

The microfabrics of a porphyroclast-rich quartzitic mylonite, Mjølfjell, Jotun Nappe Complex, Norway

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This paper describes the microfabrics of a quartzitic mylonite from a shear zone which separates major tectonic units in the Upper Jotun Nappe, a part of the Jotun Nappe Complex. The mylonite is rich in porphyroclasts, consisting of a variety of minerals such as feldspar, garnet, clinopyroxene, epidote and titanite. The porphyroclasts display a large variation in shape from plate and needle with extreme aspect ratios to ellipsoid and sub-spherical. Many of the porphyroclasts are asymmetric, fish-shaped, demonstrating a top-to-ESE transport direction in the shear zone. Relict subgrain microstructures in the largest porphyroclasts indicate that the precursor was a gneiss, which was deformed by dislocation creep. Compositional zoning is common among the porphyroclasts. In titanite this zoning is clear evidence of diffusive mass transfer, which indicates that dissolution-precipitation creep was a dominant process in the shaping of the porphyroclasts during mylonitisation. A change in the metamorphic environment is demonstrated by the microstructures. These include (1) larger garnet porphyroclasts are enclosed by a corona-like mineral aggregate, which includes a new generation of garnet, and (2) a silicification of plagioclase porphyroclasts, which suggests that the mylonitisation was accompanied by an influx of silica-rich fluids. The crystallographic preferred orientation of garnet porphyroclasts adds no support to recent reports that garnet plasticity may explain, at least partly, the elongate shapes. Misorientation angles of the garnet porphyroclasts demonstrate a close-range orientation relationship, which is ascribed to fragmentation and drifting apart processes during mylonitisation. The quartz matrix is medium- to coarse-grained. A large fraction of the porphyroclasts is completely included in these quartz grains, which indicates that the formation of porphyroclasts was followed by annealing and grain growth in the quartz matrix. Quartz displays no, or a very weak, shape-preferred orientation but a very strong crystallographic preferred orientation, compatible with glide on the {m} <a> system. This, together with interlobate grain boundaries, lattice bending which grades into subgrain microstructures, and evidence of deformation lamellae, is taken to indicate that the annealing period was followed by a combination of dislocation creep and dislocation glide under medium- to high-temperature conditions. Arrays of transverse fracture systems in the elongate porphyroclasts are ascribed to tensile stresses set up during exhumation and cooling. Contrary to an earlier interpretation it is argued that the origin of this stress system is not distant but of a local nature. Because of petrological similarities with nearby plutonic rocks it is considered unlikely that the quartzite has a supracrustal origin, but is rather a mangeritic gneiss, which was highly enriched in silica. Comparison with recent geochronological data leads to the conclusion that the most likely time of formation of the shear zone was during the Sveconorwegian Orogeny.

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Introduction

Mylonites are important separators between tectonic units in orogenic zones. Characteristic features of mylonites are (1) a strong fabric, which reflects the high strain, and (2) a content of porphyroclasts consisting of the rheologically stronger minerals of the precursor, such as feldspar in a quartz matrix (Grunsky et al. 1980), quartz in a calcite matrix (Bestmann et al. 2000), and orthopyroxene in an olivine matrix (Ishii & Sawaguchi 2002). These porphyroclasts are commonly ellipsoid or asymmetric, fish-like in shape, and often carry important information about the geometry of the high strain, such as shear sense in the mylonite zone (Passchier & Simpson 1986).

The origin of the ellipsoid or fish-like shapes is controversial. Are the porphyroclasts dismembered parts of a former, larger crystal and/or were they deformed into their present shapes? This paper reports the results of a study of a quartzitic mylonite, which is rich in porphyroclasts. Major goals are (1) to seek explanations for

the wide variation in shape among the porphyroclastic minerals, (2) to throw light on the formation of the fish-shaped porphyroclasts, (3) taking garnet as an example, to explore possible orientation relationships between separate porphyroclasts of the same mineral, and (4) to establish the kinematic and metamorphic evolution of the mylonite from the observed microfabrics.

The origin of the quartzite itself is also controversial, with suggestions ranging from magmatic via sedimentary to metamorphic. It is positioned at the tectonic boundary between major units in the Norwegian Caledonides. The age and significance of this tectonic boundary is uncertain at present, although a Sveconorwegian age is favoured in this paper. Hopefully, this study of the petrography and microstructure of the quartzite will provide a basis for geochronological studies in the future, which will lead to a clearer understanding of its origin and geological significance.

Crystallographic orientation of minerals is measured with the EBSD/SEM technique (e.g. Prior et al. 1999),

applying a NORDIF camera and CHANNEL 5 software from HKLTECHNOLOGY. This equipment is mounted on a CAMSCAN MX2040SLi SEM, which is also used for BSE and OC imaging (Prior et al. 1996).

Geological setting

The quartzitic mylonite is from a major shear zone within the Jotun Nappe Complex, which is part of the Caledonian pile of far-travelled nappes in southwestern Norway. Traditionally the Jotun Nappe Complex is considered as part of the Middle Allochthon, implying an origin in the western margin of the pre-Caledonian Baltic Shield (Bryhni & Sturt 1985; Fossen 1992; Milnes et al. 1997) (Fig. 1). Major translation towards southeast took place in the Silurian Scandian Orogeny, resulting from the collision between Baltica and Laurentia. In late- to post-orogenic time this tectonically thickened crust was thinned by extensive, gravity driven, normal faulting, directed towards northwest (e.g. Fossen 1992, Andersen 1998). These late faults have a strong influence on the present appearance and distribution of the pile of nappes and its substratum.

The Jotun Nappe Complex and the smaller Dalsfjord and Lindås Nappes further to the west are all slices of a Proterozoic crust, which is dominated by polymetamorphosed and polydeformed plutonic rocks of similar appearance and history (e.g. Lundmark et al. 2007). Only the Caledonian overprint seems to differ, since only the Lindås Nappe, which is part of the Bergen Arc Complex, has experienced Caledonian high-pressure metamorphism (e.g. Jolivet et al. 2005).

The Jotun Nappe Complex rests tectonically on phyllites and quartzites, which make up the parautochthonous cover upon the Proterozoic basement rocks of the Baltic Shield (Fig. 1). It can be subdivided into two tectonic units: the Lower and Upper Jotun Nappes. The Lower Jotun Nappe consists mainly of syenitic to monzonitic and gabbroic rocks of mid-Proterozoic age, metamorphosed to amphibolite facies conditions during a late phase of the Sveconorwegian Orogeny (Schärer 1980). The Upper Jotun Nappe is characterized by the widespread occurrence of partially retrograded granulite facies gneisses of granitic, syenitic, monzonitic, dioritic and gabbroic composition. A recent geochronological study by Lundmark et al. (2007) has established that the magmatic age of these gneisses is essentially mid-Proterozoic. During the Sveconorwegian Orogeny these masses of plutonic rocks were deformed and metamorphosed up to granulite facies conditions. A mid-Sveconorwegian phase of deformation and retrograde metamorphism up to amphibolite facies is dated to ~950 Ma, which was followed by a renewed episode of heating, again leading to granulite facies conditions, and dated to ~934 Ma.

A number of descriptions exist of shear zones with greenschist facies mineralogy in the Jotun Nappe Complex, interpreted to be of a Caledonian origin since they overprint all other structures (e.g. Bryhni et al. 1983; Olesen 1986; Milnes et al. 1997). Definite proof of a Caledonian age is often missing. However, a swarm of granitic dykes in the central part of the Jotun Nappe Complex has been demonstrated by Lundmark & Corfu (2007) to have a Caledonian age (427 ± 1 Ma), and the swarm was named by them as 'the Årdal dyke complex'. The dykes occur

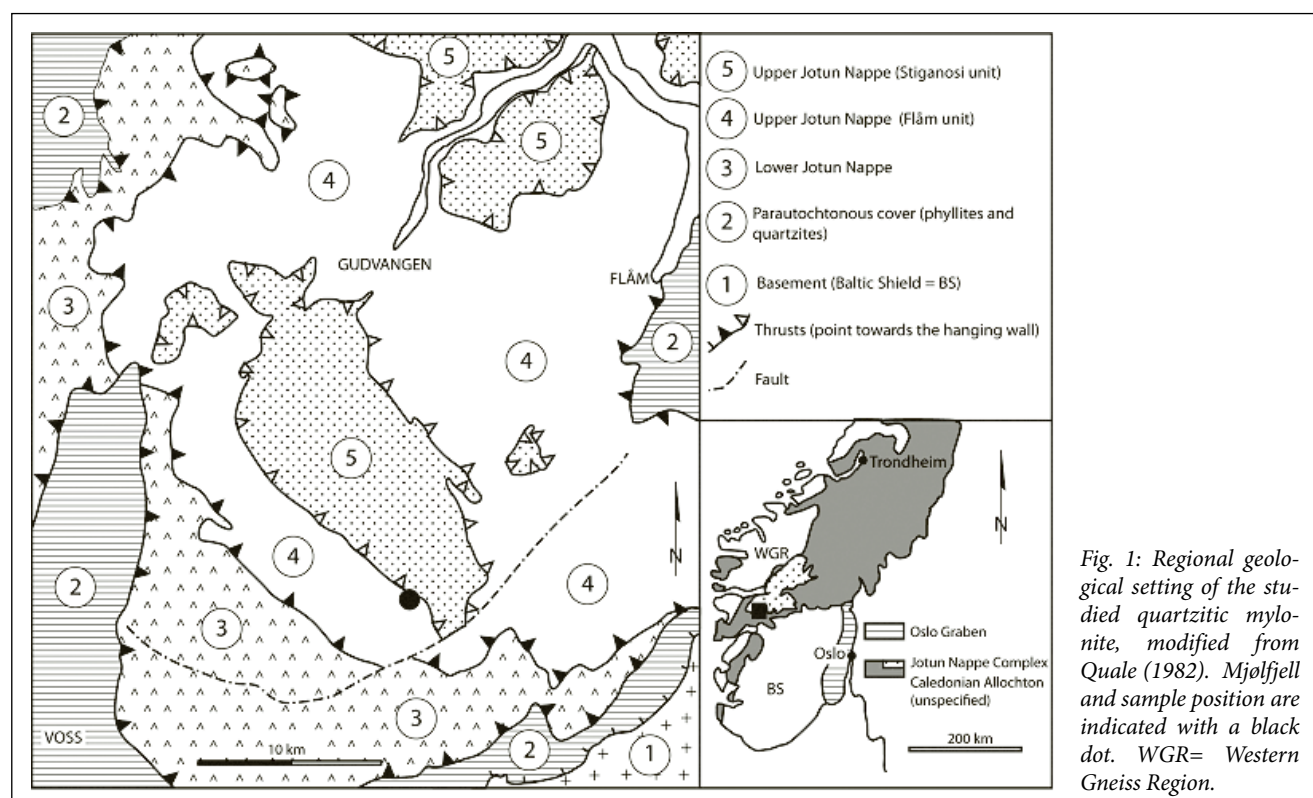


Fig. 1: Regional geological setting of the studied quartzitic mylonite, modified from Quale (1982). Mjølffjell and sample position are indicated with a black dot. WGR= Western Gneiss Region.

in the Upper Jotun Nappe, but not in the Lower Jotun Nappe, which implies that the boundary between these two major tectonic sheets must have been established during Caledonian nappe translation after the intrusion of the dykes. Also, where these dykes occur they permit a direct distinction to be made between structures of (1) Proterozoic and early Caledonian ages and (2) younger Caledonian ages. An overprinting ductile deformation is definitely of Caledonian age. Since some of the dykes are folded and boudinaged they are clearly syn-kinematic, and an overall top-to-SE shearing on shear zones is described by Lundmark & Corfu (2007) and interpreted by them to be related to Scandian thrusting of the nappe.

The study area is in the southwestern part of the Jotun Nappe Complex, and lies in the Upper Jotun Nappe (Fig. 1). This area is further characterized by the occurrence of large massifs of anorthosites and associated gabbro/troctolite, the protolithic age of which was dated recently to ~965 Ma (Lundmark & Corfu 2008). These rocks are also polydeformed and metamorphosed up to granulite facies conditions (e.g. Bryhni et al. 1983; Olesen 1987). The relationship between these meta-anorthosites and the other high-grade gneisses is unclear at present. Tectonic contacts seem to exist between them, and Bryhni et al. (1983) identified an upper tectonic sheet, the Stiganosi unit, dominated by the anorthosite-gabbro-troctolite suite, and a lower tectonic sheet, the Flåm unit, dominated by gneisses of syenitic and gabbroic composition (Fig. 1). It should be noted, however, that there are localities where the Flåm unit constitutes the hanging wall of the tectonic contact. A prominent example occurs south of Gudvangen (Fig. 1), as reported by Bryhni et al. (1983) and Clausen (1986). They describe the tectonic contact as folded on a large scale around fold axes with east or west dipping directions. It is, however, unclear if the “inverted” tectonic contact is due to large scale folding or is an original, thrust-related geometry.

Quartzite, interlayered with amphibolite, is a prominent rock type in the contact zone between the Flåm and Stiganosi units. It also occurs at various positions within the Flåm unit (e.g. Bryhni et al. 1983), but is particularly common (and up to several hundred meters thick) at this major boundary. The origin of these quartzites is controversial. They have been interpreted as (1) rocks of magmatic origin (the ‘silexites’ of Hødal 1945), (2) supra-crustal rocks (Bryhni et al. 1977; Quale 1982), and (3) the result of regional scale retrogressive mineral reactions (Olesen 1986). It is such a strongly mylonitized quartzite at Mjølfjell (Fig. 1) which is studied here.

The mylonites at Mjølfjell display a strong linear fabric, oriented WNW-ESE (Fig. 2). This orientation is widely observed in the Middle Allochthon (e.g. Bryhni & Sturt 1985). As will be demonstrated, this fabric was formed under medium- to high-grade metamorphic conditions, and it is concluded below that the likely time of formation of the mylonites was in the Sveconorwegian Orogeny.

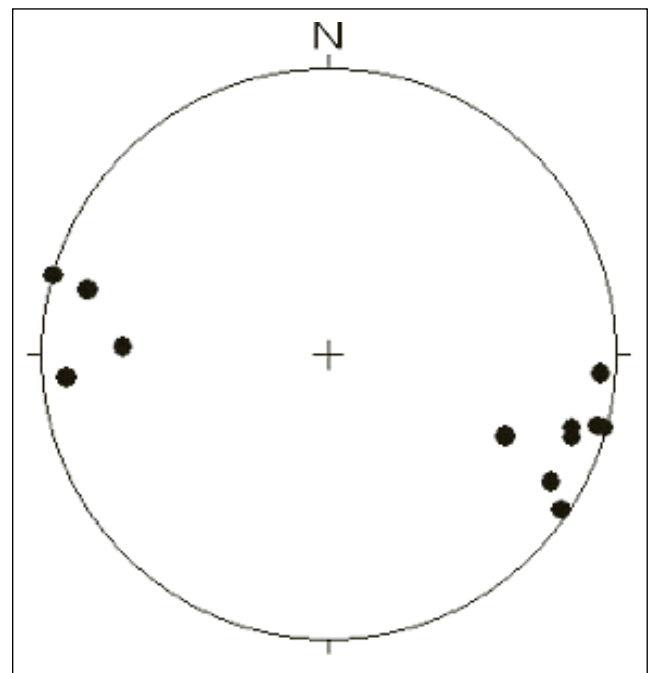


Fig. 2: The linear fabric in quartzitic mylonites at Mjølfjell, after Rasmussen (1998). Equal Area projection, lower hemisphere. $N=11$.

The quartzitic mylonite

Petrography and microstructure

The grey to slightly greenish coloured specimen was sampled approx. 500 meter east of Mjølfjell Railway Station (UTM: 32VLN828309). It is layered (S_0) on a mm to cm scale, due to variations in quartz content. A weak planar (S_1) and strong linear (L_1) fabric are defined by the shape-preferred orientation (SPO) of mafic minerals and feldspar. S_1 is axial planar to isoclinal folds in S_0 and is inclined 15° to S_0 in the studied specimen.

A right-handed coordinate system (CS0) provides the frame in the following presentation of microstructures. The system is defined such that $+X0 = L_1$ and it points towards ESE, and $+Z0$ is perpendicular to S_1 and points upwards.

The approximate modal composition of the quartzitic mylonite is presented in Table 1. The quartz grain size is 0.5 to 1 mm, and there is no readily visible SPO (Fig. 3). However, image analysis of the quartz matrix by Rasmussen (1998) revealed a weak SPO sub-parallel to $S1$. All quartz grains display lattice bending, which grades into an elongate subgrain microstructure. Deformation lamellae are visible in a small number of the quartz grains. Grain boundaries are interlobate, indicating grain boundary mobility, and recrystallization has generated a small fraction of new grains with a size of 20 to 50 μm , developed preferentially near grain boundaries.

Table 1.		
Mineral	Abbrev.	Approx. vol. %
Quartz	Q	92
Epidote	E	2
Plagioclase	P	1
Clinopyroxene	X	1
Garnet	G	1
Alkali-feldspar	A	< 1
Hornblende	H	< 1
Titanite	T	< 1
Calcite	C	< 1
White mica		<< 1
Biotite		<< 1
Zircon		<< 1
Apatite		<< 1
Opaque phases		<< 1

Table 1: Approximate modal composition of the studied quartzitic mylonite. Abbreviations used in micrographs are also indicated.

All other minerals occur as porphyroclasts, either as part of a polymineral aggregate or as single crystals (Fig. 3 & 4). The shapes of the porphyroclasts range from subspherical, over ellipsoid and asymmetric fish-like shapes, to platy and needle shapes, some with extreme aspect-ratios (~25:1). The largest porphyroclasts are several millimetres in their longest dimension. In this group we find plagioclase, clinopyroxene and garnet. As a rule the long dimension of all porphyroclasts is subparallel to S_1 and L_1 but is inclined systematically, thus creating a slight tilting effect (Fig. 4). A large number of porphyroclasts are just fractions of a millimeter long and are commonly included completely in the larger quartz grains (Fig. 3). The sense of asymmetry of the fish-like shapes (Fig. 5 & 6) is a persistent feature among the porphyroclasts, demonstrating a top-to-ESE transport direction. When seen in the optical microscope most porphyroclasts bear no signs of lattice strain, except for some small plate/needle-shaped epidote and hornblende crystals, which are slightly bent. As a rule the porphyroclasts are without a subgrain microstructure. However, applying the SEM a few subgrain boundaries are observed in some of the largest garnet and clinopyroxene porphyroclasts (Fig. 5e), and

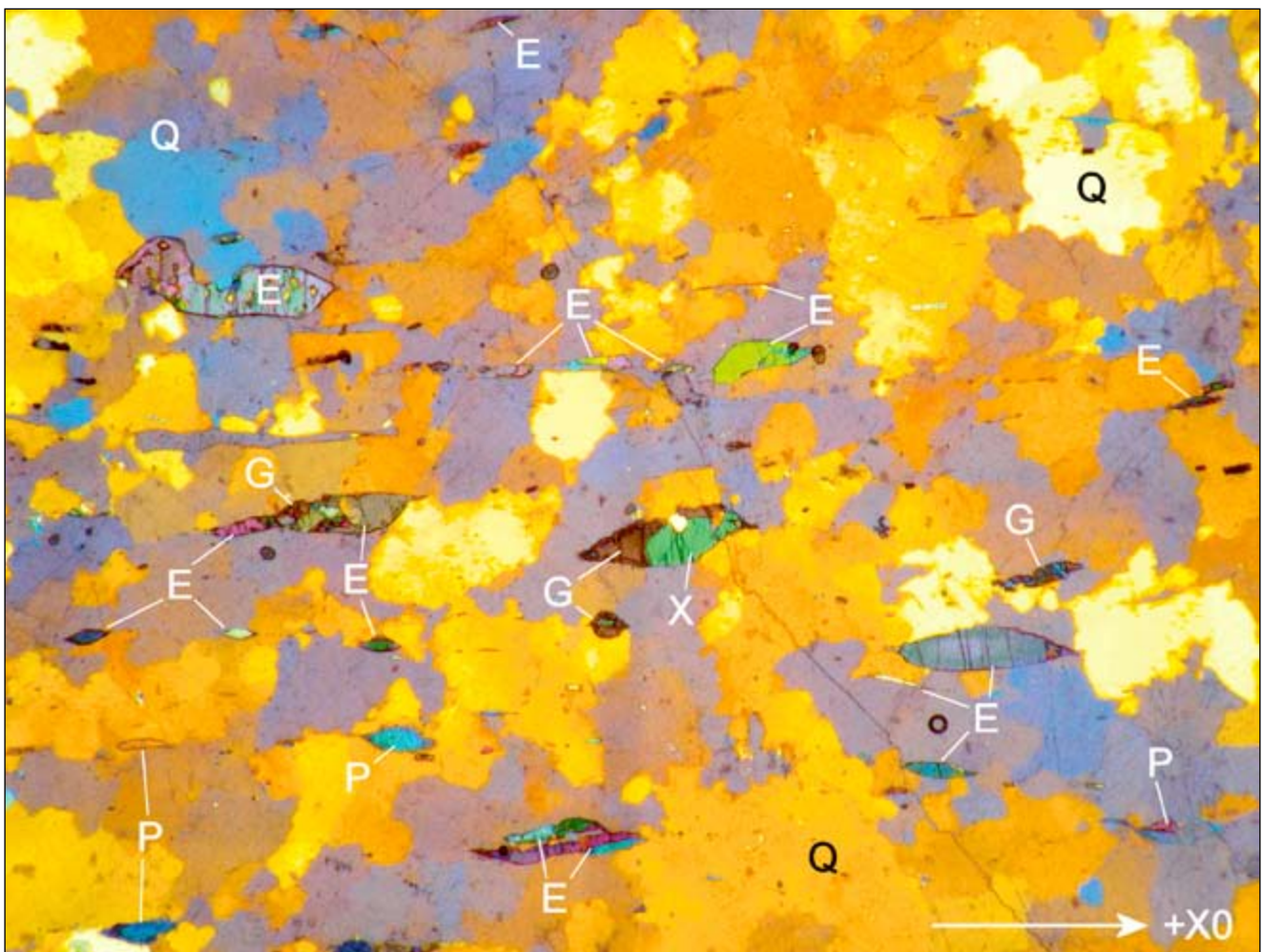


Fig. 3: Optical micrograph of the quartzitic mylonite, observed in a section parallel to the L_1 -fabric and almost perpendicular to the S_1 -fabric. Partly crossed nicols and inserted lambda-plate. Mineral abbreviations as indicated in Table 1. Long dimension of image: 4.0 mm. View towards NNE.

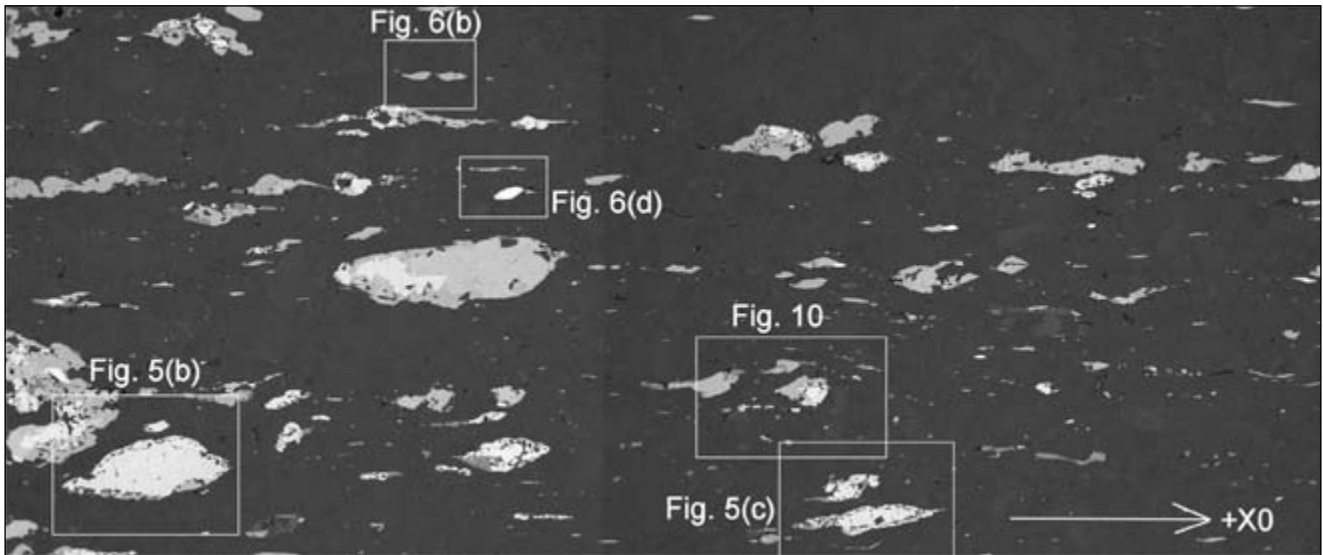


Fig. 4: BSE/SEM image, displaying the variation in size and shape of the porphyroclasts. Quartz is dark grey to black and displays a weak orientation contrast. Long dimension of image: 8.3 mm. Orientation as in Fig. 3.

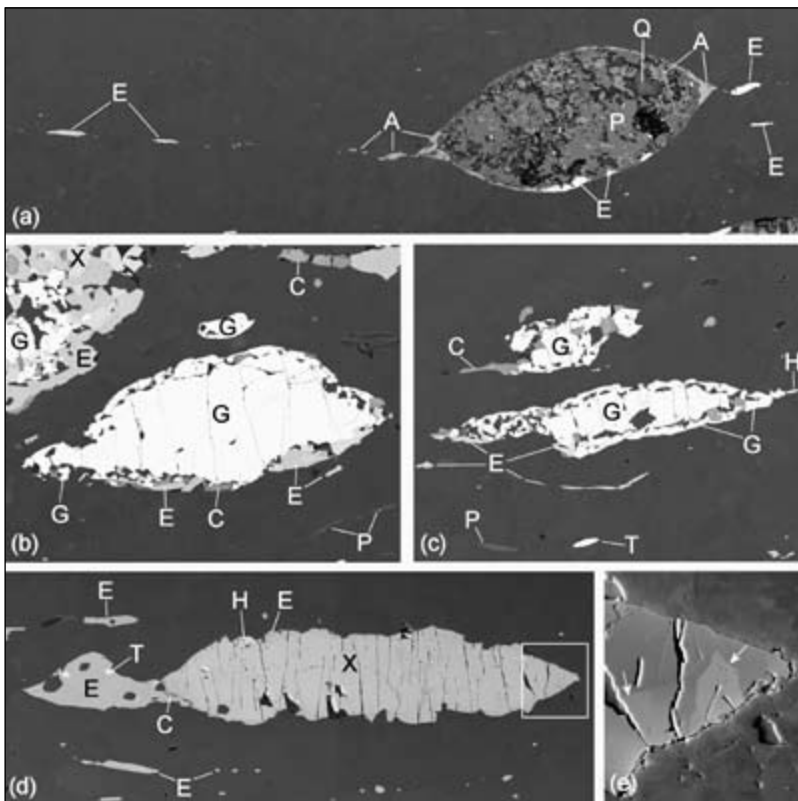


Fig. 5: BSE/SEM images of ellipsoid, fish-shaped and platy porphyroclasts: (a) Plagioclase (~An40), partly replaced by quartz, alkali-feldspar and epidote. Long dimension of image: 3.9 mm. (b) Garnet with transverse fractures and corona-like margin. Long dimension of image: 1.1 mm. (c) Same as (b). Long dimension of image: 996 micrometers. (d) Clinopyroxene, intensely fractured and with an irregular boundary towards the matrix quartz. Long dimension of image: 1.7 mm. (e) Enlargement of white frame of (d), observed with forescatter detector, which enhances the orientation contrast. A substructure in clinopyroxene is displayed, and arrows point to subgrain boundaries. Quartz is dark grey to black in all images, and it displays a weak orientation contrast. Orientation of images as in Fig. 3.

Rasmussen (1998) reported coarse subgrains in a plagioclase porphyroclast.

Three basic types of boundary between the porphyroclasts and quartz matrix have been observed, (A) corona-like mineral-aggregates, (B) irregular, and (C) smooth and gently curving.

(A) Most of the larger garnet porphyroclasts are enclosed by a corona-like aggregate of \pm epidote \pm garnet \pm quartz \pm calcite \pm hornblende (Fig. 5b&c). Thus two stages of garnet growth are observed, (1) the original, elongate

porphyroclasts (high Ca- and Fe-content) and (2) the garnets, which are part of the 'coronas' (lower Ca- and higher Mn- and Al-content). Note that the high-Ca garnet cores have type B irregular boundaries against the 'coronas'.

(B) Clinopyroxene porphyroclasts (sodian augite) display grain boundaries towards the quartz matrix that may be very irregular (Fig. 5d), suggesting that resorption was active after the formation of the elongate shapes.

(C) All large plagioclase porphyroclasts (~An40) have boundaries that are smooth and gently curving. The por-

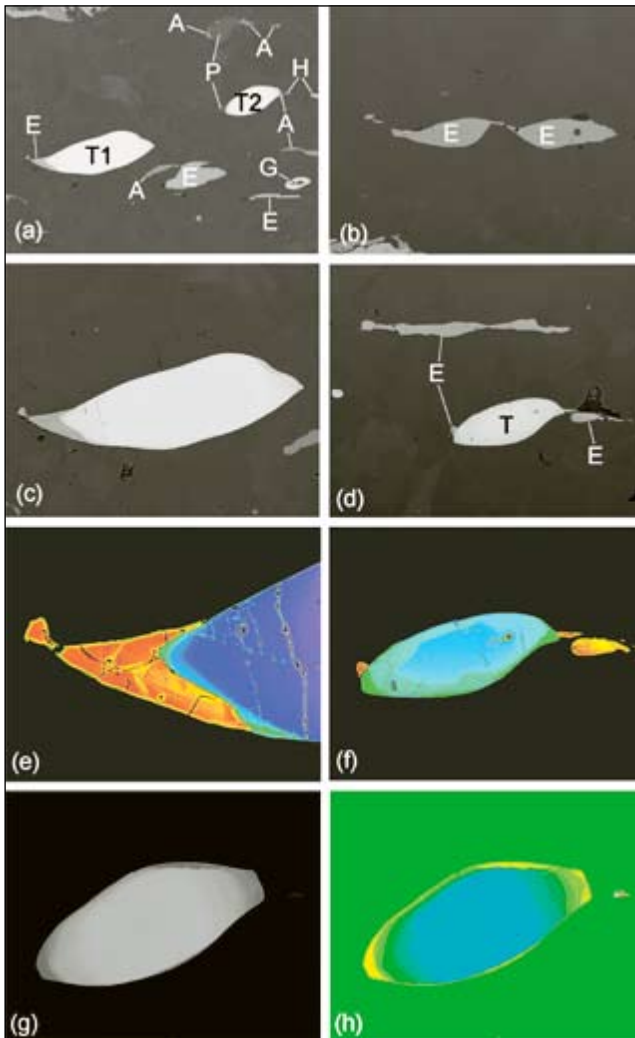


Fig. 6: BSE/SEM images of fish-shaped and platy porphyroclasts: (a) Titanite, epidote, garnet and feldspar. Quartz is dark grey to black and displays a weak orientation contrast. Long dimension of image: 1.1 mm. (b) Fish-shaped epidotes, connected by a narrow 'bridge', which is just broken. Long dimension of image: 550 micrometers. (c) Enlargement of titanite (T1) of (a). (d) Platy epidote and fish-shaped titanite with wings of epidote. Long dimension of image: 512 micrometers. (e) Compositional zoning in titanite of (c), highlighted by false colours. Blue and green colours: titanite (green = highest Ti-content). Yellow and orange colours: epidote. Note healed transverse fractures. (f) Enlargement of titanite of (d), displaying compositional zoning which is highlighted with false colours. Colours as (e). (g) Enlargement of titanite (T2) of (a). (h) Compositional zoning in titanite of (g), highlighted by false colours (yellow = highest Ti-content). Orientation of images as in Fig. 3.

porphyroclasts are all subject to metamorphic transformation, as they are partially replaced by \pm quartz \pm epidote \pm alkalifeldspar \pm white mica. Rims and wings of epidote and alkalifeldspar are common (Fig. 5a). Porphyroclasts of epidote, titanite and apatite also display type (C) boundaries. Larger epidotes are commonly symplectites, intergrown with quartz.

Hornblende is only present in the small grain size fraction. It is mostly associated with clinopyroxene, and aggregates commonly form 'wings' (extensions) connecting separate clinopyroxenes.

Many single crystal porphyroclasts of epidote and titanite are compositionally zoned, and in general the zones follow the porphyroclast outlines, as may be observed in Fig. 3 (large epidote in lower right quarter) and Fig. 6d&f (titanite). Also clinopyroxene porphyroclasts are zoned with an increase in the Mg- and a decrease in the Fe- and Al-contents from core to rim.

The compositional zoning in the fish-shaped titanite porphyroclasts is especially noteworthy. The tapering ends of the porphyroclasts display a zoning, which only follows the outline of the crystal shapes of these ends and is truncated by the "long" sides of the porphyroclasts (Fig. 6c to h). Some zonal boundaries are rounded, others are facet-like. The Ti-, Si-, and Ca-contents increases and the Fe- and Al-content decreases from core to rim, and the highest Ti-content is observed at the tapered ends (Fig. 6h). The zoning may be either a relict of growth zoning in a pre-existing, possibly euhedral titanite, which has been resorbed to give its present shape, or it is due to growth zoning formed during the final shaping of the porphyroclast, during which material was redistributed by diffusion. The second interpretation is strongly favoured since the shape of the zones may mimic in detail the shape of the tapering end of the titanite (Fig. 6e). This interpretation is further supported by the observation that the shaping of titanite is commonly completed by growth of epidote, feldspar or hornblende as wings (Fig. 6a&d).

The titanite of Fig. 6g&h displays an additional, less common, feature of thin, discontinuous, marginal zones with high Ti- and Ca-contents along the "long" sides of the titanite, clearly intersecting and postdating the zoning described above. The wavy boundary suggests that these zones are diffusion-related, and that the boundary is an arrested diffusion front.

An array of transverse fractures transects many porphyroclasts (Fig. 3 and 5b,c&d), a feature which is described also from mylonites elsewhere (e.g. Ji & Martignole 1994). The fractures are extensional in nature, and are not related to the orientation of the crystal lattice but to the shape of the crystal. They nucleate at the porphyroclast-quartz interphase, propagating inwards at a high angle to the long dimension of the porphyroclast. They postdate the formation of the corona-like margin around the garnets (Fig. 5c). There are examples of trails of fluid inclusions, which are parallel to fractures (Fig. 6e&f). These trails are interpreted as healed fractures. Since porphyroclasts may contain both healed and unhealed fractures it appears that the fracturing process took place over a time span.

Quartz CPO

Measurement of the crystallographic preferred orientation (CPO) of quartz demonstrates a very strong fabric (Fig. 7). The {001} direction (i.e. the c-axis) displays an elongate, strong point maximum, spread along a partial great circle girdle, which (1) includes the Y_0 axis and (2)

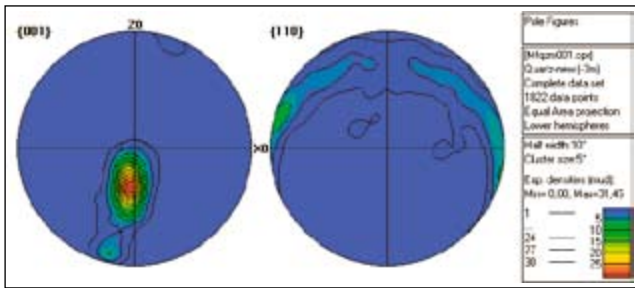


Fig. 7: CPO of quartz, presented in the CS0 coordinate system. Automatic sampling mode. Step size: 100 micrometers.

is tilted $\sim 20^\circ$ from the Z_0 axis. The centre of the point maximum is positioned $\sim 20^\circ$ off the Y_0 axis. The $\{110\}$ direction (i.e. the $\pm a$ -axis) is also spread along a great circle girdle, which (1) includes the X_0 axis, (2) is tilted $\sim 20^\circ$ from the Z_0 axis, and (3) displays a moderate maximum, which is tilted $\sim 20^\circ$ from the X_0 axis.

The CPO is compatible with a creep mechanism, which is dominated by glide on the $\{m\} \langle a \rangle$ system (e.g. Passchier & Trouw 1996). It is noteworthy, however, that the kinematic system, responsible for this CPO, is distinctly different (rotated) from the system defined by the porphyroclasts (CS0: X_0, Y_0, Z_0). This may reveal either two kinematic events, which are separated in time, or the quartz CPO reflects the latest part of a continuous, but non-coaxial, kinematic event.

CPO of the garnet porphyroclasts

Some of the layers, which have a higher concentration of porphyroclasts, contain garnet. One of these layers is selected for a closer inspection of its microstructure. Garnet serves as an example, and it is anticipated that a study of other porphyroclastic minerals such as clinopyroxene will reveal similar features.

The layer is 2 mm across, and a small fraction is illustrated in Fig. 4. In a 23 mm long section the crystallographic orientation of 104 garnet porphyroclasts in 111 datapoints has been measured. The result is presented in Fig. 8 as $\{111\}$, $\{110\}$ and $\{100\}$ pole figures. Weak, low

intensity maxima are spread in a non-systematic way over all three diagrams. It is clear that the garnets have a crystallographic orientation close to random, as will be documented below.

MD of the garnet porphyroclasts

The misorientation (i.e. orientation relationship) between two identical crystals, such as two garnets, may be expressed by (1) a common crystallographic direction, i.e. the misorientation axis, and (2) a rotation around this axis to coincidence of the two crystals, i.e. the misorientation angle (e.g. Wheeler et al. 2001). A systematic calculation of misorientation axes and angles results in the misorientation distribution (MD).

MISORIENTATION ANGLE DISTRIBUTION (MAD)

The selection of crystal pairs may be taken (1) on a random basis from the population, which leads to the uncorrelated MAD (identical to the random-pair misorientation distribution of Wheeler et al. 2001) or (2) from neighbouring grain pairs, which leads to the correlated MAD (identical to the neighbour-pair misorientation distribution of Wheeler et al. 2001). In this study the nearest neighbour is found in all directions in the plane of observation (illustrated in Fig. 3 & 4), i.e. parallel to L_1 as well as transverse to S_1 .

The misorientation angle distribution of the garnet porphyroclasts is presented in Fig. 9. Also shown are the theoretical values for a random distribution of crystals for the point group $m3m$, which is valid for garnet (Mackenzie 1958). The relative frequency of the misorientation angles of the uncorrelated MAD (5000 pairs) follows closely the theoretical relative frequency, thus giving strong support to the conclusion that the garnet population displays no significant preferred crystallographic orientation. The relative frequency of the misorientation angles of the correlated MAD departs, however, significantly from the theoretical relative frequency. Higher frequencies are present in the lower and highest angular ranges, and lower frequencies are present in the 35° - 50° range.

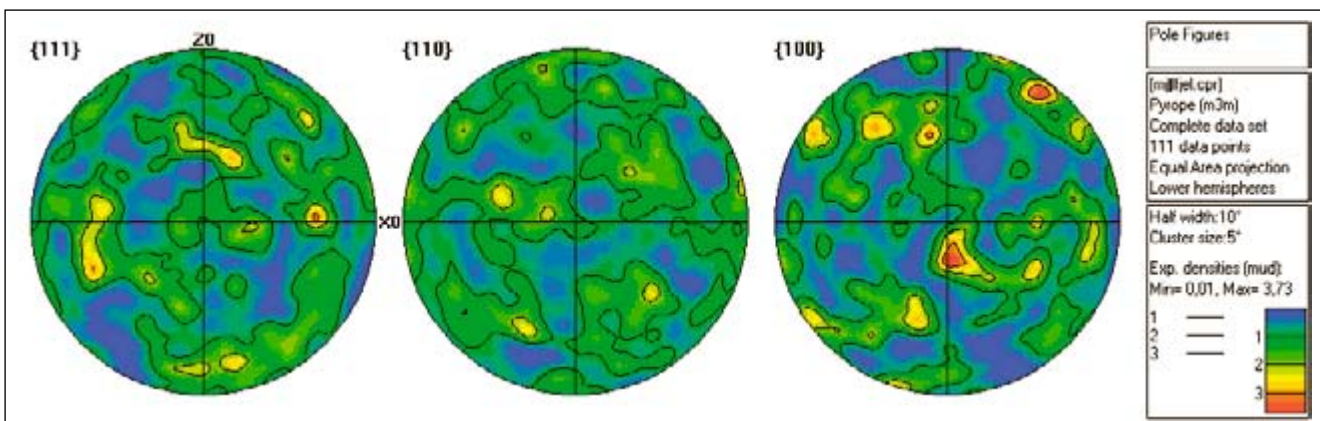


Fig. 8: CPO of garnet porphyroclasts, presented in the CS0 coordinate system. Interactive sampling mode.

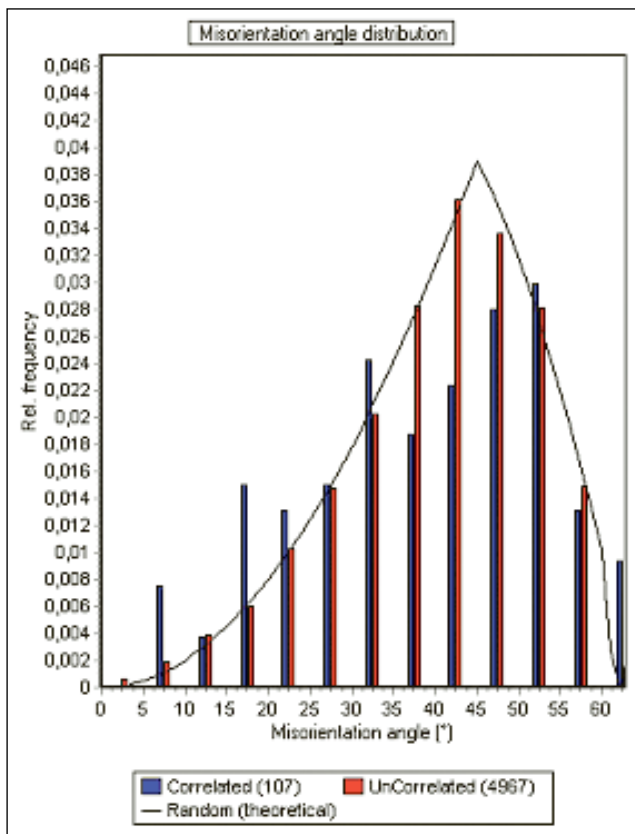


Fig. 9: MAD of the garnet porphyroclasts.

As advised by Prior (1999) a lower limit of 5° is chosen in the calculation of the correlated MAD, due to intrinsic errors in the EBSD technique. The great majority of garnet porphyroclasts (104) have just one datapoint, while a few of the largest porphyroclasts have more than one

datapoint (with almost identical orientations). This will result in some very small misorientation angles, but due to the cut-off value of 5° these angles are eliminated from the misorientation angle distribution in Fig. 9. The general pattern implies that there is a close-range crystallographic orientation relationship within the population of garnet porphyroclasts.

An example of such a close-range orientation relationship is presented in Fig. 10, where the microstructure and crystallographic orientation of seven clearly separate garnet porphyroclasts is presented. This illustrates the general feature that grains of the same mineral commonly occur in a row along S_1 and that a crystallographic relationship may be present in this row (note also rows of calcite and epidote in Fig. 10).

MISORIENTATION AXIS DISTRIBUTION

Calculation of the misorientation axis distribution may unravel possible crystal lattice rotations during porphyroclast formation (e.g. Wheeler et al. 2001). Neighbour-pair misorientation axes are presented in inverse pole figures, i.e. in a crystallographic reference frame (Fig. 11). A lower cut-off value of 5° is applied here, too, for identical reasons. It should be noted that misorientation angles $\geq 45^\circ$ lead to a forbidden zone in the inverse pole figure, and the extent of this forbidden zone increases with increase in the misorientation angle (Wheeler et al. 2001). In the lower angle range ($<25^\circ$) the area around $\langle 101 \rangle$ is unpopulated, while in the medium angle range (25° - 45°) the area around $\langle 001 \rangle$ is unpopulated. In the highest angle range ($>45^\circ$) the unpopulated area around $\langle 001 \rangle$ is also present, but this is due in part to the presence of

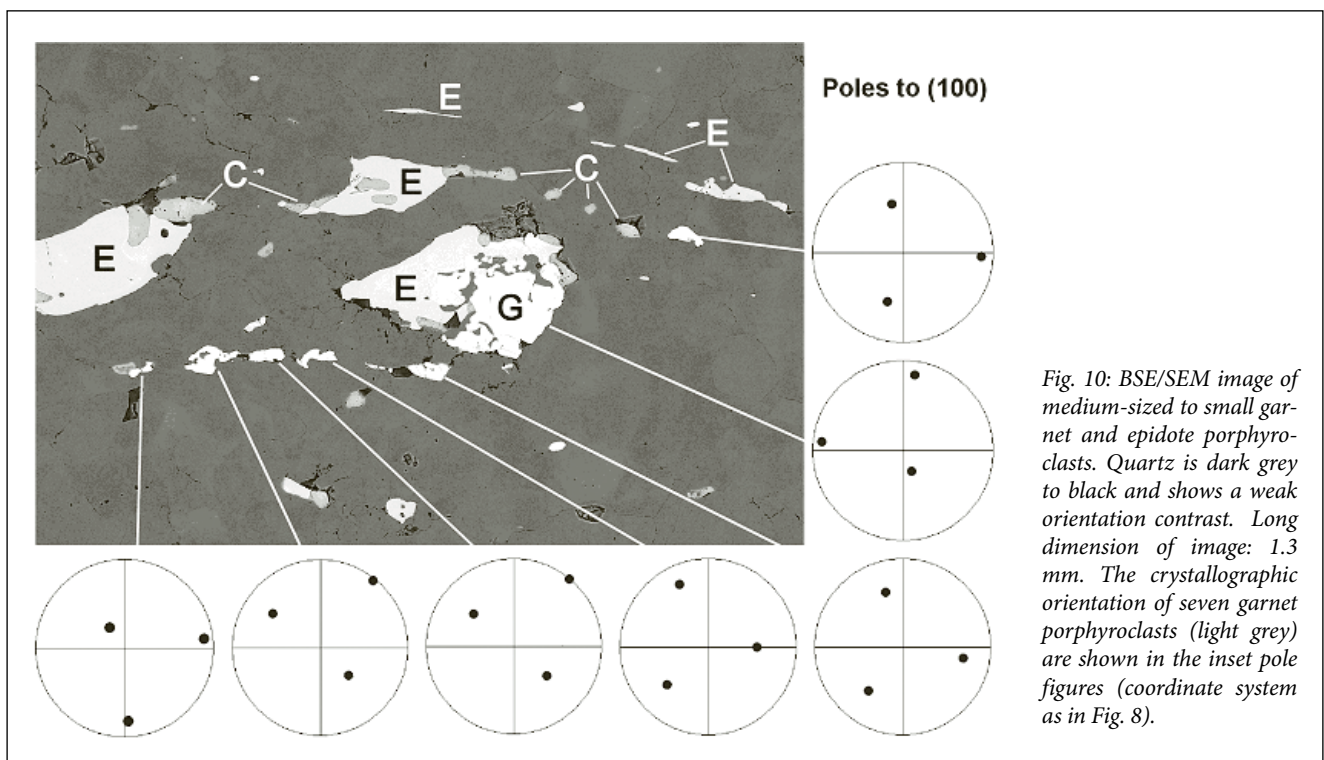


Fig. 10: BSE/SEM image of medium-sized to small garnet and epidote porphyroclasts. Quartz is dark grey to black and shows a weak orientation contrast. Long dimension of image: 1.3 mm. The crystallographic orientation of seven garnet porphyroclasts (light grey) are shown in the inset pole figures (coordinate system as in Fig. 8).

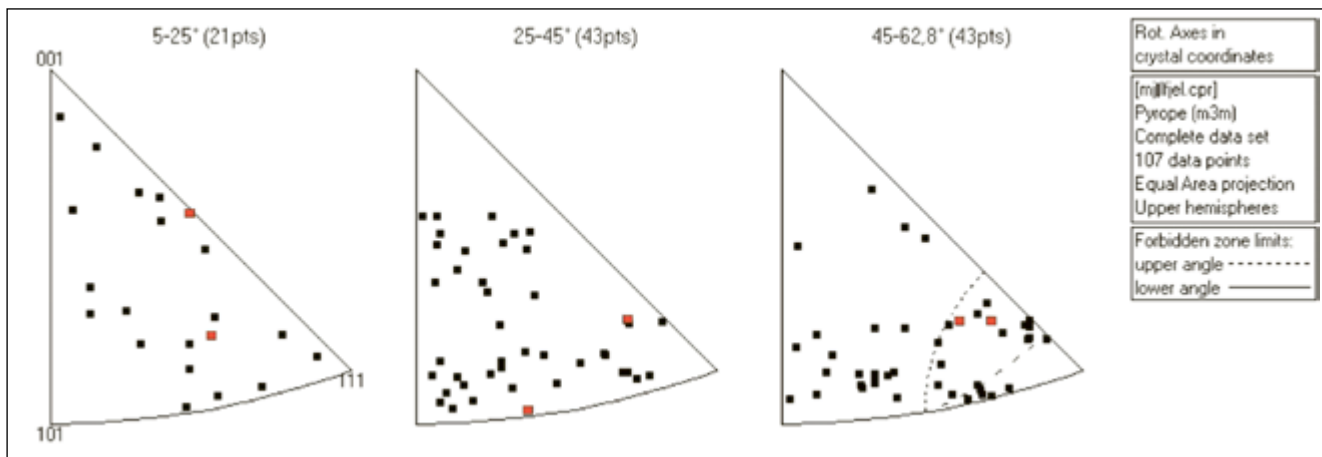


Fig. 11: Misorientation axis distribution of the garnet porphyroclasts. The misorientation axes of the seven garnet porphyroclasts of Fig. 10 are marked in red.

the forbidden zone. In conclusion, there is no clear indication of an overall crystallographic control on possible rotations of porphyroclasts, but a close inspection of the data shows that groups of close, but separate, garnet porphyroclasts such as the seven garnets of Fig. 10 may be characterized by rotation axes, which are crystallographically related (Fig.11).

Discussion

The quartz matrix

The common appearance of a mylonite is a rock with a fine-grained matrix in which more coarse-grained porphyroclasts are distributed (examples in e.g. Passchier & Trouw 1996). The mylonite studied here is different. A major fraction of the porphyroclasts is more fine-grained than the quartz matrix, the grain size of which indicates an annealing phase, which has resulted in grain coarsening. This phase must have followed the initial mylonitisation, which created the porphyroclasts (and L_1/S_1), since many porphyroclasts are completely included in quartz grains. Possibly the weak quartz SPO subparallel to S_1 was formed during the annealing, due to the controlling effect on grain growth (pinning) by the very elongate and strongly oriented mafic porphyroclasts (e.g. Vernon 2004).

The strong quartz CPO together with subgrain microstructures and indications of renewed grain boundary mobility indicate a phase of dislocation creep, dominated by slip on the $\{m\} \langle a \rangle$ system under medium to high temperature conditions (e.g. Stipp et al. 2002). The presence of lattice bending and deformation lamellae point to deformation under lower temperature conditions. Stipp et al. (2002) made similar observations in the medium to high temperature zone of their 'natural laboratory' in the Italian Alps. They interpreted this to be due to a late strain increment under decreasing temperature conditions. An alternative interpretation is suggested here,

namely that the deformation took place under relatively high differential stress, leading to a combination of dislocation creep and dislocation glide (e.g. Passchier & Trouw 1996).

Similar quartz CPO's are reported from this mylonite zone by Rasmussen (1998) and Sørensen (2001). Clausen (1986) also reported similar quartz CPO's from a quartzitic mylonite, situated approx. 5 km towards the NE in a similar geological setting.

The $\sim 20^\circ$ rotation of the quartz $\{001\}$ direction away from S_1 indicates that the kinematic system (i.e. shear plane and shear direction) changed from one orientation during mylonitisation to a different orientation in the deformation phase recorded by the quartz CPO. Dietrich & Durney (1986) reported a similar rotation between the visible LS-fabric and the CPO-defined calcite fabric in limestones of the Helvetic Nappes, Switzerland. They concluded that the CPO fabric is only recording the latest deformation event, while the LS-fabric is less easily reoriented in a progressive strain evolution involving a changing (rotating) kinematic system. Another example was described by MacCready (1996), who observed quartz CPO, which is misaligned (i.e. rotated) relative to the visible LS-fabric in amphibolite facies quartzites of the Ruby Mountains Core Complex, Nevada. Also in this case it was argued that the CPO records only the final increments of strain, while the LS-fabric records the full strain history.

A similar interpretation is favoured in this study. However, microstructures indicate the presence of an annealing phase between formation of the LS fabric (CS0) and the deformation responsible for the quartz CPO. The duration of this time span, characterized by low differential stresses and high temperatures, is not known at present.

The porphyroclasts

THE PRECURSOR

Since porphyroclasts are remains of larger grains in the rock, which predate the mylonite formation, it is assumed that the largest porphyroclasts indicate the minimum grain size of this precursor, i.e. a grain size of several millimetres. Subgrains are only observed in the largest porphyroclasts, suggesting that this substructure is relict from the precursor. The porphyroclast mineralogy suggests that this precursor was a mangerite, a common rock type in the Flåm unit (e.g. Bryhni et al. 1983). Furthermore, since subgrains are preserved in garnet, clinopyroxene and plagioclase, this indicates that it was a tectonite, i.e. a mangeritic gneiss, which was deformed by dislocation creep under medium- to high-grade conditions (e.g. Passchier & Trouw 1996). In fact, it is only the very high quartz content that distinguishes this mylonite from a 'normal' mangeritic gneiss of the Flåm unit (ignoring the strong deformation). This means it is unlikely that the quartzite has a supracrustal/sedimentary origin.

THE PORPHYROCLAST-FORMING PROCESSES

Dislocation creep is a deformation mechanism, which will produce as a rule (1) a grain elongation, the elongate shape of the porphyroclasts being inherited, at least partly, from this precursor, and (2) a non-random CPO in the involved minerals (e.g. Stipp et al. 2002). Kleinschrodt & McGrew (2000), Kleinschrodt & Duyster (2002), Ji et al. (2003) and Mainprice et al. (2004) studied elongate garnets in some high-temperature deformation zones. The weak CPO of these garnets were interpreted as evidence of garnet plasticity, in some cases supported by characteristic microstructures such as subgrains. The near-random CPO of the garnet porphyroclasts of this study gives no support for a similar conclusion. However, simulations of garnet CPO by Mainprice et al. (2004) demonstrate that due to the many possible slip-systems it is to be expected that the CPO is weak, and the weakest CPO is modelled in a simple shear situation. Thus the garnet CPO of this study cannot exclude the possibility that the elongate shape of the garnet porphyroclasts is due to plastic deformation/dislocation creep. However, a different interpretation is favoured, as will be described below.

MAD analysis of the garnet porphyroclasts shows that the process of fragmentation of larger porphyroclasts, followed by fragments drifting apart, must have been a basic process. Many examples in the literature illustrate porphyroclasts separating and drifting apart for short distances, and proven by matching shapes of the fragments (e.g. dolomite by Bestmann et al. 2000, and garnet by Kleinschrodt & Duyster 2002). In this study garnet porphyroclasts show relationships over larger distances, proven only by their crystallographic orientations. It has not been possible to identify a general pattern in the crystallographic control of the separation process, which might indicate that planes of separation are specific lat-

tice planes such as {111}. In a local (mm-scale) context there is, however, an indication of a crystallographic control on the separation, drifting and subsequent rotation in the mylonitic (non-coaxial) strain regime.

The elongate, fish-shaped titanites carry important information about the shaping of the porphyroclasts, which may be extended to the other porphyroclastic minerals. The generally anhedral compositional zone boundaries are clear indications that the shaping is due to metamorphic overgrowth (e.g. Wintsch & Yi 2002). The asymmetric shape of the compositional zones and of the crystals themselves indicate that the titanites were formed under conditions of dissolution-precipitation creep (e.g. Wintsch & Yi 2002) during which material was transported by diffusion from titanite grain boundaries with high normal stresses to grain boundaries with low normal stresses. Thus material was added to the tapered ends by syntaxial growth of titanite with an increased Ti- and Ca-content. Growth of titanite wings were followed by other minerals such as epidote, feldspar and hornblende, which are indicators of the metamorphic conditions prevailing during the process.

Terry et al. (2000) described a fish-shaped monazite porphyroclast from a mylonite in the UHP-terrain of Fjortoft (Western Gneiss Region, Norway). The monazite displays a similar asymmetry in the Y-zoning, which they interpreted to be due to resorption. Bestmann et al. (2004) described σ -shaped (i.e. fish-shaped) quartz porphyroclasts in a greenschist facies ultramylonitic marble. They concluded that the wings grew syntaxially as a result of diffusive mass transfer, in full accordance with the interpretation of the titanite porphyroclasts.

The fish-shaped titanite porphyroclasts also demonstrate that compositional changes may have been imposed on the porphyroclasts after they are formed by dissolution-precipitation creep (Fig. 6h). It is unclear at present to what extent this may explain the commonly observed compositional zoning in, for example, the epidote and clinopyroxene porphyroclasts.

Inspired by the microstructure of the epidote porphyroclasts of Fig. 6b (and many similar observations), the plate- and needle-shaped porphyroclasts are interpreted as former wings and 'bridges', which grew synkinematically between drifting fragments of larger porphyroclasts, thus creating extreme aspect ratios. This means that they are not porphyroclasts in the strict sense of the word.

The partial replacement of the large plagioclase porphyroclasts by epidote clearly signals a change in metamorphic conditions. The significance of the silicification and replacement by alkalifeldspar is not well understood, however. It is suggested that it signals an increase of silica (and possibly K) in the mylonite, due to the influx of silica-rich, hydrous fluids. Such an influx of hydrous fluids would facilitate dissolution-precipitation creep.

THE FRACTURE SYSTEMS

The arrays of extensional, transverse fracture systems, observed in many porphyroclasts, are considered to be the result of tensile stresses set up during exhumation and cooling. Similar microstructures in garnet porphyroclasts in mylonites from the Morin shear zone (Grenville Province) are described and analysed in great detail by Ji et al. (1997). Using a modified shear-lag model they explained the fractures as due to tensile stresses, established in the rocks during uplift and cooling. According to Fei (1995) there is only a minor difference in the coefficients of thermal expansion (volumetric) between garnet and α -quartz, which led Ji et al. (1997) to the conclusion that the tensile stresses must be distant rather than the result of the thermal mismatch between garnet and the quartz matrix. This conclusion is questioned here for the following reasons. Ji et al. (1997) ignored that (1) the coefficient of thermal expansion (linear) is highly anisotropic in α -quartz, and it has the highest value perpendicular to the {001} direction (Skinner 1966; Raz et al. 2002), and (2) the quartz matrix may display a strong CPO. In this study the quartz matrix is oriented preferably with the $\langle a \rangle$ directions close to the X0-Z0 plane (Fig. 7), in which we also find the long dimension of the porphyroclasts. In other words, the X0-Z0 plane of the quartzitic mylonite of this study is the plane that contains the axes of extension of the porphyroclasts, and it is also the plane in which the largest thermal contraction of the quartz matrix takes place during exhumation and cooling. This contraction is almost isometric in the plane and it is more than twice the contraction of the garnet and clinopyroxene (Skinner 1966). It is argued here that this difference cannot be ignored, and it may be the dominant (if not sole) cause of the fracture systems. The actual reduction in temperature needed for the fracturing to take place is not known. A likely cause of the cooling is

the Caledonian exhumation of the Sveconorwegian crust during the Scandian Orogenesis.

Correlation of microstructures and geochronological events

Geochronological studies of the rocks of the Upper Jotun Nappe reveal a long and complex Proterozoic intrusive and tectonometamorphic history, terminating in a Caledonian overprint of highly varying intensity (Table 2). These studies are almost absent from the Mjølfjell area, and therefore the following attempt to correlate the microstructural events observed in the quartzitic mylonite with known geochronological ages is speculative.

Only the time of intrusion of the anorthosite body, located immediately to the north and east of Mjølfjell, has been determined (Lundmark & Corfu 2008) in a study of a meta-anorthosite from the Gudvangen quarry (Fig. 1 and Table 2). Lundmark et al. (2007) report two well-supported Sveconorwegian events in their studies of the central parts of the Upper Jotun Nappe, (1) a time of local, but widespread, shearing, hydration and retrogression to medium metamorphic grade of previously high-grade gneisses at ~954-950 Ma, followed by (2) a time of regional heating and in situ anatexis at ~934 Ma, which again resulted in coarse-grained, high-grade metamorphic rocks. It is suggested here that this time of regional heating may be treated as a regional scale time marker, and that the annealing phase leading to the coarse grain size of the quartz matrix of the mylonite is part of this event. As a consequence, the high-strain event which shaped the porphyroclasts during the tectonic juxtaposition of the Flåm and Stiganosi units predates ~934 Ma, and an obvious candidate is the event recorded by the ~954-950 Ma age.

Table 2.			
Main geochronological events in the Upper Jotun Nappe	References	Ages	Microstructural events in the quartzitic mylonite
Intrusion of granite, syenite, monzonite, diorite and gabbro	Lundmark et al. (2007)	~1660-1630 Ma	
Intrusion of anorthosite	Lundmark & Corfu (2008)	~965 Ma	
Formation of high-grade gneisses	?	?	Relict substructures in porphyroclasts
Shearing, hydration and retrogression to medium-grade metamorphic conditions	Lundmark et al. (2007)	~954-950 Ma	Formation of porphyroclasts and asymmetric mylonitic fabric during tectonic juxtaposition of the Flåm and Stiganosi units
Regional heating and in situ anatexis	Lundmark et al. (2007)	~934 Ma	High-temperature annealing and grain coarsening of the quartz matrix
Metamorphic event	Lundmark & Corfu (2008)	~913 Ma	?
Metamorphic event	Lundmark et al. (2007)	~909 Ma	Reactivation of the shear zone?
Metamorphic event	Lundmark & Corfu (2008)	~892 Ma	?
Intrusion of the Årdal dyke complex and Caledonian deformation and metamorphism	Lundmark & Corfu (2007)	~427 Ma	Fracture systems in porphyroclasts

Table 2: Tentative correlation of microstructures and geochronological events in the Upper Jotun Nappe.

The post-annealing strain increment, which took place in a different kinematic system, reflects a reactivation of the shear zone under conditions of medium to high-grade metamorphism. Several late-Sveconorwegian metamorphic events are reported by Lundmark et al. (2007) and Lundmark & Corfu (2008), and it appears likely that the reactivation took place during one of these events (Table 2). Since Caledonian top-to-SE shearing is documented by Lundmark & Corfu (2007) from the central part of the Upper Jotun Nappe it is evident that also a Caledonian age must be taken into consideration. However, until now all shear zones interpreted to be of Caledonian age are formed under greenschist facies conditions (e.g. Milnes et al. 1997), and hence a Sveconorwegian age is preferred. A definite answer to this question must await further geochronological studies.

Conclusions

The observations and discussion above lead to the following conclusions:

1. The pre-mylonitisation rock was a tectonite, deformed under medium- to high-grade metamorphic conditions. Dislocation creep was the active deformation mechanism, as revealed by relict subgrains in clinopyroxene, garnet and plagioclase. Ignoring the very high quartz content, this rock was a mangeritic gneiss, in which a first SPO was established. Because of the petrological similarity with nearby plutonic rocks it is considered unlikely that the quartzite has a supracrustal origin.
2. This gneiss experienced an overprinting and strong deformation under medium- to high-grade metamorphic conditions in a shear zone with a top-to-ESE transport direction. The aspect ratio of the porphyroclasts was much enhanced, creating wings, 'bridges' and fish-like porphyroclast shapes due to chemical diffusion and mass transfer (dissolution-precipitation creep). Fragmentation and drifting apart processes were active. Metamorphic conditions changed during the mylonitization process as demonstrated by e.g. (1) compositional zoning in many porphyroclasts, (2) garnet porphyroclasts enclosed by corona-like margins, which contain new garnets with a different composition, and (3) resorption of clinopyroxene and formation of hornblende wings at and between clinopyroxenes. Possibly the quartz content increased during the mylonitization due to injection of silica-rich hydrous fluids, as signalled by the widespread silicification of the plagioclase porphyroclasts. It is suggested that this mylonitization took place during the Sveconorwegian Orogeny (~954-950 Ma).
3. An annealing phase of unknown duration followed. It resulted in grain growth in the quartz matrix and is interpreted to reflect regional scale thermal heating and anatexis, documented by geochronological studies (~934 Ma).
4. Then followed an overprinting deformation under medium- to high-grade metamorphic conditions in a new (rotated) kinematic system. This reactivation of the shear zone modified the quartz CPO and distorted the crystal lattice of some of the smaller porphyroclasts. The microstructure of quartz indicates that a combination of dislocation glide and dislocation creep was active, due to a relatively high creep stress. The active glide system was {m} <a>. Also this strain increment is interpreted as having been produced under the Sveconorwegian Orogeny.
5. Finally, exhumation and cooling resulted in the production of extensional fracture systems in many porphyroclasts, due to tensile stresses. Most likely, these stresses were of a local origin (thermal mismatch between porphyroclasts and the quartz matrix). Tectonic slicing and uplift of the Sveconorwegian crust during the Caledonian Orogeny is the assumed cause of the cooling.

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