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The Caledonides of northern Norway: relation between preferred orientation of quartz lattice, strain and translation of the nappes

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SUMMARY: In the area of Birtavarre (eastern Troms) evidence of nappe tectonics exist at all scales. The preferred orientation of the *c*-axis of quartz shows a monoclinic symmetry and consists of a girdle containing Y and oblique to Z. The obliquity of the girdle–angle θ between the *c*-axis girdle and the YZ plane–is interpreted in terms of simple shear, and the strain is calculated from these data. The results from this study are: (1) almost all the quartz-bearing samples give a consistent sense of simple shear (movement towards the SE) except for some gneisses supposed to be allochthonous Precambrian. (2) the calculated strain is too low to explain the displacement of the nappes (more than 40 km for a 2 km thick unit): X/Z ratio is less than 10 on the average. Possible reasons for this are discussed.

The allochthonous character of the Caledonian Nappes of eastern Troms (N Norway) is now widely accepted (Gayer & Roberts 1973; Gayer 1973; Quenardel 1977; Sturt & Roberts 1978; Gustavson 1978; Binns 1978). A pile of thin nappes, the Kalak Nappe complex, is found in the Birtavarre and Skibotn valleys. The regional foliation is nearly horizontal and the associated stretching lineation has a relatively constant NW–SE trend (Fig. 1). The regional foliation is penetrative and is found throughout the entire thickness of the metamorphic rocks in the nappe pile. In Laksefjord (Finnmark), Gayer *et al.* (1978) and Williams (1978) concluded that the L–S tectonite fabric is essentially due to simple shear deformation in the Kalak and Laksefjord Nappes. Thus, a model involving progressive, homogeneous simple shear deformation (Escher & Watterson 1974) could be applied for the formation of the L–S fabric in the same nappe sequence in eastern Troms. By using the crystallographic preferred orientations of quartz grains we attempt to determine the strain and the shear sense on the Caledonian nappes of the Birtavarre area. This has been done to determine the mechanism of nappe emplacement, in an area where the tectonic evolution of the structural features appears to be relatively simple, but where no strain markers are known to exist.

Geological setting

The tectonostratigraphic sequence

The tectonostratigraphic sequence recognized by Quenardel (1978) on a section across the eastern Troms segment (Kåfjord meridian) is summarized in Table 1. Upper internal units occur only in southern Troms. They wedge out between Narvik and the Birtavarre region. Detailed mapping has revealed that major tectonic discontinuities separate the units (Quenardel & Boullier, 1979). Within the units both upper and basal truncations of layering may occur. One of the most important features of the nappe succession is the increase of Caledonian metamorphic grade by successive jumps from lower units to upper ones (Table 1). This pattern supports the assumption of different metamorphic conditions in the nappes before their tectonic superposition. The metamorphism has been dated at 417 ± 5 m.y. in the middle internal units (Trollvik Nappe) by Dangla *et al.* (1978).

It is widely accepted that the translation direction of the nappes is from NW to SE (e.g. Gustavson 1972). The amplitude of this translation is at least 40 km for the middle external unit and 200 km for the rootless internal units in view of the Alta-Kvenangen basement window (Fig. 1).

Mesoscopic scale deformation

It is possible to distinguish several tectonic units which have experienced different tectonic and metamorphic histories (see Fig. 1 & Table 1).

(1) The lower and middle internal units in which four phases of Caledonian deformation are recorded (Quenardel 1978; Dangla 1979). During the first phase (D_1) rare isoclinal to tight folds occur contemporaneously with the S_1 foliation. The second phase of deformation

TABLE 1. *Schematic tectonostratigraphic sequence recognized by Quenardel* (1977) *on a section across the eastern Troms segment* (*see Fig.* 1).

	Lithologic composition	Climax of Caledonian metamorphism	Presumed age
Upper internal units		Absent in the studied area	
Middle internal units	Metasedimentary rocks (micaschists, quartzites, marbles), Amphibolites. Granitic sheet and dykes in the Tyrollvik Nappe	Medium to high grade with local migmatization (Dangla 1979) (kyanite-sillimanite)	Cambrian Ordovician? Silurian?
Lower internal unit (Birtavarre Nappe)	Metasedimentary rocks (schists, quartzites, marbles) Metagraywackes Amphibolites	Medium grade (andalusite-staurolite)	Eocambrian? Cambrian Ordovician? Silurian?
Upper external unit ("basement" slab)	Infracrustal and supracrustal rocks	Medium retrograde metamorphism (muscovite, epidote, garnet, biotite) from Precambrian medium to high grade rocks	Precambrian sedimentary cover (or Eocambrian?) Precambrian basement
Middle external unit (Saana Nappe)	Meta-arkoses Quartzites and schists	Low to medium grade (muscovite, epidote ± garnet ± biotite)	Eocambrian + Cambrian?
Lower external unit (Jerta Nappe)	Quartzites Shales	Very low to low grade (chlorite, sericite)	Eocambrian Cambrian
Autochthonous baltic shield	Hyolithus schists on Precambrian gneisses	None	Cambrian on Precambrian basement

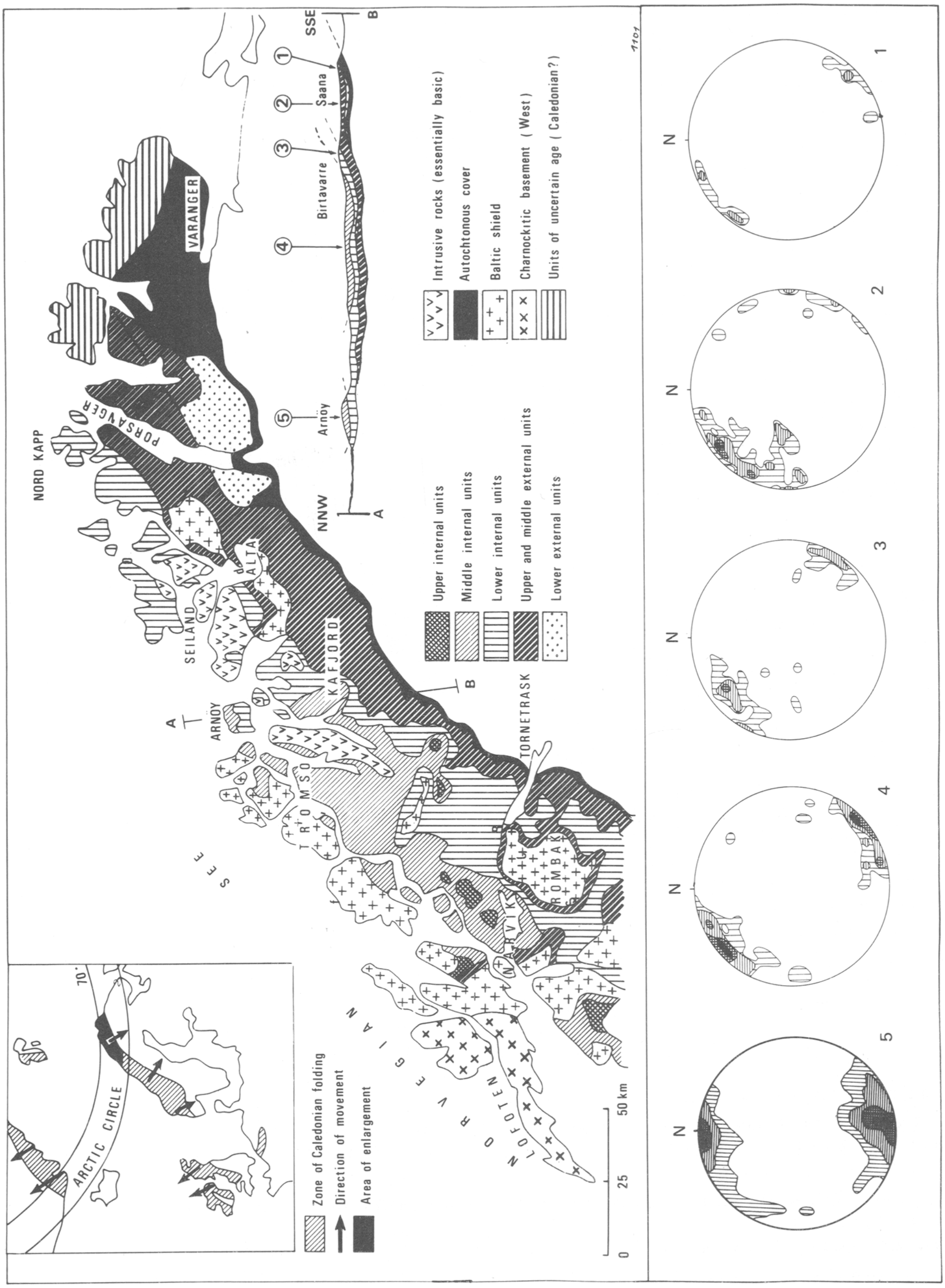

FIG. 1. Sketch map of the northern Scandinavian Caledonides (after Quenardel 1977) and stereograms of the stretching lineation. Equal area projection on the lower hemisphere. 1. middle external unit. 2. upper external unit. 3. lower internal unit. 4. middle internal units. 5. middle internal unit in Arnöy and Sauköy (after Bechennec & Hervé 1973).

(D_2) also corresponds to isoclinal folds and to the development of a nearly horizontal S_2 foliation which is very widespread; S_2 appears as the regional foliation and bears a NW–SE stretching lineation defined by quartz and feldspar ribbons or by a mineral alignment. D_3 is characterized by the development of dragfolds, often verging to SSE, and of boudinage-like structures: both structures are interpreted as the result of bulk differential displacement (Quenardel & Boullier 1979). The last phase of deformation (D_4) produces chevron folds and flexures of the thrust planes.

(2) The upper external unit, in which the tectonic and metamorphic evolution of the basement slab is more complicated. The three last phases recognized in the internal units are usually seen in the basement slab; but, boudinage-like structures and a mylonitic foliation predate the development of the regional S_2 foliation. These pre-S_2 structures are thought to be Precambrian (Quenardel 1976).

(3) The middle external unit, in which the sequence of deformation phases is difficult to establish due to the lack of marker units. A blastomylonitic foliation is observed in the feldspathic meta-quartzites and this foliation, which exhibits a strong NW–SE trending stretching lineation, is probably the equivalent of the S_2 regional foliation. At the front of this unit (Saana, Finland) a continuous reduction of the grain size of the rocks can be followed downwards, from low to medium grade blastomylonites to mylonites and ultramylonites. These are, in turn, folded and crushed under very low grade metamorphic conditions at the sole of the thrust.

Microscopic deformation

Our observations are principally on thin sections cut parallel to the XZ plane of the strain ellipsoid (XY plane assumed parallel to the S_2 foliation and the X direction assumed parallel to the l_2 stretching lineation). We concentrated our work on the quartzofeldspathic samples and on the simple cases where the S_2 foliation was not visibly reworked by later deformation. The regional S_2 foliation is blastomylonitic as defined by Higgins (1971) and Sibson (1977) and corresponds to different metamorphic conditions in different structural units. Apart from the different nature of the porphyroblasts, the same characteristics are present within the different structural units: the S_2 foliation is defined by mica layers and quartz ribbons. The latter are polycrystalline and composed of large irregular grains and subhedral smaller ones (II-4 type of Boullier & Bouchez 1978). The larger quartz crystals have undulatory extinction and show prismatic subgrain boundaries which are oblique to the XY plane. The examination of XZ thin sections with an inserted gypsum plate shows that the quartz grains have a strong preferred lattice orientation. The porphyroblasts, which are epidote, feldspar or garnet in the external units, or feldspar, garnet or kyanite in the internal units, are slightly deformed (bent twins or bent cleavage planes). The porphyroblasts deflect the mica- and quartz-layers. Their inclusion pattern and the asymmetry of the deflected layers often indicate a rotation sense which is generally consistent with thrusting to the SE. This indicates that the blastomylonites have suffered a plastic deformation (strained porphyroblasts, substructure and lattice preferred orientation of quartz grains) which is contemporaneous with and slightly follows the thermal peak of metamorphism. The metamorphic grade varies from one unit to the other, with the result that the temperature conditions during the deformation were lower in the external unit than in the internal ones.

Preferred lattice orientation of quartz

Description

Measurements of quartz c-axis orientations were made with a U-stage on three typical blastomylonites from the upper external unit (Fig. 2). The data have been plotted on the lower hemisphere using the counting programme of Bouchez & Mercier (1974). The diagrams show a large pole-free area around X and that the quartz c-axes define a girdle passing through Y and oblique to the Z direction (monoclinic symmetry). The monoclinic symmetry of quartz c-axis preferred orientation is also revealed by examination of XZ thin sections on an ordinary stage. The intersection of (0001) basal plane with the surface of thin section is determined inserting a gypsum plate. The data from this method are plotted on rose-diagrams (Fig. 3). This technique is not as informative as the U-stage measurements, since it does not take into account the dip of the (0001) plane; but it is quicker and more convenient for determining the angular relationships between the (0001) basal plane of quartz and the foliation plane. In this study, it appears that there is a well-defined asymmetry of the (0001) plane relative to the XY plane (S_2 foliation) and that the sense of the obliquity angle is almost homogeneous.

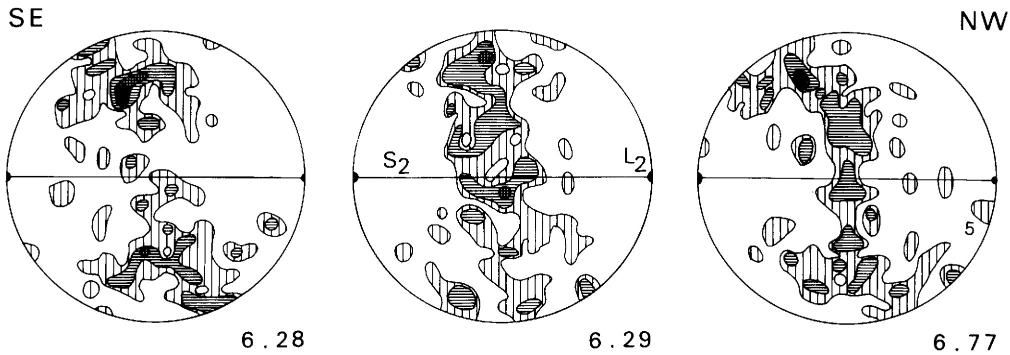

FIG. 2. Preferred orientation of quartz c-axis in blastomylonites of upper external unit. Equal area projection on the lower hemisphere. Contours: 1, 2, 4, 6%. S_2 foliation plane and l_2 stretching lineation are represented respectively by the line and the half-dots—100 measurements for each stereogram.

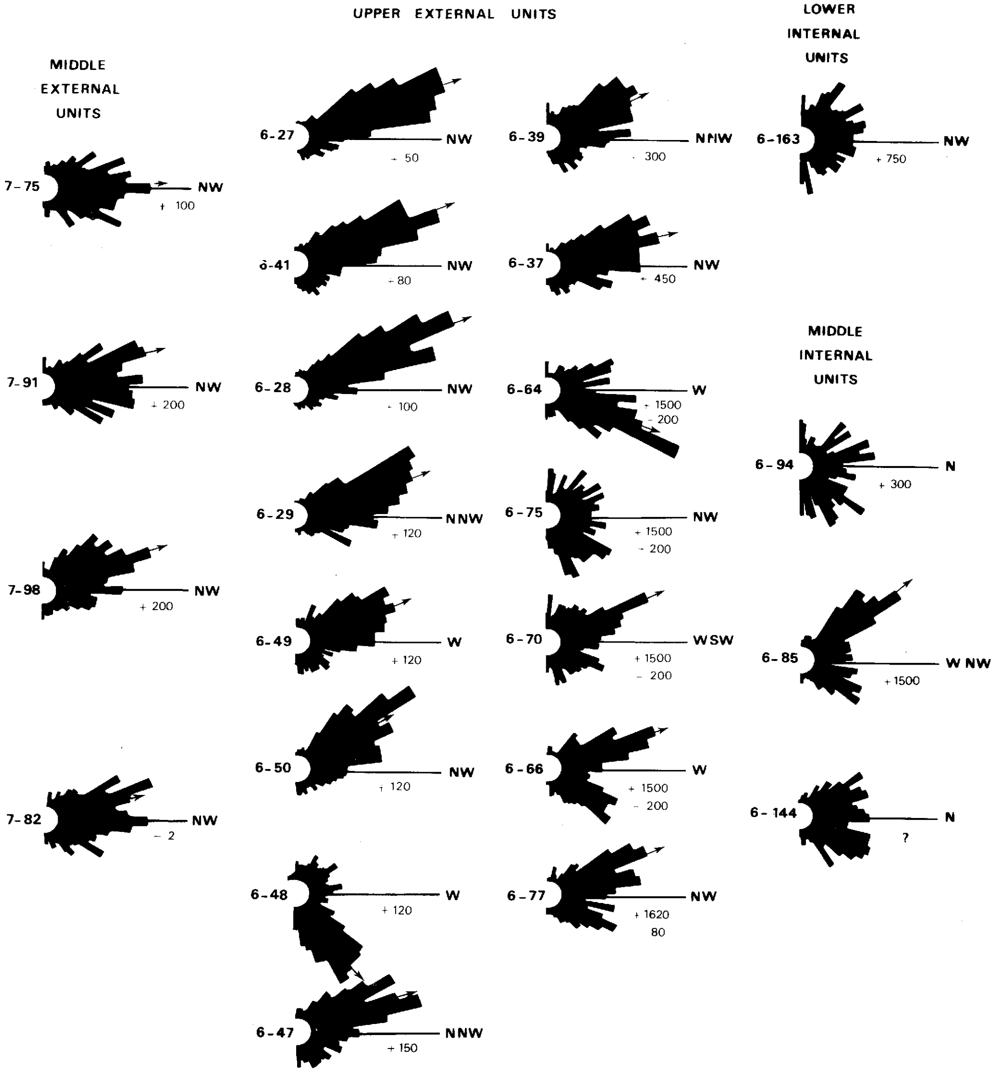

FIG. 3. Rose diagrams or weighted projections of the (0001) plane traces of quartz in blastomylonites. 300 measurements for each diagram in thin section normal to S_2 foliation and parallel to l_2 stretching lineation.

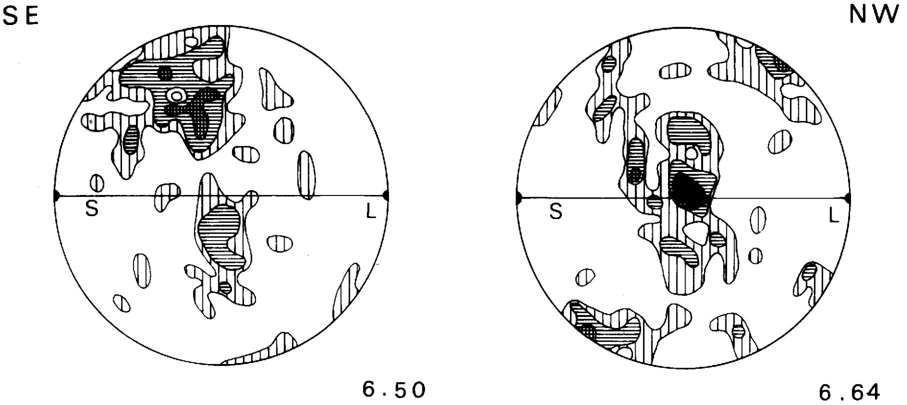

FIG. 4. Preferred orientation of quartz c-axis in two gneiss samples of the upper external unit (see discussion in text). 100 measurements. Equal area projection on the lower hemisphere. Contours: 1, 2, 4 and 6%.

Additional measurements have also been made on two groups of samples which have peculiar (0001) weighted projections. The first group (6.50 and 6.48) shows a well-defined (0001) trace peak at high angle from the foliation plane (30 and 55° respectively) corresponding to a high angle between the prismatic subgrain boundaries and the S foliation plane in a XZ section S_2–l_2. In a YZ section sporadic minor folds superimposed on the mylonitic foliation can be observed. An analysis of the c-axis preferred orientation of sample 6.50 (Fig. 4) shows a strong maximum at 30–60° from Z in an outline of oblique girdle similar to the girdles presented in Fig. 2. The second group of samples (6.75, 6.70 and 6.64) are orthogneisses in the same area, where the stretching lineation has an irregular direction but where no post foliation deformation could be observed. The rocks are characterized by a low grade Caledonian metamorphism superimposed on the orthogneissic foliation which corresponds to a higher grade metamorphism. The 6.75 sample does not show any well-defined (0001) trace concentration (Fig. 3) but 6.70 and 6.64 have an inverse sense of obliquity with reference to the dominant sense. The c-axis preferred orientation of 6.64 (Fig. 4) shows a strong Y maximum scattered in one girdle oblique on the XY plane, and a secondary maximum which lies in the XZ plane and defines the (0001) trace peak in the rose diagram.

Interpretation of the lattice preferred orientation of quartz

We have seen that, in the samples studied here, the quartz grains show evidence of plastic deformation which has produced a lattice preferred orientation by intracrystalline gliding. The pattern of preferred orientation can be interpreted in terms of slip systems (Tullis *et al.* 1973; Lister *et al.* 1978) and of geometric characteristics of the deformation (Nicolas *et al.* 1971, 1973). In the present case, that is c-axis girdle oblique to the XY plane and assuming that the stretching lineation is close to the flow direction we conclude that:

(1) the dominant slip direction should be a direction at high angle to the [0001] because of the large [0001] free area around the flow direction X (Fig. 2) and of the prismatic subgrain boundaries in quartz grains. Bouchez (1978) has shown that the pole maxima of the prismatic subgrain boundaries which have been optically determined, are close to the flow direction (X). These pole maxima also coincide with the $\langle a \rangle$ axis maxima determined with a X-ray goniometer (Bouchez, op cit.). Thus the optically visible subgrain boundaries are tilt walls normal to the slip direction which is an $\langle a \rangle$ axis, the easiest slip direction in quartz (Christie *et al.* 1964). The glide plane cannot be uniquely determined from the fabric diagrams, but gliding on any plane containing $\langle a \rangle$ could explain the fabric patterns described here. The most commonly reported glide planes in quartz are (0001), $\{10\bar{1}0\}$ and $\{01\bar{1}1\}$ (Carter *et al.* 1964; Tullis *et al.* 1973; Blacic 1975) and we infer that these were the active slip planes during deformation of these rocks.

(2) the deformation is mainly rotational (simple shear): this assumption can explain the monoclinic symmetry of the c-axis preferred orientation on the XY plane. The pole of the c-axis girdle does not correspond to X, but should represent the $\langle a \rangle$ maximum, i.e. the

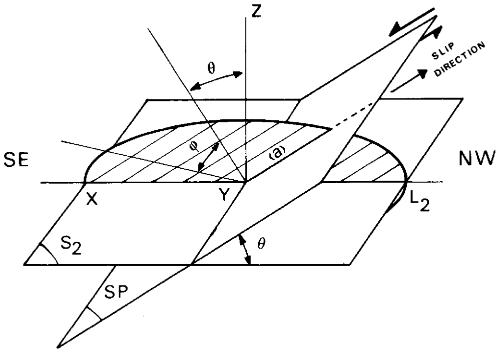

FIG. 5. Deformation of a previously roundshape quartz grain by intracrystalline gliding in the ⟨*a*⟩ direction (after Laurent & Etchecopar 1976). θ is the angle between the slip plane (SP) and the foliation S_2 (XY plane of the strain ellipsoïd). ϕ is the shear angle.

average slip direction (see Bouchez 1978; Bouchez *et al.* 1979). The angle between X and the ⟨*a*⟩ maximum defines the asymmetry of the crystallographic preferred orientation and is sensitive to the data which plot near the ZX plane, i.e. by the grains in which basal slip is probably dominant.

Many authors have recently deduced the shear sense from the lattice preferred orientation of quartz (Bouchez & Pecher 1976; Laurent & Etchecopar 1976; Brunel & Geyssant 1978; Bossière & Vauchez 1978; Berthé *et al.* 1979). Burg & Laurent (1978) and Van Roermund *et al.* (1979) have clearly shown the relation between the asymmetry of the *c*-axis girdle and the shear sense in a small-scale shear zone. Following these authors, we interpret the *c*-axis girdle as due to a rotational deformation (simple shear) which corresponds to a thrust movement in the SE direction (see Fig. 5). This sense is consistent with the large-scale observations (Quenardel & Boullier, 1979).

The two peculiar groups of samples (Fig 4) warrant further discussion. We interpret the *c*-axis preferred orientation of the first one (6.50) as due to the effect of the minor fold phase on the pre-existent D_2 preferred orientation (probably an oblique girdle with a Y maximum) because the substructure in quartz (prismatic subgrain boundaries) seems to be related to that latter deformation. Thus, in such cases, the S_2–l_2 reference strain ellipsoid is probably not appropriate, and further detailed studies should take into account the late deformation as proposed by Brunel (1980). In the second group of samples (6.64), the *c*-axis preferred orientation, and particularly the strong Y maximum, is attributed to the high grade orthogneissic foliation. This kind of *c*-axis pattern has previously been described in high temperature mylonites (Wilson 1975; Boullier & Bouchez 1978). These particular samples belong to an unusual unit of mylonitic gneisses, gneisses and metasediments, thought by Quenardel (1976) to be Precambrian. We think that, in this case, the D_2 simple shear deformation accompanied by a low grade metamorphism, was not strong enough to rotate the pre-existing orthogneissic foliation completely and to bring the associated stretching lineation in the flow direction, nor strong enough to reorganize the *c*-axis pattern.

We have studied only a few samples on the internal units (Fig 3). Except for 7.85, they do not show any (0001) trace maximum on the weighted projections and quartz grains are black when observed between crossed Nicols in a XZ section (*c*-axis pattern tending towards Y maximum). We know that the deformation temperature was higher in this sample (higher metamorphic grade, see Table 1). Hence we infer that gliding on prismatic planes was predominant in these samples, as observed in high temperature experiments. In this case, no statement can be made about the geometric characteristics of the deformation by looking solely at thin sections.

Strain measurements

The method

Ramsay & Graham (1970) have calculated strain profiles across shear zones by using the relationship between the shear angle (ϕ) and the angle θ defined by the foliation (XY plane) and the shear plane. Burg & Laurent (1978) have applied this method of strain calculation to a small-scale shear zone in a granodiorite, demonstrating that a good correlation exists between the θ angle defined by the *c*-axis girdle and the θ angle deduced from strain measurements and calculations. Therefore, assuming that the foliation is the XY plane of finite strain and that the pole of the *c*-axis girdle is the shear direction (see Fig. 5), we have applied this method of strain calculation to our samples. θ is determined on the rose diagrams as the angle between the arithmetic average of the main (0001) trace peak (arrows in Fig. 3) and foliation plane. The data are presented in Table 2. θ is known with an accuracy of ±2°5. When two peaks exist, the dominant one is chosen; the secondary peak is

TABLE 2. *Values of the shear angle ϕ, the shear strain γ and the X/Z ratio of strain ellipsoid, calculated from the obliquity angle between the* (0001) *plane trace maximum and the S_2 foliation plane* (*see Fig.* 3).

Sample	Distance to thrust plane (m)	θ	ϕ	γ	X/Z	
7.75	+100	<1°				
7.91	+200	17.5°	70.1°	2.9	10.1	Middle external unit (Saana Nappe)
7.98	+200	20°	67.2°	2.4	7.5	
7.82	(−2)	13.5°	75.7°	3.9	17.4	
6.27	+50	20°	67.2°	2.4	7.5	Upper external unit (basement slab)
6.41	+80	21.5°	65°	2.1	6.4	
6.28	+100	23.5°	61.8°	1.9	5.3	
6.29	+120	17.5°	70.7°	2.9	10.1	
6.49	+120	20°	67.2°	2.4	7.5	
6.50	+120	30°	49.1°	1.1	3.0	
6.48	+120°	55°	"negative strain"			
6.47	+150	19.5°	68.0°	2.5	8.0	
6.39	+300	24°	61.0°	1.8	5.0	
6.37	+450	14.25°	74.8°	3.7	15.5	
6.64	+1500 (−200)	22.5°	63.4°	2.0	4.8	
6.75	+1500 (−200)		no peak defined			
6.70	+1500 (−200)	23.5°	61.8°	1.9	5.3	
6.66	+1500 (−200)	18.5°	69.3°	2.6	8.9	
6.67	+1620 (−80)	22.5°	63.4°	2.0	4.8	
6.163	+750	no peak defined				Lower internal unit (Birtavarre Nappe)
6.94	+300	no peak defined				middle internal units
7.85	+1500	37.5°	28.2°	0.5	1.7	
7.144	? Arnöy	no peak defined				

interpreted as due to crystals showing a reverse shear sense (i.e. referring to the general shear sense). This choice is justified by the results obtained by Etchecopar (1977) with a two dimensional simulation model.

Interpretation of the results

In the middle external unit, sample no 7.75 has a very low θ angle and hence a very high strain which is coherent with the strong mylonitic foliation and the very fine-grain size of the rock. In the same unit, the shear strain seems to increase towards the base (7.75) and the roof (7.82) of the nappe, but more data are needed to verify such an interpretation. This seems not to be the case in the first section of the upper external unit (samples 6.27–6.37, except 6.50 and 6.48): the strain is heterogeneous inside this unit and would indicate that there are at least three slices in this section. Thus, no clear relationship between shear strain and the limits of the nappes can be established as Chapman *et al.* (1979) have done for the Laksefjord Nappe (N Norway).

On average, the X/Z ratio does not exceed 10. This is a maximum value of finite strain recorded by intracrystalline gliding in quartz since a small component of pure shear would rotate the XY plane towards the shear plane and then lower the θ angle (Burg & Laurent 1978). Assuming the thickness of the upper external unit to be approximately 2 km, this ratio would give a value of 20 km for X. Consequently, even if we neglect the thrust front erosion, the simple shear due to S_2 and recorded by the lattice preferred orientation of quartz, is not sufficient to explain the emplacement of the nappes (at least 40 km horizontal movement for the upper external units).

Discussion

The discrepancy between the shear strain deduced from preferred orientation and the minimum horizontal movement of the nappes could be explained in three ways.

(i) The c-axis preferred orientation and θ could have been stablized during simple shear. In this case, the γ determination by preferred orientation would have only limited value for large strain deformations. Carreras *et al.* (1977) describe a stable microstructure and a stable microfabric relative to the axis of finite strain in quartzites for shear strain greater than 2. The stabilization of the microstructure can be due to a continuous cyclic recrystallization (White 1977) but this phenomenon does not explain the stable c-axis pattern. In our case we do not observe stable microstructure in quartz ribbons since large grains coexist with small ones. Moreover, other authors have recently demonstrated that quartz fabric is controlled in orientation by kinematic framework (Burg & Laurent 1978; Van Roermund *et al.* 1979), as predicted by the simulation model of Lister (1977).

(ii) The simple shear by plastic flow in quartz does not represent the total strain undergone by the rocks during the D_2 deformation phase and some other mechanisms could have been operating, e.g. pressure solution, discontinuous sliding on mica rich layers as described by Berthé *et al.* (1979), grain boundary sliding. However we have no evidence of the existence of such mechanisms in the rocks studied here, except may be for the grain boundary sliding, but its effect cannot be quantified.

(iii) The simple shear by plastic flow in quartz is representative of almost all the strain associated with the S_2 regional foliation. In this case S_2 represents the early stage of nappe development and probably of initiation of the pile formation, by a similar mechanism of simple shear to that proposed by Escher & Watterson (1974). The translation of the pile is almost entirely accommodated by deformation in a thin layer of mylonites, ultramylonites and cataclasites at the base of the lower unit (the middle external unit in the Birtavarre cross-section). This schematic evolution has been proposed by Gee (1978), Guézou (1977) and Prost *et al.* (1977) for the central Caledonides and by Olesen (1971) for the Langedalen area (Troms). But the Birtavarre area differs from the Langedalen by the following characteristics: The D_2 associated stretching lineation has a constant direction throughout the entire pile (see Fig. 1) and the stretching lineation has the same SE trend in the ultramylonitic layer at the base of the pile. Moreover, the D_3 folds also indicate a south-eastwards thrusting. This continuity of direction indicates that there is no significant kinematic change in the flow direction during the deformation in the nappes; the formation of the nappe pile and its translation. Hence, the stress direction seems to have been more or less constant during this tectonic evolution.

Conclusions

In this work we have shown that a good correlation exists between the shear sense as deduced from the c-axis preferred orientation and that observed in the field on map to mesoscopic scales. The exceptions can be reasonably explained by particular aspects of their deformation history. The quantitive results obtained by this method must be used very carefully but provide the approximate strain undergone by the rocks. More detailed investigations on the strain measurements together with c-axis preferred orientation analysis are required in order to improve the method. We have demonstrated, however, that the flow direction and probably the stress direction seem to have been constant during the major tectonic evolution of the nappes in the Lyngenfjord area.

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