformation cycle which, in time, obliterates the earlier fabric. The initiation of a new cycle (deformation phase) may be triggered by changes in dip of the thrust planes or cleavage planes (Bell 1978), caused, e.g., by the bending of nappes around others or wrapping of cleavage around competent masses. Platt (1983) also suggests that changes in strain rate can cause the foliation planes to rotate through the shear plane, thus initiating folds. In the Joma area, evidence of three such cycles has been identified, labelled D1, D2 and D3 phases. The variation in the of number of cycles recognized in different areas within the central Scandinavian Caledonides, illustrates the heterogeneity of deformation on a regional scale and indicates the problems in correlating deformation phases over large distances on the basis of fabric type and style alone.

D3 and later deformation: F3 and later folds fold the major thrust planes and therefore post-date the major nappe emplacement event. F3 folds occur as a conjugate set, the dominant of which trends north to northeast as already described. The subdominant set trends east-west with rather variable axial plane orientations and shallow west to northwest plunges. This set are best developed east and south of the Joma area, where dome and basin structures are locally developed (Halls et al. 1977, Sjöstrand 1978).

Superimposed on and therefore postdating the regional northeast trending folds, are a set of folds and kinks with subhorizontal axial planes and variable, but commonly northeast, plunges which correlate with D4 structures of the Joma area. This deformation varies widely in intensity from occasional minor kinks or weakly developed crenulation cleavage to near isoclinal folds of chevron style with well developed crenulation cleavage, occasionally penetrative. In areas where D4 structures are only weakly developed they are most commonly observed on steep standing schistosities (Stephens 1979, Sjöstrand 1978). Wherever observed, D4 folds verge down the dip of the previous schistosity and therefore show opposite vergence on east and west limbs of many of the major F3 folds (Zachrisson 1969).

In the Joma area, D4 structures were found to have a complimentary spacial relationship with D3 deformation, being best developed in and adjacent to the Gjersvik Nappe (Roberts 1979, Lutro 1979) where D3 deformation is weak. From descriptions of the structure of the Lierne district (Aukes et al. 1979), it is possible that D3 and D4 structures show a similar relationship in the Köli and Seve Nappes there. Close to tight folds with subhorizontal axial planes (F3 of Aukes 1979) in the Offerdal Nappe and in the Lower and Upper Köli sequence probably correspond to F4 folds of the Joma area. This deformation is described as most intense in the Lower Köli where a strong crenulation cleavage is developed. In the Seve Nappe to the east, no mention is given of flat lying folds but their Group II folds, open folds with steeply dipping axial planes which fold the regional foliation, can be interpreted as corresponding to F3 of the Joma area. Westwards from the Lower Köli sequence, F4 folds become more open and isoclinal folds dipping moderately to steeply northwest (their F2) become dominant. These could represent F2 or F3 folds described here. It thus appears that there is a zone of flatlying folds (D4?) trending approximately northeast from the pronounced bend in the Grong-Olden culmination west of Nordli which may be flanked by zones where northwest trending, moderately to steeply dipping folds (D3?) are developed. If this is the case, it may be that the spacial relationship between D3 and D4 deformation described in the Joma area is a more general phenomenon and may exist, still to be described, in other areas.

Relationship and possible origin of F3 and F2 folds

F3 folds deform the major thrust planes and therefore post-date the main thrusting event. Analysis of folded L2 lineation patterns and finite strain from the Joma area indicate that F3 folding was generated by dominantly simple shear and it is suggested that D3 deformation is a continuation of the deformation that occurred during the main thrusting event. The cause of cessation of movement on the major thrust planes is unknown but could have been caused by, for instance, a decrease in fluid pressure resulting from a decrease in overburden thickness or rotation of the thrust planes into an unfavourable orientation.

Within the central Scandinavian Caledonides, the majority of large scale F3 folds are described from the region to the east of the broad antiformal structure passing through the Bjørgefjell Massive (FIG.1), and this suggests the possibility that they may be associated with late movement of this massive. The Bjørgefjell Massive is one of a series of domal features within the central Scandinavian Caledonides in which basement is exposed, others of which include the Bångfjället dome to the northeast, the Grong-Olden culmination to the south and the Tommerås anticline of the Trondheim region. The majority of these inliers are thought to be autochthonous basement. However, the lack of any negative residual gravity anomaly commonly present over these inliers (Gabrielsen et al. 1981), with the strong Caledonian deformation present in the Børgefjell Massive suggests that the basement exposed in this window may be allochthonous (Greiling 1981). A rise of the Bjørgefjell Massive, either by ductile diapiric rise of the basement or a late eastward movement of the massives on a deep seated thrust plane, would tend to steepen the dip of the major thrust planes, rendering them less effective for accommodating subhorizontal compression. The resulting deformation either from a direct push provided by the rising massive or by gravity sliding of the nappe pile eastwards off the rising dome, would them lead to the development of large scale, upright folds whose axes trended approximately perpendicular to the direction of maximum compression. The location of F3 folds predominantly to the east of the Bjørgefjell Massive, would suggest that some lateral, easterly directed, as well as vertical movement occurred. The evidence that the Joma synform developed under simple shear deformation favours the interpretation that the massives are underlain by a deep seated thrust along which late movement took place.

The spacial relationship between D3 and D4 intensity in the Joma region has led to the suggestion that these two deformation phases are closely linked. In contrast to F3 folds, F4 folds do not form major structures. Their consistent down-dip, sense of overturning, regardless of dip direction, and their subhorizontal axial plane orientation, makes it difficult to relate them to any late movements associated with the main thrusting event, as has been suggested for F3 folding. Late tectonic folds of similar style and orientation are also found in the Trondheim region where they too are consistently overturned down-dip. The subhorizontal attitude of F4 axial planes indicate an approximately vertical direction of maximum compression which with the sense of overturning down dip, is consistent with gravity as the driving force and it has been suggested (Roberts 1967, Roberts et al. 1970) that these structures are the result of gravitation collapse of the nappe pile after the relaxation of the compression responsible for the development of the Caledonides. In the Kopperå-Riksgrensen area (Roberts 1967), he postulates an origin by gravitational sliding towards the deep rooted core of the early Stjørdalen fold. Although correlation of deformation phases across the Grong-Olden culmination is problematic, the similarity in style, orientation, intensity and the late timing suggest a similar origin and Roberts (in Kollung 1979) has also suggested that the structures north of the Grong-Olden Culmination are of gravitational origin, forming on the flanks of pre-existing folds.

Previous to D4 deformation, fold and thrust structures indicated an approximately horizontal orientation for the maximum compression direction and thus between the third and fourth deformation the horizontal stress were reduced to a level less than that induced by the overburden. However, because all rocks of the Caledonides do not show well developed D4 structures, the resulting differential stresses became large enough to generate significant deformation only in selected areas. It has been suggested that F3 folds could have resulted from late stage movements of the Bjørgefjell Massive which generated compression east of the uplift zone. Such an uplift would also have resulted in reduced horizontal compression overlying the massive. If the horizontal compression were reduced sufficiently, the vertical stress due to overburden pressure could become the maximum stress direction and could have led to the development of folds with subhorizontal axial planes, the gravitational collapse mechanism described by Roberts (1967).

In this model, the relative timing between the development of steeply dipping, northeast trending and subhorizontal folds is dependent on the movement direction of the massives and the pre-existing stress system. It is likely that the stress system prior to the development of F3 folds was one of horizontal compression. It may therefore have required little extra compression to initiate the steeply dipping folding to the east. However, to reduce the horizontal compression to less than the overburden pressure by an amount large enough to generate subhorizontal folds probably comprised a greater change in the stress system. Thus folds due to gravitational forces would be likely to post-date the steeply dipping,northeast trending folds. As the compressional stresses that were responsible for the development of the Caledonian orogeny waned, all rocks would eventually experience a maximum vertical stress due to overburden. However, as subhorizontally oriented minor structures are poorly developed throughout most of the central Scandinavian Caledonides, it seems that, by this time, the overburden thickness had been reduced by erosion so that the vertical stress was no longer sufficient to cause significant ductile deformation.

It is suggested, therefore, that reactivation of movement involving the Bjørgefjell Massive occurred late in the history of the central Scandinavian Caledonides. These movements created compression, most pronounced to the east of the massive, and probably tilted the major thrust planes so that they were no longer effective. This resulted in the development of major upright, northeast trending folds, largely to the east of the major Bjørgefjell Massive. Movement of the massive caused reduced horizontal compression over its crest so that vertical stress due to overburden became the maximum stress which, in the Gjersvik Nappe of the Joma area, became large enough to cause the development of folds with subhorizontal axes. The relative timing of D3 and D4 deformation phases can be explained by the magnitude of the changes in the stress system needed to initiate these deformations. From descriptions of late, subhorizontal folds in the Lierne district (Aukes et al. 1979) and the Trondheim region (Roberts 1967, Roberts et al. 1970) deformation associated with subhorizontal folds is widespread throughout at least the central Scandinavian Caledonides. It is not known whether they show a similar relationship with the previous fold phase in these areas, but both in the Lierne and Kopperå-Riksgrensen areas they occur in areas adjacent to basement massives (the Grong-Olden culmination and Tommerås anticline, respectively). It may be, therefore, that late uplift of basement massives also played a role in the development of subhorizontally oriented folds in other areas.

Way up of the Leipikvattnet Nappe in relation to the rest of the Middle Köli

Much of the Middle Köli Nappes have been established as comprising largely inverted stratigraphies. Stephens (1982) established the stratigraphy within the Stikke Nappe as (oldest) graphitic phyllite, metavolcanics (Stekenjokk volcanics), calcareous phyllites (Blåsjö phyllites), (youngest). This stratigraphy and the occurrences of sulphide mineralizations within it are inverted in the Stikke and Gelvanåko Nappes. In the Gjersvik Nappe, the Limingen Group calcareous phyllites are derived from, but structurally underlie, the Gjersvik metavolcanics, thus inferring an inverted stratigraphy for the Gjersvik Nappe (Halls et al. 1977). This is supported by inverted stratigraphies found in the vicinity of the Skorovass (Halls et al.1977) and Gjersvik (Reinsbakken 1986c) ore bodies.

Kollung (1979) suggested that, within the Leipikvattnet Nappe, the stratigraphy quartzite, greenstone phyllite was inverted (on the basis of way up from a few pillow lava localities) and repeated by folding. This was seemingly supported by the work of Olsen (1980) which established that the stratigraphy within the Joma ore deposit was inverted. Stephens et al. (1985) have correlated the Remdalen Group and the Blåsjø phyllite of the Stikke Nappe with the Røyrvik Group and Brakkfjället phyllite of the Leipikvattnet Nappe. The location of the Brakkfjället phyllite structurally below the Røyrvik Group then inferred the inversion of stratigraphy within the Leipikvattnet Nappe although it was admitted that the relationship between the Brakkfjället phyllite and the Røyrvik Group was uncertain.

The present study of the Joma area suggests that the stratigraphy (oldest) greenstone, quartzitic phyllite, graphitic phyllite (youngest) is repeated tectonically and that the bulk of the Leipikvattnet Nappe is the correct way up. The outcrop pattern in the middle greenstone indicates that the ore body lies in the overturned limb of a major F2 fold and thus the inversion of the ore body does not imply general inversion of the stratigraphy within the Leipikvattnet Nappe. Pillow lavas were generally found to be too deformed to be reliable as way up indicators. It has been tentatively suggested that not only the middle and inner greenstones but also the outer greenstone has a tectonic lower contact. If this is so, the Brakkfjället phyllite is separated by a thrust located at the base of the outer greenstone from the Røyrvik Group and need not imply inversion of the stratigraphy.

Stephens (1986) suggests that the inverted stratigraphy of the Middle Köi Nappes developed from a series of early, overturned large scale, east facing folds and that later thrusting cut out the right way up limbs. If the Leipikvattnet Nappe is dominantly the correct way up it represents an exemption to this pattern. A possible reason for this may lie in the presence of the large mass of greenstone now represented by the Røyrvik greenstones. Such a competent mass may have inhibited folding and promoted the development of smaller scale internal thrusts within the Leipikvattnet Nappe which have not been identified in the other Middle Köli Nappes.

Environment of deposition of the Røyrvik Greenstone and the Joma Sulphide Deposit

Chemical analysis of the Joma pillowed greenstones by Olsen (1980), Stephens et al. (1985) and Reinsbakken (1986b) have shown that they represent tholeiitic to alkaline basalts with mid ocean ridge and within plate basalt affinities. Olsen originally interpreted them as representing a back-arc basin but subsequent data from the Middle Köli has led Stephens and Gee (1985) to interpret the Røyrvik Group of the Leipikvattnet Nappe and the Remdalen Group of the Stikke and Gelvanåkko Nappes as representing the ocean floor on which the island arc, represented by the Gjersvik igneous complex, was developed. They thus interpret the Joma pillowed lavas as representing the top layer of ocean floor in a probably off-axis situation.

Lithological and structural mapping has shown that the three greenstone layers of the Joma area probably represent tectonically repeated segments of an originally single horizon which was composed of massive and pillowed flows and volcaniclastic deposits. The greenstone layers show a marked thickening of their outcrop in the core of the Joma Synform which was attributed by Kollung (1979) to deformation associated with this fold. However, detailed structural mapping of the greenstone units has shown no correlation of the outcrop pattern with the intensity of either D2 or D3 deformation and it is thought that their shape reflects an original thickness variation.

Returning the three layers of greenstone to their probable original relative positions by transporting the middle and inner greenstone east of the outer greenstone would suggest that the massive lavas grade laterally into pillowed lavas which are overlain by volcaniclastic deposits. Both the middle and outer greenstones thin and finally disappear against the location of probable thrusts southwards along the east limb of the Joma synform. To the east the greenstone horizons become thin and are composed of numerous horizons intercalated with phyllites. Here, no remnants of the pillow structures have been seen and the greenstone most closely resembles the volcaniclastic deposits of the Joma area (H. Horbach, pers.comm.). Thus it seems that the massive and pillowed lava flows that compose a significant proportion of the greenstone in the Joma area are of limited extent and grade laterally and upwards into volcaniclastic deposits.

The pillow lavas indicate basaltic eruption in an aqueous environment. The massive flows probably indicate eruption in a subaerial environment and the thin layer of phyllites within the massive flows can be interpreted as mixed chemical/biological and volaniclastic sediments deposited in shallow lakes on the lava flow surfaces. This, coupled with the oceanic environment indicated by their chemical composition, suggests that the greenstones represent the remnants of an volcanic oceanic island. The laminated nature of the overlying volcaniclastic deposits suggests that they were water lain, with the most likely sediment source being the island itself. The contact between greenstone and phyllites is thought to be primary and therefore suggests that the oceanic island finally sank beneath sea level after which the quartzitic phyllites, which have been interpreted as ribbon cherts (Stephens 1986), and graphitic phyllites were deposited, the fine grain size presumably indicating a location far from any sediment source.

The Joma sulphide deposit, which has been proposed to be of exhalative, submarine origin on the basis of stratigraphy and chemical composition (Olsen 1980, Reinsbakken 1986b), is situated within the pillowed lavas. This suggests that the hydrothermal activity associated with the deposit occurred on the flanks of the oceanic island slightly removed from the main centre of igneous activity. Similar, though smaller centres of hydrothermal activity, are probably represented by the sulphide occurrences approximately 1km to the southwest of the main Joma deposit and at Borvasselv, approximately 9km west of Joma, both within the middle greenstone unit.

Summary

The Leipikvattnet Nappe in the Joma area is composed of the twice repeated structural sequence; greenstone, quartz phyllite, graphitic phyllite, with a third greenstone unit outcropping adjacent with the thrust contact with the overlying Gjersvik Nappe. Field evidence has shown that this sequence has been tectonically repeated and that the upper two greenstone units (termed the middle and inner greenstone, respectively) and possibly the lowest unit (the outer greenstone) are underlain by thrusts internal to the Leipikvattnet Nappe. The rocks show evidence of four phases of deformation of which the first two are associated with the major nappe emplacement event and the thrusts internal to the Leipikvattnet Nappe.

The main penetrative cleavage is associated with D2 deformation and the vergence of F2 folds within the quartzitic phyllites indicates the possible presence of an antiform to the north and synform to the south. D1 structures are occasionally preserved within the quartzitic phyllites and fold interference patterns and lineations indicate that D1 and D2 deformations are essentially coaxial. The outcrop pattern of pillowed lavas and volcaniclastic deposits of the middle greenstone and bore hole logging by Reinsbakken (1986a) indicates the presence of a large scale F2 antiform whose lower limb, containing the Joma sulphide deposit, is cut by the thrust at the base of the middle greenstone. Further evidence of this fold is given by the vergence of F2 folds in the Joma deposit which are of opposite to those in the quarztitic phyllites. Lithological and chemical studies (Olsen 1980, Reinsbakken 1986b) have shown that the ore body is of exhalitive, submarine origin and that its stratigraphy is inverted. Its presence on the overturned limb of the large F2 fold therefore implies that the structural sequence; greenstone, quartzitic phyllite, graphitic phyllite, is also stratigraphical. Major folds within the other greenstone units are not suspected, and thus the majority of the Leipikvattnet Nappe is interpreted as being the correct way up. It has been established by other authors (Stephens 1982, Halls et al. 1977) that most of the other nappes within the Middle Köli (Stikke, Gelvanåkko and Gjersvik) contain largely inverted stratigraphies and in this respect the Leipikvattnet Nappe appears to the exception to the rule. A possible reason for this may lie in the presence of the large competent mass formed by the Røyrvik greenstones before disruption by thrusting which may have inhibited folding and encouraged the development of internal thrusts which have not been identified in the other nappes of the Middle Köli.

Regionally, between one and three deformation phases which pre-date the major F3 folds, and are generally agreed to be associated with the major thrusting event, are identified. Fold axes associated with penetrative cleavages trend generally eastwards while those associated with crenulation cleavages trend north to northeast. This is interpreted as reflecting a repeated cycle of deformation similar to that described from shear zones (Escher and Watterson 1974, Bell 1978, Platt 1981) in which folds initially form with axes perpendicular to the shear direction and rotate into this direction with progressive deformation while accompanied by a progression from crenulation to penetrative cleavage.

The third phase of deformation (D3) post-dates movement on the major thrust planes and formed the major upright, open to tight Joma Synform with which a crenulation cleavage, rarely penetrative, is associated. F3 folds are characteristically discontinuous along strike and the Joma Synform itself dies out southwards to be replaced by another F3 fold to the west. Distributions formed by the folded L2 lineations suggest that deformation during D3 was dominantly simple shear. Strain analysis of variolitic structures within the pillow lavas of the outer greenstone indicates plane strain regardless of intensity of D2 or D3 deformation. This is consistent with coaxial simple shear deformation during D2 and D3 and the asymmetry of the Joma synform indicates a similar shear sense. It is therefore suggested that D3 deformation is a late expression of the major event that led to the development of the nappe pile.

The majority of the major upright F3 folds in the central Scandinavian Caledonides are located to the east of the Bjørgefjell Massive and it is suggested that they have resulted from the late movement of this massive which structural and geophysical evidence (Greiling 1981, Gabrielsen et al. 1981) suggests is of allochthonous character. The cessation of movement on the thrust planes that occurred prior to D3 deformation may then have been connected with an easterly tilting associated with the rise of the massive which rotated the thrusts into an unfavourable orientation to accommodate compression.

The subhorizontal attitude of D4 folds implies that the direction of maximum compression changed from subhorizontal during D3 to subvertical during D4, while the spacial relationship between D3 and D4 deformation in the Joma area is thought to indicate a close link between the two phases. It is therefore suggested that D4 folds resulted from reduced horizontal compression over the top of the rising Bjørgefjell Massive when the vertical stress induced by the overburden was high enough to result in ductile deformation. This is similar to the gravitational collapse mechanism suggested by Roberts (1967) for similar folds in the Trondheim region but also suggests that, in the Joma area, their origin is closely linked to movement of the Bjørgefjell Massive. Reports of a possible similar spacial relationship between D3 and D4 structures in the Lierne district (Aukes et al. 1979) may indicate that this mechanism is more wide spread.

Restoring the three greenstones within the Leipikvattnet Nappe of the Joma area to their original position, shows that massive lavas (interpreted as subaerial flows) graded laterally into pillow lavas (extruded in a marine environment), overlain by probably water lain, volcaniclastic deposits. Chemical analysis of the pillowed greenstones of the Røyrvik greenstone (Olsen 1980, Stephens et al. 1985, Reinsbakken 1986b) have shown that they are of tholeitic and alkaline basalt character with mid-ocean-ridge and within-plate basalt affinities. The Røyrvik Group greenstones have been correlated with the Remdalen Group of the underlying Stikke and Gelvaåkko Nappe and interpreted as representing the ocean floor on which the island arc of the Gjersvik group was built (Stephens and Gee 1985). On the basis of lithological and chemical characteristics, it is suggested that the Røyrvik greenstones represent the remnants of a basaltic oceanic island, on the flanks of which hydrothermal action led to the deposition of the Joma sulphide ore body.

References

Aukes P.G., Reymer A.P.S., de Ruiter G.W.M., Stel H., Swart H.T., 1979 The geology of the Lierne District, northeast of the Grong culmination, central Norway. *Nor. geol. unders., 354*, 115-129.

Bell T.H. 1978 Progressive deformation and reorientation of fold axes in a ductile mylonite zone: the Woodroffe thrust. *Tectonophysics 44*, 285-320.

Cheeney R.F. 1983 Statistical methods in geology. George Allen & Unwin, Publ. 169p.

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

Gabrielsen R.H., Ramberg I.B., Mørk M.B.E., Tveiten B. 1981 Regional geological, tectonic and geophysical features of Nordland, Norway. *Earth Evol.Sci.,1*, 14-26.

Gendzwill D.J., Stauffer M.R. 1981 Analysis of triaxial ellipsoids; their shapes, plane sections and plane projections. *Math.Geol., 13*, 135-152.

Greiling R. 1981 Caledonian thrusting in the basement rocks of the Bjørgefjell window (north-central Scandinavian Caledonides) as related to major nappe transport. (Abstract) *Terra Cognita 1*, 47p

Häggbom O. 1978 Polyphase deformation of a discontinuous nappe in the central Scandinavian Caledonides. *Geol. Forën. Stock. Förh., 100*, 349-354.

Halls C., Reinsbakken A., Ferriday I., Haugen A. 1977 Geological setting of the Skorovass orebody within the allochthonous volcanic stratigraphy of the Gjersvik Nappe, central Norway. *Spec.Pub. 7, Geol.Soc.Lond.*, 128-151.

Kollung S. 1979 Stratigraphy and major structures of the Grong district, Nord-Trondelag. *Nor. geol. unders., 354*, 1-51.

Lisle R.J. 1977 Estimation of the tectonic strain ratio from the mean shape of deformed elliptical markers. *Geol.Minj., 56*, 140-144.

Lisle R.J. 1984 Strain discontinuities within the Seve-Köli Nappe complex, Scandinavian Caledonides. *J. Struct. Geol., 6*, 101-110.

Lutro O., 1979 The geology of the Gjersvik area, Nord-Trøndelag, central Norway. *Nor. geol. unders., 354*, 53-100.

Odling N.E. (in press) Deformation of the Joma sulphide deposit, Caledonides of N. Trøndelag, Norway. *Proceed. VII Quad. IAGOD Symp.* E. Schweizerbart'sche, Stuttgart.

Olsen J. 1980 Genesis of the Joma stratiform sulphide deposit, central Scandinavian Caledonides. *Proceed. V Quad. IAGOD Symp.*, E. Schweizerbart'sche, Stuttgart, 745-757.

Platt J.P. 1983 Progressive refolding in ductile shear zones. *J. Struct. Geol.,5*, 619-622.

Ramberg I.B. 1981 The Brakkfjellet tectonic lens: evidence of pinch-and-swell in the Caledonides of Nordland, north central Norway. *Nor. Geol. Tidsskr., 61*, 87-91.

Ramsay J.G. 1967 Folding and fracturing of rocks. McGraw-Hill Ltd. 562p.

Reinsbakken A., 1986a *The geology of the Joma sulphide deposit, Nord-Trøndelag, Norway. Part II: Stratigraphical, petrological, mineralogical and geochemical studies of the ore and its surroundings.* Unpubl.rep., Geol.Inst., N.T.H., Univ. Trondheim, 70pp.

Reinsbakken A. 1986b The Joma Cu-Zn massive sulphide deposit hosted by mafic metavolcanites. *In*: Stephens M.B. (Ed.) Stratabound sulphide deposits in the central Scandinavian Caledonides. *Sver. geol. unders., Ca60*, 45-49.

Reinsbakken A. 1986c The Gjersvik Cu-Zn massive sulphide deposit in a bimodal metavolcanic sequence. *In*: Stephens M.B. (Ed.) Stratabound sulphide deposits in the central Scandinavian Caledonides. *Sver. geol. unders., Ca60*, 50-54.

Reinsbakken A., Stephens M.B. 1986 Lithology and deformation in the massive sulphide-bearing Gelvanåkko and Leipikvattnet Nappes, Upper Allochthon. *In*: Stephens M.B. (Ed.) Stratabound sulphide deposits in the central Scandinavian Caledonides. *Sver. geol. unders., Ca60*, 42-45.

Roberts D. 1967 Structural observations from the Kopperå-Riksgrense area and discussion of the tectonics of Stjørdalen and the N.E. Trondheim region. *Nor. geol. unders., 245*, 64-122.

Roberts D. 1979 Structural sequence in the Limingen-Tunnsjøen area of the Grong district, Nord-Trøndelag. *Nor. geol. unders., 354*, 101-114.

Roberts D., Springer J., Wolff F.C., 1970 Evolution of the Caledonides in the northern Trondheim region, Central Norway: a review. *Geol. Mag., 107*, 133-145.

Sandwall J. 1981 Caledonian geology of the Jofjället area, Västerbotten County, Sweden. *Sver. geol. unders., C778*, 105pp.

Shimamoto T., Ikeda Y. 1976 A simple algebraic method for strain estimation from deformed ellipsoidal objects. I Basic theory. *Tectonophysics 6*, 315-337.

Sjöstrand T. 1978 Caledonide geology of the Kvarnsbergsvattnet area, Northern Jämtland, central Sweden: stratigraphy, metamorphism and deformation. *Sver. geol. unders., C735*, 107pp.

Stephens M.B. 1977 Stratigraphy and relationship between folding, metamorphism and thrusting in the Tärna-Björkvattnet area, northern Swedish Caledonides. *Sver. geol. unders., C726*, 146pp.

Stephens M.B. 1982 Field relationships, petrochemistry and petrogenesis of the Stekenjokk volvanites, central Swedish Caledonides. *Sver. geol. unders., C786*, 111pp.

Stephens M.B. 1986 Metallogeny of stratabound sulphide deposits in the central Scandinavian Caledonides. *In*: Stephens M.B. (Ed.) Stratabound sulphide deposits in the central Scandinavian Caledonides. *Sver. geol. unders., Ca60*, 5-16.

Stephens M.B., Gee D.G. 1985 A tectonic model for the evolution of the eugeoclinal terranes in the central Scandinavian Caledonides. *In*: Gee & Sturt (eds.) The Caledonian Orogen - Scandinavia and Related areas. Wiley & Sons Ltd., 953-978.

Stephens M.B., Gustavson M., Ramberg I.B., Zachrisson E. 1985 The Caledonides of central-north Scandinavia - a tectonostratigraphic overview. *In*: Gee & Sturt (eds.) The Caledonide Orogeny - Scandinavia and related areas. Wiley & Sons Ltd., 135-162.

Stephens M.B., Reinsbakken A. 1981 Excursions in the Scandinavian Caledonides. Successions related to island arcs in the Köli Nappes, central Scandinavian Caledonides. U.C.S. Excursion Guide No. B14, Uppsala Caledonide Symposium (UCS).

Trouw R.A.J. 1973 Structural geology of the Marsfjällen area, Caledonides of Västerbotten, Sweden. *Sver. geol. unders., C689*, 115pp.

Zachrisson E. 1964 The Remdalen syncline, stratigraphy and tectonics. *Sver. geol. unders., C596*, 53pp.

Table 1. Results of average ellipse and arithmetic average methods applied to specimen 7, faces 1 to 3.

	long axis orientation		axial ratio	
n	Ave. Ellipse	Arith. Ave.	Ave.Ellipse	Arith. Ave.
specimen 7, face 1				
20	9.5	10.0 ± 3.3	2.14	2.26 ± 0.17
30	10.3	10.7 ± 2.7	2.13	2.24 ± 0.12
40	10.9	11.3 ± 2.2	2.10	2.20 ± 0.10
50	9.9	10.4 ± 2.0	2.14	2.25 ± 0.09
specimen 7, face 2				
20	-3.5	-3.5 ± 2.4	1.74	1.77 ± 0.06
30	-0.0	0.0 ± 3.3	1.63	1.70 ± 0.06
40	0.1	0.6 ± 2.9	1.62	1.69 ± 0.06
50	1.6	1.8 ± 2.7	1.63	1.71 ± 0.06
specimen 7, face 3				
20	1.3	1.1 ± 2.0	3.22	3.39 ± 0.24
30	1.2	1.1 ± 1.8	3.06	3.25 ± 0.20
40	0.5	0.3 ± 1.5	3.15	3.35 ± 0.20
50	0.5	0.4 ± 1.4	3.13	3.33 ± 0.17

Table 2. Results of strain analysis for specimens 1 to 10.

	axis lengths		axis orientations	
Specimen	a	b	X	Z
1	1.45	1.92	62 300	28 116
2	1.57	1.79	25 124	46 244
3	1.31	1.40	04 095	86 294
4	1.15	1.39	24 266	60 123
5	1.65	1.71	unknown orientation	
6	1.47	2.03	50 355	02 086
7	1.52	2.09	34 054	17 312
8	1.57	1.68	66 104	05 004
9	2.18	2.39	33 059	07 325
10	3.33	4.38	36 059	06 154

Figure Captions.

Fig.1 Map of the Central Scandinavian Caledonides after Stephens and Reinsbakken (1981), Häggbom (1978), Ramberg (1981) and Reinsbakken (unpublished data). The Leipikvattnet Nappe outcrops over a distance of 120km from north of the Grong-Olden Culmination to north of the Bjorgefjell Massive.

Fig.2 Geological map of the Joma area, adapted from Kollung (1979) and including additional mapping by the present author.

Fig 3 Stereoplot of poles to S2 cleavage and F2 axial planes. The distribution approximates a great circle whose pole approximates the fold axis of the F3 Joma Synform. Contours at 2, 4, 6, 8, 10, 15 and 20 points per 1% area.

Fig. 4 Map of D2 deformation intensity in the middle greenstone, estimated from S2 cleavage development. Deformation is most intense adjacent to the greenstone lower contact and least intense in the vicinity of the pillow lava outcrop (ornamented).

Fig. 5 Structural cross-section A-B (Fig.4) through the middle greenstone, constructed from long drill holes logged by A. Reinsbakken (Reinsbakken 1986). The greenstone lithologies are reflected about an F2 fold trace and refolded by the F Joma Synform. The Joma sulphide ore body lies on the F2 fold lower limb and both the ore body and the fold are cut by the thrust at the base of the middle greenstone.

Fig.6 Stereoplots of D3 planar structures (S3 crenulation cleavage and F3 fold axial planes) on (a) the northwest limb and (b) the southeast limb of the Joma Synform. Contours at 2, 4, 6, 8, 10 and 20 points per 1% area.

Fig.7 Map showing the variation in L3 plunge in the Joma area and D3 deformation intensity (lined ornament) in the middle greenstone. L3 lineations plunge gently southwest in areas A and B, and subhorizontally to gently northeast in area B. D3 deformation is most intense in the inner arc and the northwestern limb of the Joma Synform within the middle greenstone.

Fig.8 Stereoplots of L3 lineations for areas A, B and C shown in Fig.7. L3 lineations plunge gently southwest (averages of 30^o and 20^o, respectively) in areas A and C, and subhorizontally to gently northeast (average of 8^o) in area B. Contours at 2, 4, 6, 8 and 10 points per 1% area.

Fig.9 Stereoplots of L2 lineation distributions in areas A, B and C and the theoretically expected distributions produced by simple shear and concentric folding. The shear fold model provides the best fit to the data. Contours at 2, 4, 6, 8, 10, 15 and 20 points per 1% area.

Fig.10 Stereoplot showing D4 planar and linear minor structures in the Leipikvattnet Nappe (contoured) and Gjersvik Nappe (solid symbols).

Fig.11 (a) Logarithmic deformation plot of axial ratio 'a' (maximum/intermediate) versus axial ratio 'b' (intermediate/minimum) for the finite strain results obtained from variolitic greenstone, specimens 1 to 10. (b) stereoplot showing finite strain principal axis orientations for specimens 1 to 10.

Fig.12 Map of the Central Scandinavian Caledonides showing mineral lineations, pebble elongations and fold hinge trends for deformation associated with the movement on the major thrusts, constructed from information in the literature mentioned in the text. Outlines of the nappe units are as for FIG.1. Mineral lineations, pebble elongations and fold hinges associated with penetrative cleavage trend northwest-southeast to east-west, parallel to the generally supposed direction of nappe movement. Fold hinges associated with crenulation cleavage show variable trends, mostly north-south to northeast-southwest.

Plate I Microphotograph of F1, F2, F3 and F4 folds in a thin section of quartzitic phyllite.

Plate II Microphotograph of variolitic greenstone used in the estimation of finite strain.

FIG 1.

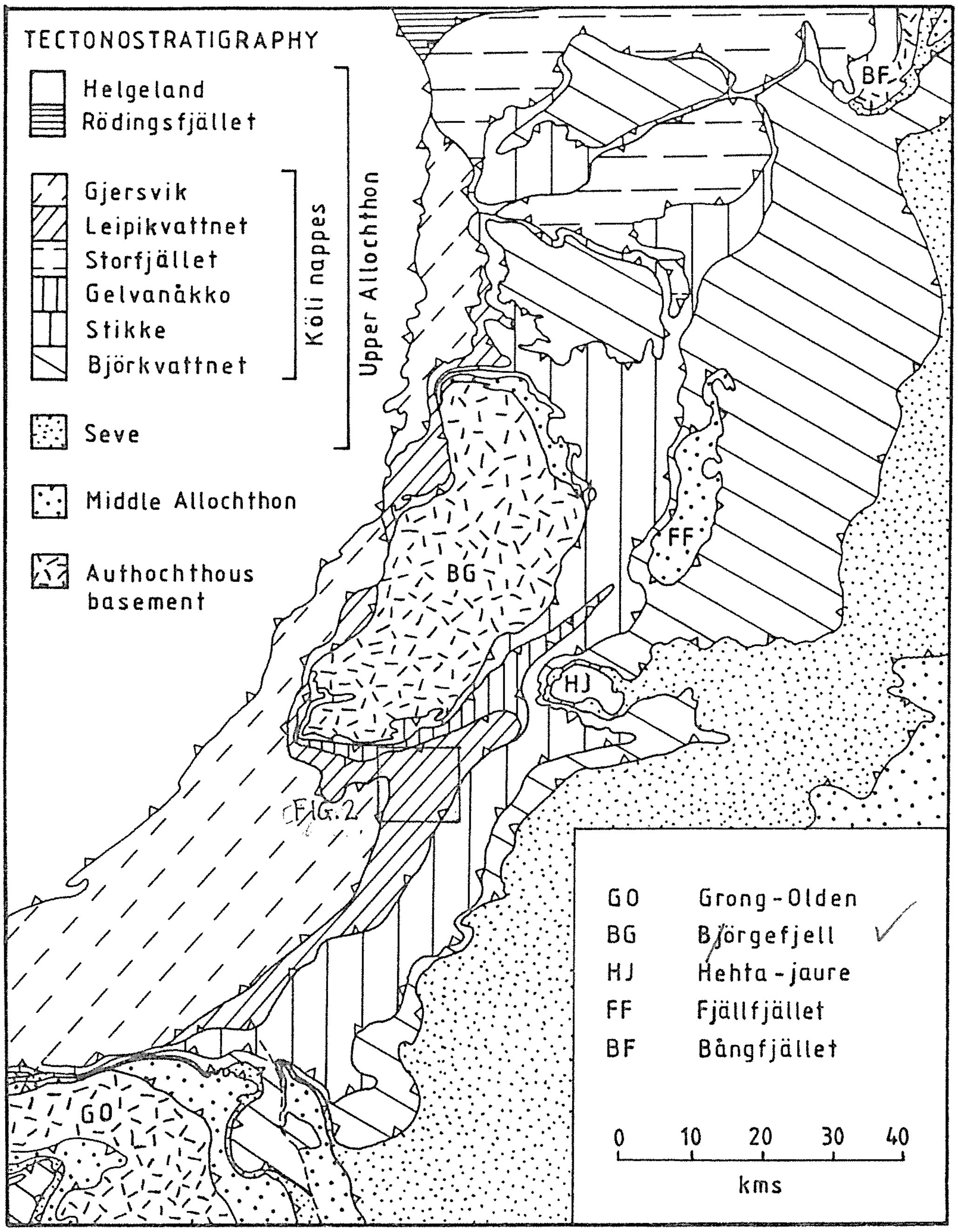
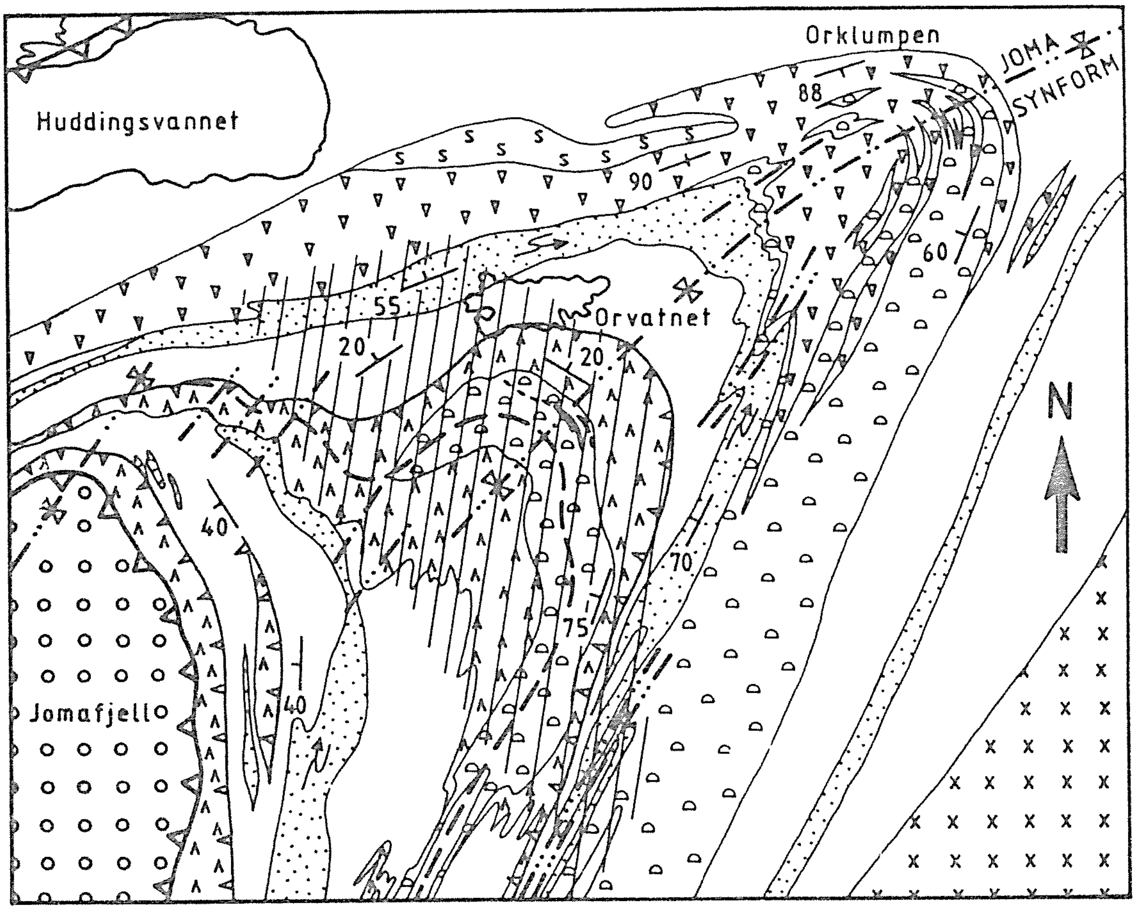

TECTONOSTRATIGRAPHY
Helgeland
Rödingsfjället
Gjersvik
Leipikvattnet
Storfjället
Gelvanåkko
Stikke
Björkvattnet
Köli nappes
Upper Allochthon
Seve
Middle Allochthon
Authochthous basement
BF
FF
BG
HJ
FIG.2
GO
GO Grong-Olden
BG Björgefjell
HJ Hehta-jaure
FF Fjällfjället
BF Bångfjället
0 10 20 30 40
kms

FIG 2



KEY

o o	Metasediments	Limingen Group	GJERSVIK NAPPE
	Graphitic phyllite	Röyrvik Group	LEIPIKVATNET NAPPE
	Quartzitic phyllite		
ʌ ʌ	Volcaniclastic greenstone		
⌓ ⌓	Pillowed greenstone		
▽ ▽	Massive greenstone		
x x	Brakkfjell schist		
s s	Serpentinite		

Outcrop of Joma sulphide deposit

Major thrust contacts to Leipikvatnet nappe

Minor thrusts within Leipikvatnet nappe

F2 fold trace

F2 fold vergence, arrow indicates plunge

F3 fold trace

Average dip of S2 deavage

Zone of subhorizontal F3 fold axes

0 1 2 3 4 5 kms

FIG 3

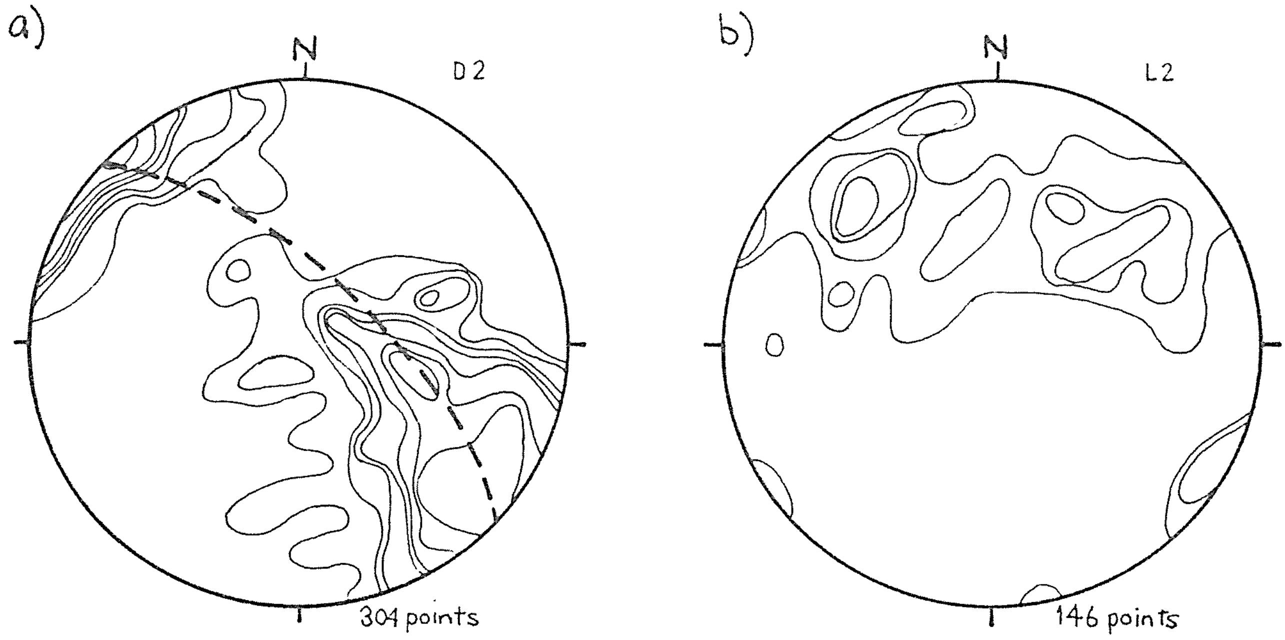


FIG 4.

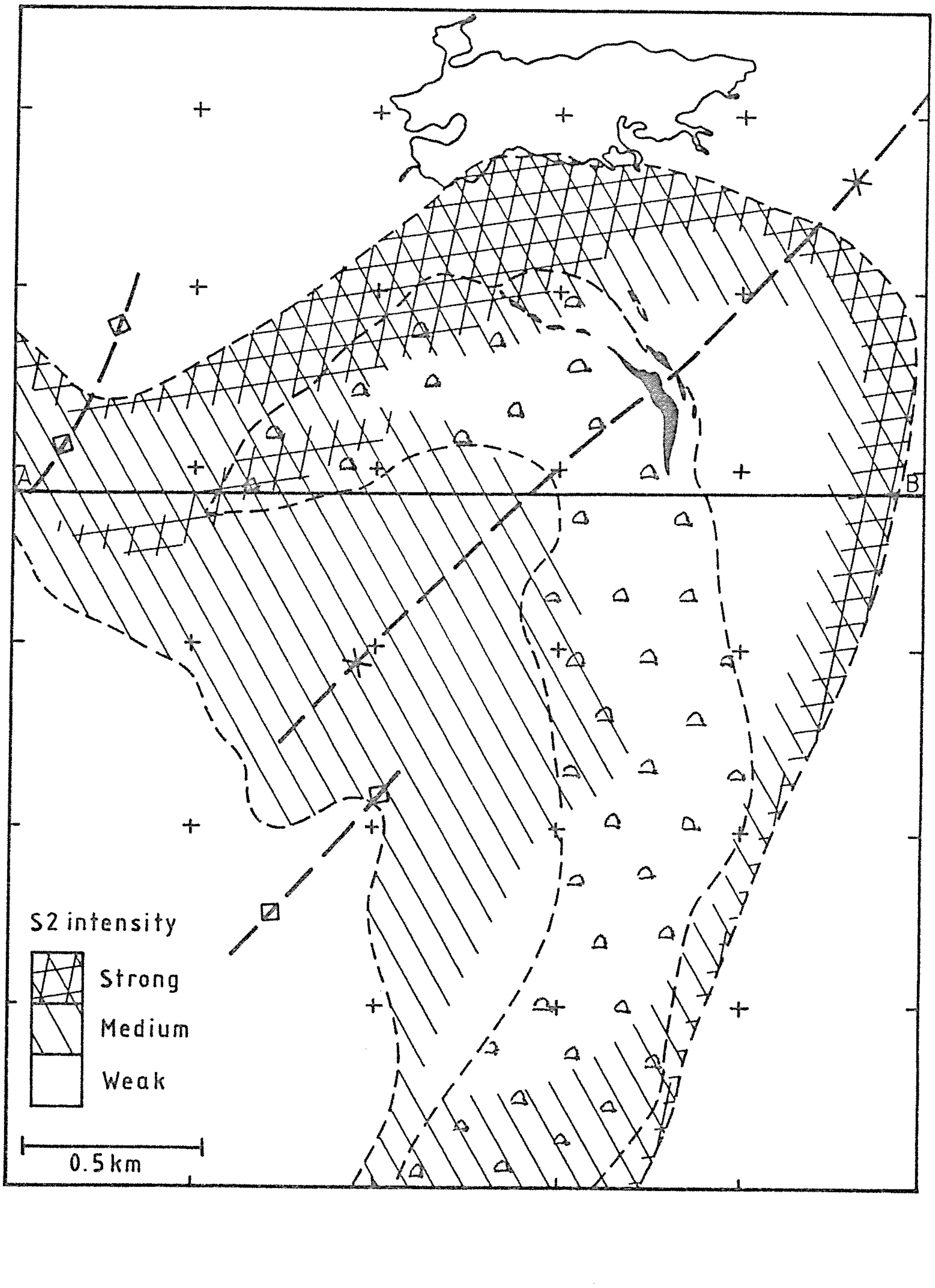
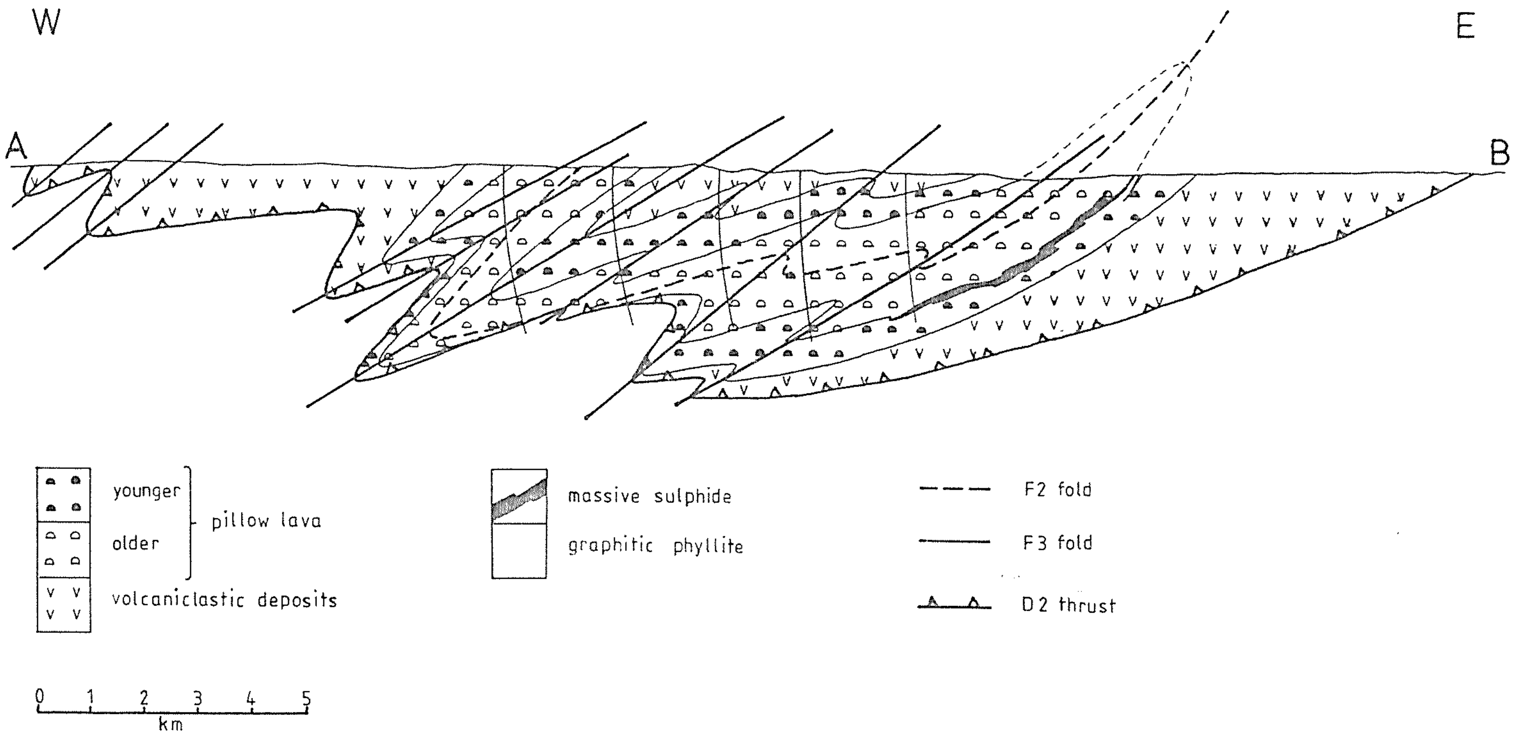
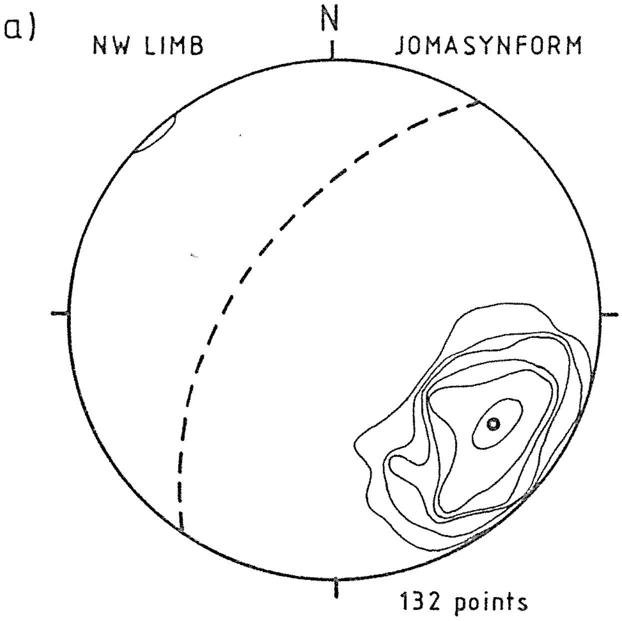


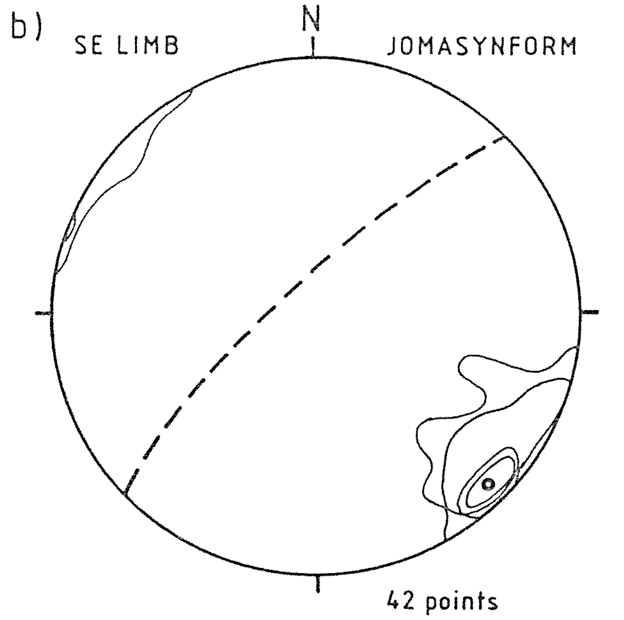
FIG. 5



W
E
A
B
younger
older
pillow lava
volcaniclastic deposits
massive sulphide
graphitic phyllite
F2 fold
F3 fold
D2 thrust
0 1 2 3 4 5
km

FIG. 6





Poles to S3 crenulation cleavage
and F3 fold axial planes.
Contours at 2, 4, 6, 8, 10 and 20 points per 1% area

FIG. 7.

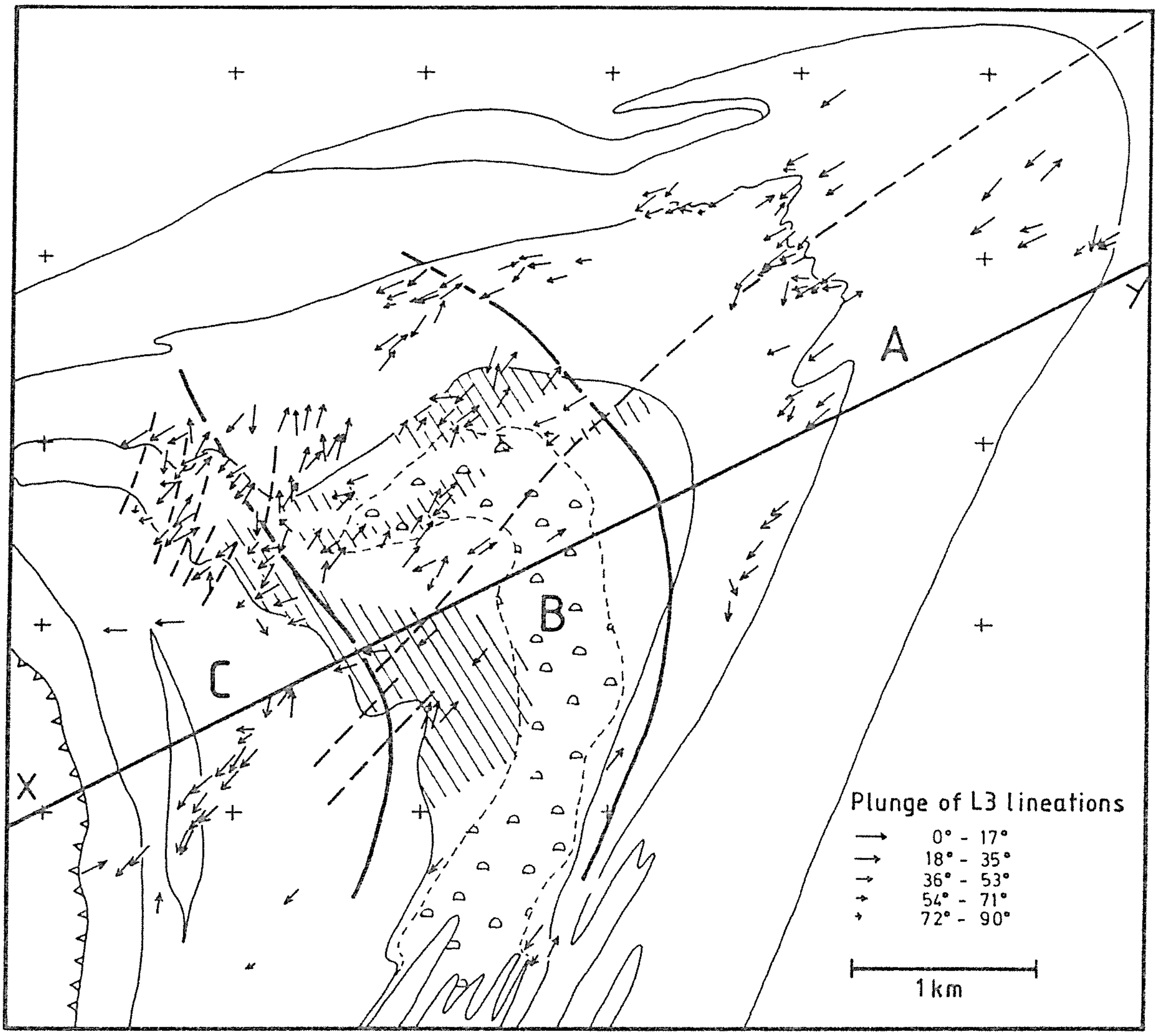
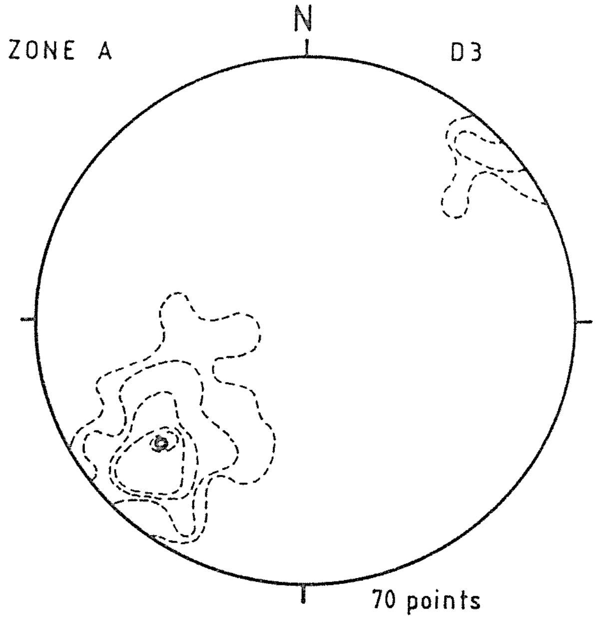
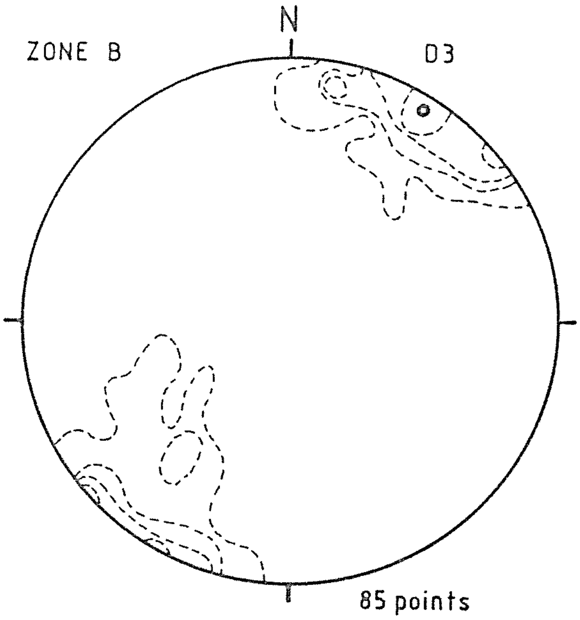
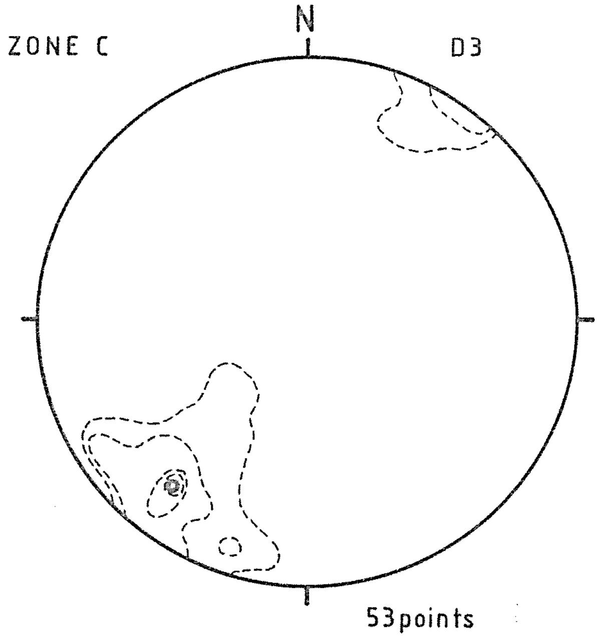


FIG. 8



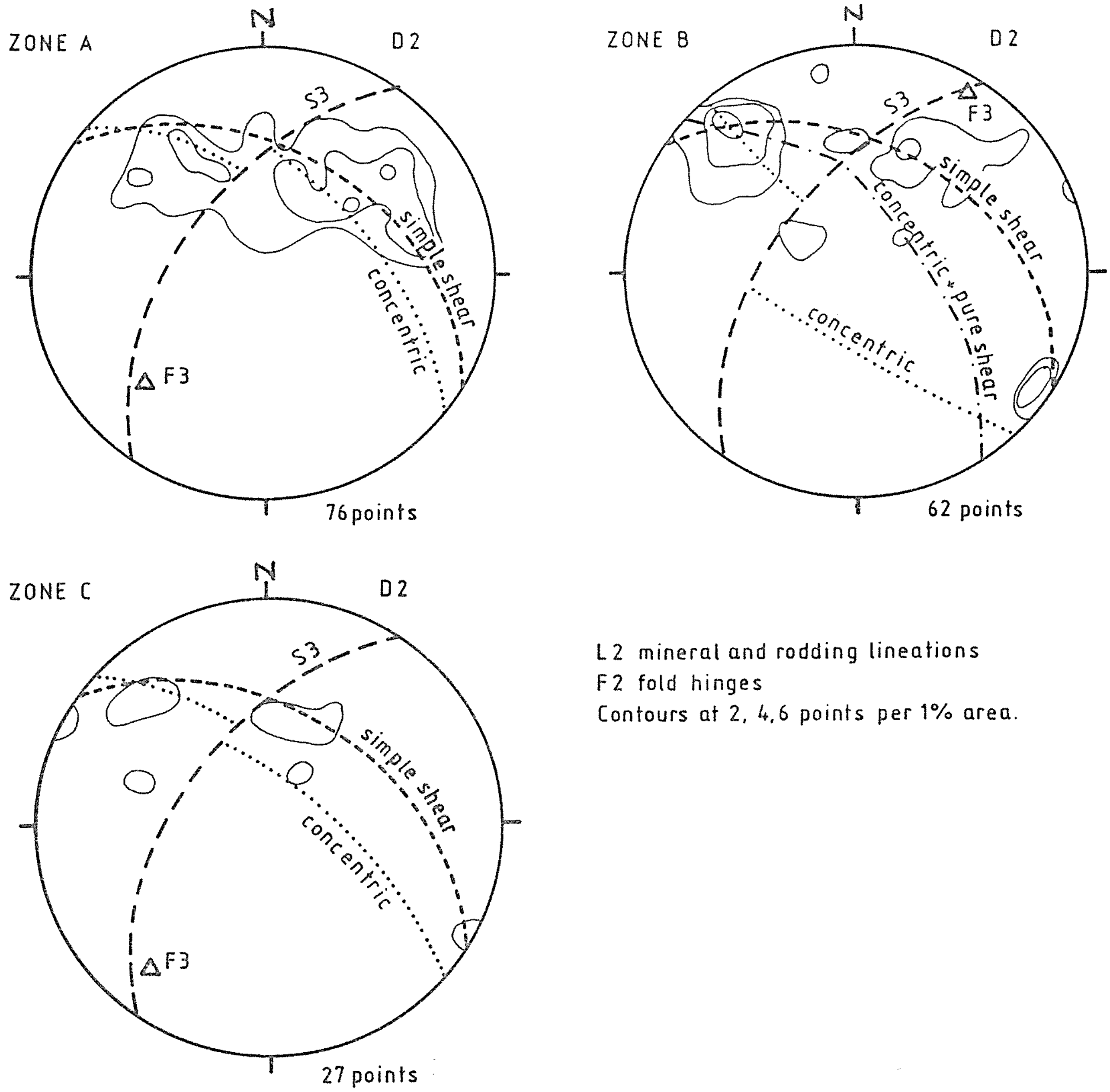




L3 crenulation lineations
F3 fold hinges
Contours at 2, 4, 6, 8, 10 points
per 1% area.

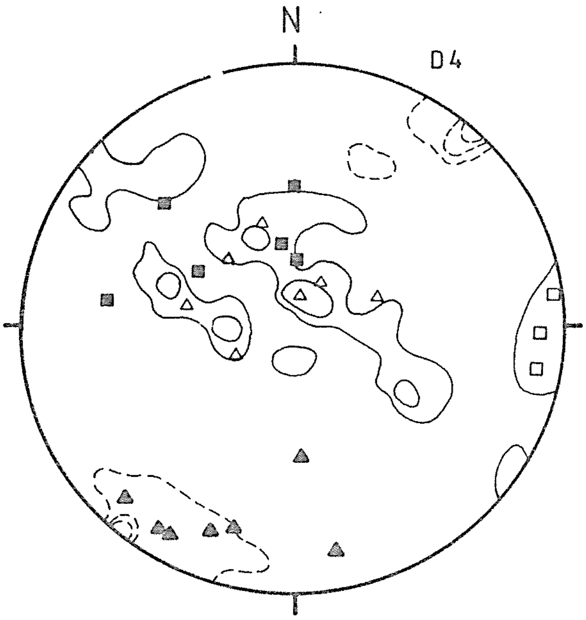
⊚ Average F3 fold hinge

FIG. 9.



L2 mineral and rodding lineations
F2 fold hinges
Contours at 2, 4, 6 points per 1% area.

FIG. 10



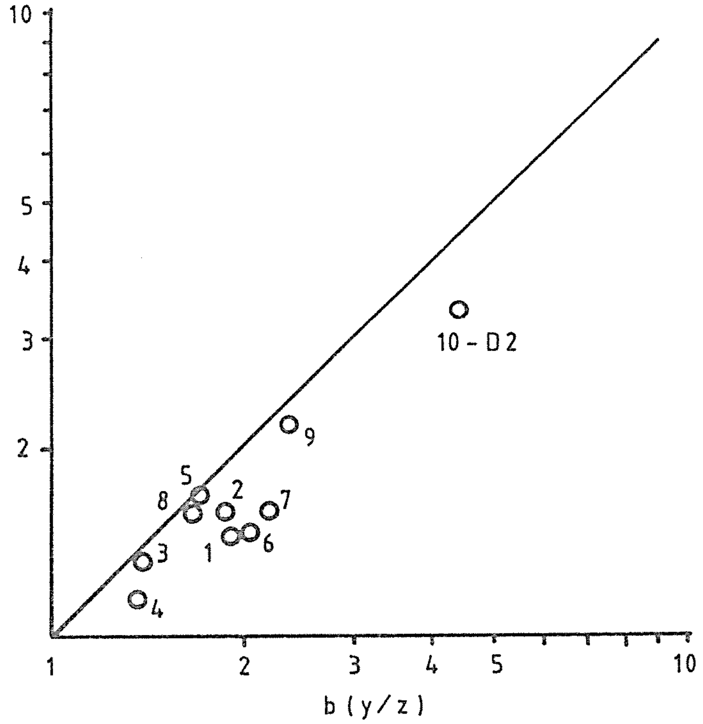
S4 crenulation cleavage and
F4 axial planes.
Contours at 1 and 2 points per 1% area
27 points.

L4 crenulation lineation on S2 and
F4 fold hinges.
Contours at 2, 4, 6 points per 1% area
28 points

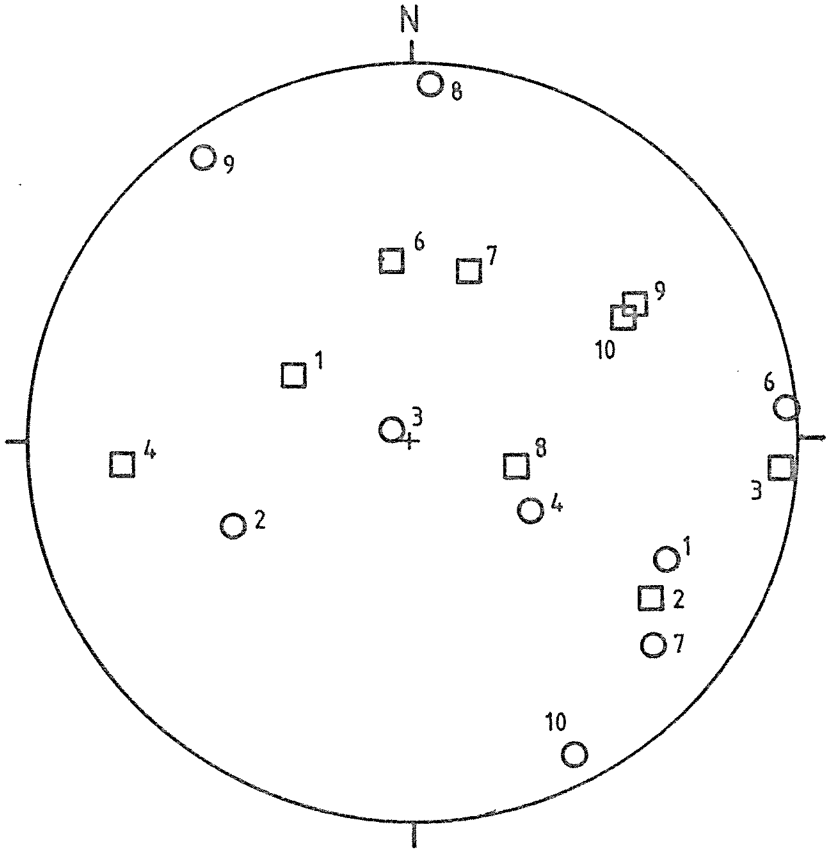
D4 fold axial planes, hinges in Gjersvik nappe.

FIG. 11.

a) LOGARITHMIC DEFORMATION PLOT — STRAIN ELLIPSOID TYPE



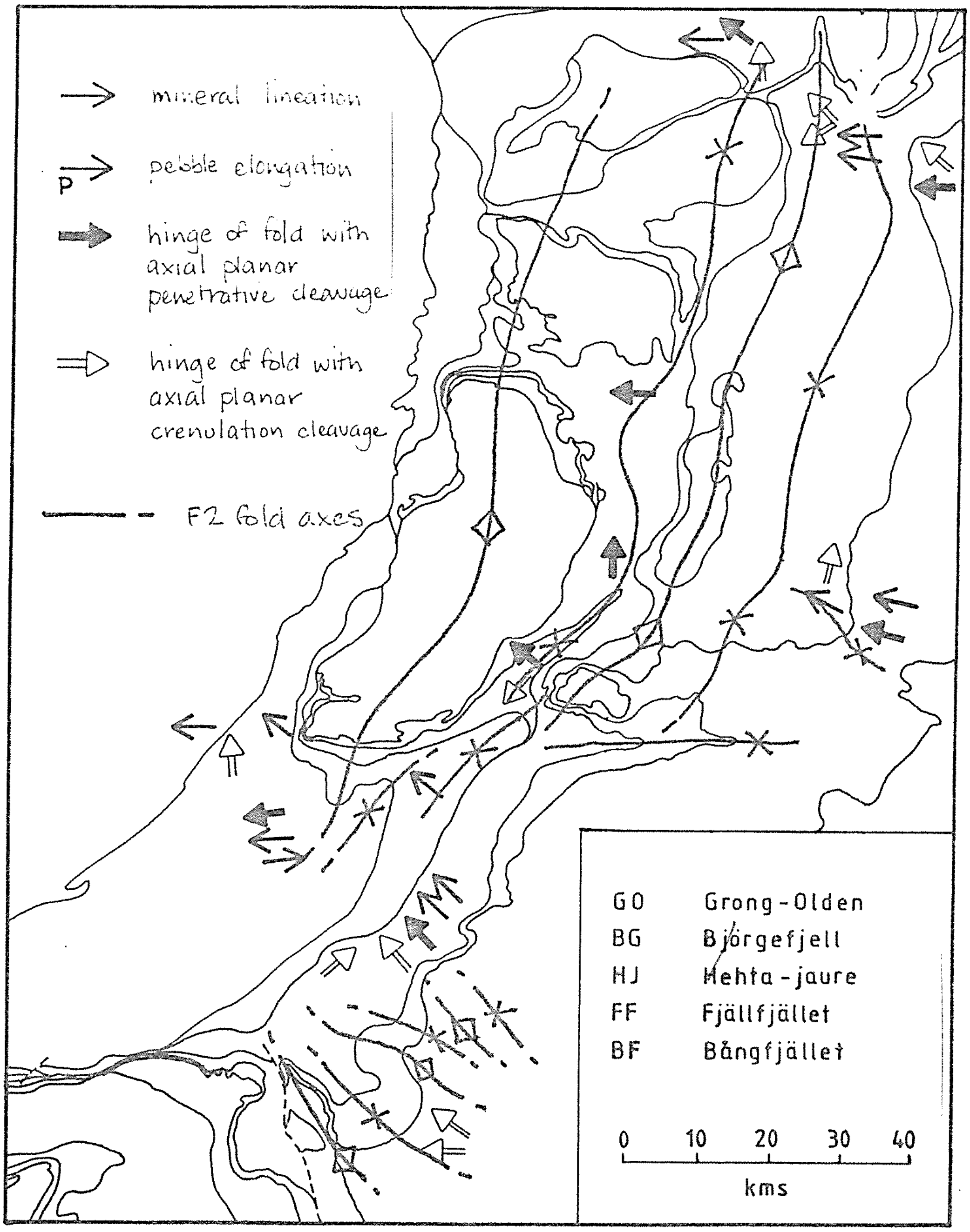
b) STEREONET — STRAIN ELLIPSOID AXIS ORIENTATION



□ Maximum (x) finite strain axis

○ Minimum (y) finite strain axis

FIG. 12



mineral lineation
P
pebble elongation
hinge of fold with axial planar penetrative cleavage
hinge of fold with axial planar crenulation cleavage
F2 fold axes
GO Grong-Olden
BG Björgefjell
HJ Hehta-jaure
FF Fjällfjället
BF Bångfjället
0 10 20 30 40
kms

PLATE II

PLATE I