Journal of Structural Geology, Vol. 12, No. 1, pp. 19 to 28, 1990
Printed in Great Britain

0191-8141/90 $03.00+0.00

Crystallographic orientation patterns of myrmekitic quartz: a fabric memory in quartz ribbon-bearing gneisses

H. STEL and M. BREEDVELD

Institute of Earth Sciences, Free University, P.O. Box 7161, 1007 MC Amsterdam, The Netherlands

(*Received* 5 *October* 1988; *accepted in revised form* 1 *May* 1989)

Abstract—Crystallographic orientation patterns are found in myrmekitic quartz inclusions in plagioclase crystals in medium-grade gneisses from a Svecofennian fold belt in SW Finland. The development of crystallographic fabrics in myrmekite is studied in progressively deformed granitic veins. Deformation of these veins is accompanied by partial transformation of K-feldspar to myrmekite, which is a common synkinematic reaction in feldspar-bearing rocks that are deformed in amphibolite facies conditions. Microstructures suggest that myrmekitic quartz nucleated epitaxially on a pre-existing independent quartz crystal adjacent to the feldspar host. An important consequence is that the orientation pattern of myrmekitic quartz reflects that of the pre-existing crystals in the host rock at the time of nucleation. As such, the pattern represents a memory of an old fabric in annealed ribbon mylonites.

INTRODUCTION

THE development of crystallographic orientation patterns in tectonites is largely controlled by deformation history and operating slip systems in the constituent minerals (Lister & Paterson 1979, Lister & Hobbs 1980, Schmid & Casey 1986). In most cases Lattice Preferred Orientation (LPO) patterns show a consistent relation with other structural elements, i.e. lineation and foliation (Sander 1950, Wenk 1985). Although many tectonites have strong crystallographic fabrics, there are many that display random patterns of preferred orientation (Hobbs *et al.* 1976, p. 111). This can be partly due to post-kinematic processes that modify and may disperse a crystallographic preferred orientation pattern (Wilson 1982, Culshaw & Fyson 1984). Moreover, a given crystallographic fabric becomes readily overprinted after minor amount of strain (<30%) (Rutter & Rusbridge 1977, Lister & Hobbs 1980). Fabric analysis would greatly improve if a fabric 'memory' could be found, i.e. a population of grains that escaped post-kinematic alteration or overprinting. In this paper we argue that syn-kinematically grown myrmekitic quartz in medium-grade metamorphic rocks represents such a fabric memory. We studied the origin of myrmekite structure and fabric in syn-tectonic pegmatite and granite veins that show progressive deformation and concurrent mineral transformations. The possible use of myrmekite as fabric memory is illustrated by a study of ribbon-bearing gneisses with largely randomized crystallographic fabric.

GEOLOGICAL SETTING

The rocks studied are found in the Svecofennian gneiss belt of SW Finland (Fig. 1). The main phase of orogeny in this belt took place at 1.92–1.7 Ga (Simonen 1980). Metamorphism reached high amphibolite facies and, locally, granulite facies conditions (Schreurs & Westra 1986). The belt is built-up of supracrustals (predominantly meta-volcanics) and infracrustals. Two main generations of orogenic plutonic rocks are distinguished. Early intrusives (1.9–1.85 Ga) are tonalitic to gabbroic in composition; microcline granites were formed at a later stage (1.82–1.78 Ga) (Wilson *et al.* 1985, Front & Nurmi 1987, Gaal & Gorbatschev 1987).

The microstructure of gneisses in a shear zone that runs through one of the older intrusives is compared with that of deformed pegmatitic and granitic veins that are genetically related to the younger intrusives. The rocks studied are part of the Simijärvi sill (Tuominen 1957), which is a composite tonalite–gabbro intrusion. The location of the rock unit is shown on Fig. 1. Intrusions of these rocks pre-dated the peak of metamorphism (Simonen 1980). The mineral assemblage in the Simijärvi tonalites: hornblende + brown biotite + plagioclase (35% An) points to amphibolite facies conditions of metamorphism.

Locally, shear zones are found in the intrusive. The Antskog shear zone (Fig. 2) is the most prominent one. Two generations of structures were recognized in this shear zone. The oldest structural element is a pervasive lineation and foliation defined by coarse quartz ribbons and alignment of brown biotite and hornblende. Locally, this fabric is overprinted by a younger shear zone (Fig. 2), and quartz ribbons are recrystallized.

MICROSTRUCTURAL EVOLUTION OF GRANITIC VEINS

Granitic veins and pegmatites are found in the entire gneiss belt. They are genetically related to late stage

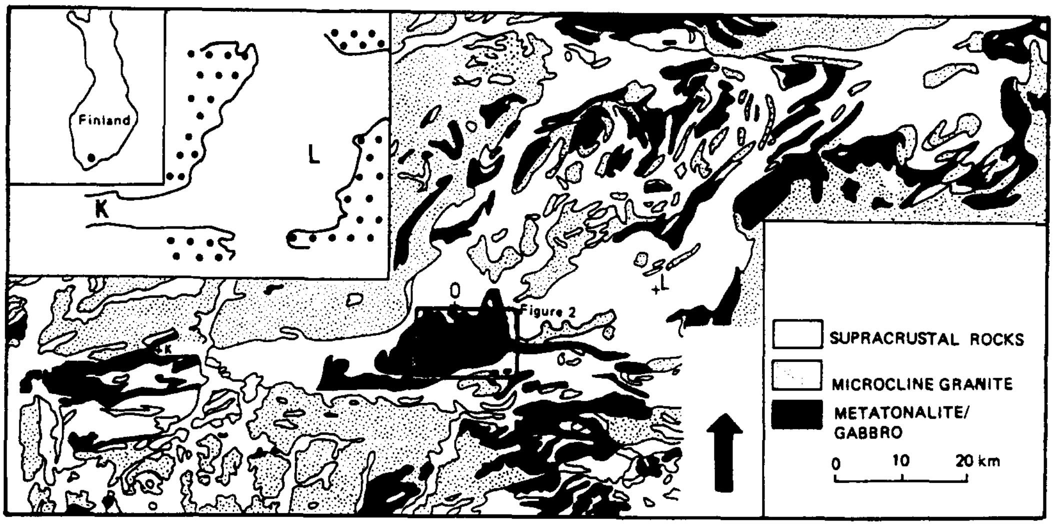


Fig. 1. Simplified geological map of SW Finland. Location of area studied is indicated. Inset: outline of the Kemiö-Lohja belt, S. Finland. K = Kemiö. L = Lohja. O = Orijärvi (after Schreurs & Westra 1986).

tectonic granites, and demonstrate diverse stages of deformation ranging from undeformed to boudinaged, folded and mylonitized.

Undeformed pegmatite veins consist mainly of subhedral K-feldspar megacrysts and quartz. Numerous quartz inclusions in feldspar are found. These inclusions define orientation domains that extend over several feldspar crystals. Undeformed migmatite and granitic veins are equigranular with mineral compositions of quartz, K-feldspar, plagioclase and some biotite.

Deformed veins show diverse stages of transformation of K-feldspar to plagioclase and quartz. Boudins of K-feldspar are completely rimmed by these minerals in a pseudo-rapakivi texture. Within these rims, plagioclase and quartz occupy different structural positions. Myrmekitic plagioclase is found at those edges of boudins that are aligned with the foliation, while quartz is found in the tail region of boudins. Quartz aggregates in pressure shadows demonstrate 'hammer-shaped' grain-boundary alignment structure such as described by Sander (1950) and Lister & Dornsiepen (1982).

In folded granitic veins quartz grains have lobate

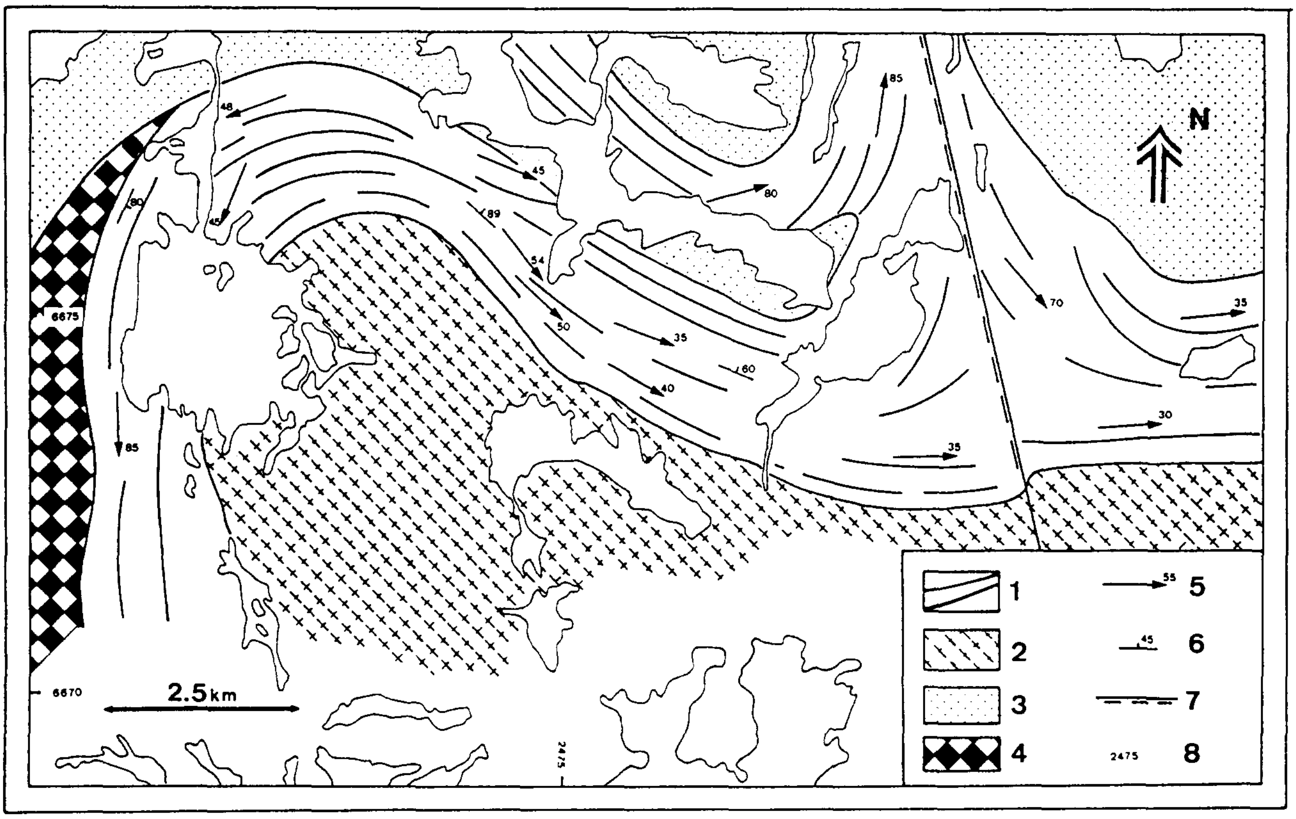
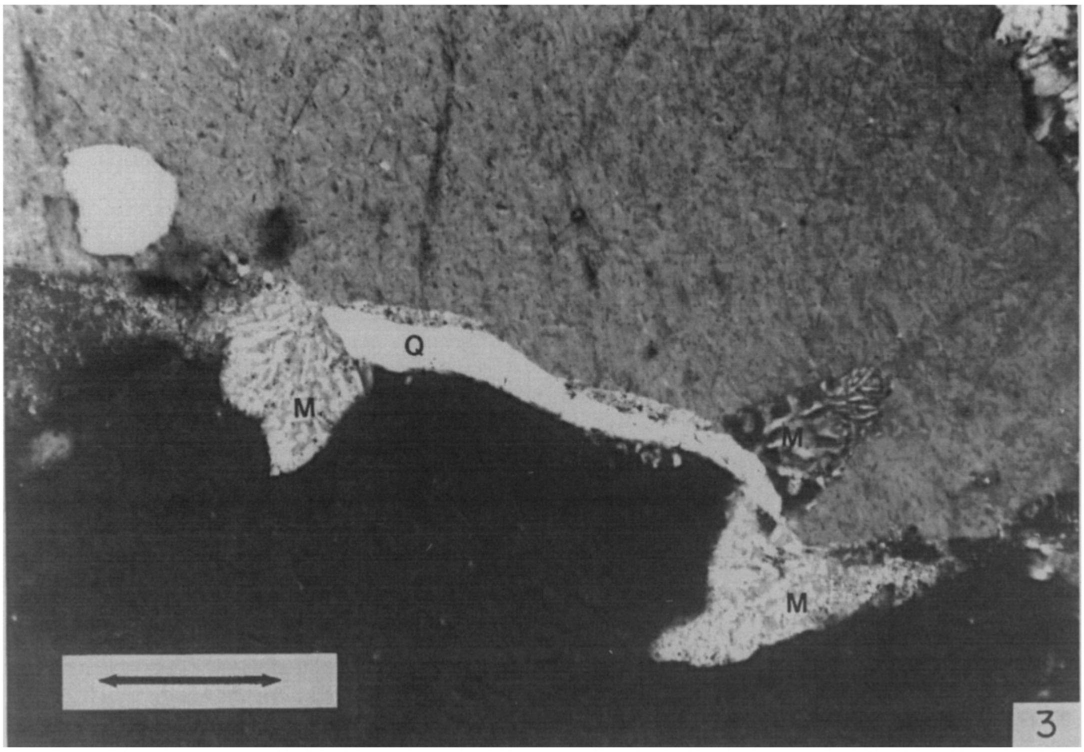


Fig. 2. Map of Antskog shear zone, located at the northern rim of the Simijärvi sill. 1. Antskog shear zone. Foliation indicated by lines; 2. Undeformed tonalite; 3. Meta-volcanics; 4. Gabbro; 5. Plunge of lineation defined by quartz ribbons; 6. Strike and dip of foliation; 7. Shear zone generated in the second deformation phase; 8. Co-ordinates of topographic map.



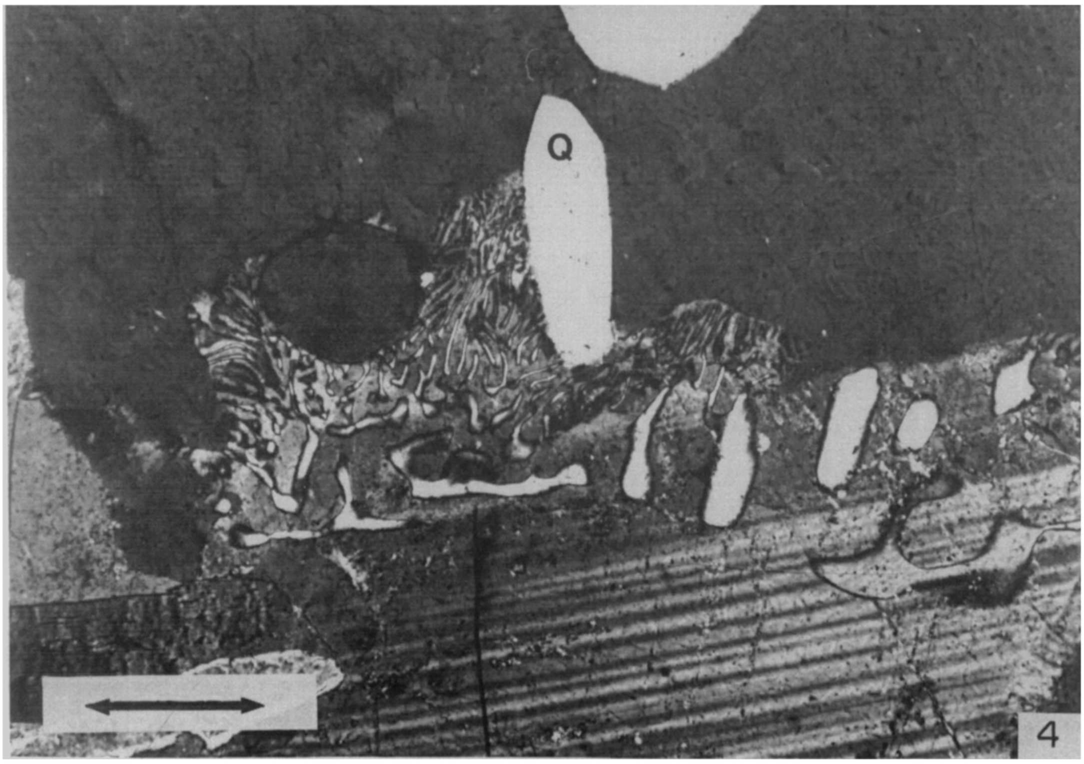


Fig. 3. Myrmekite domains (M) occurring near triple point junctions of quartz (Q) and two feldspar grains. Crossed-polarizers. Scale bar 1.5 mm.

Fig. 4. Zonal myrmekite structure at boundary of plagioclase and K-feldspar. Near the boundary, quartz constitutes a network which is in crystallographic continuity with an independent quartz grain (Q). Away from the boundary, myrmekitic quartz constitutes individual blebs. Crossed-polarizers. Scale bar 1 mm.

boundaries. In sections perpendicular to the fold axis, no shape fabric of minerals can be detected. An axial plane foliation is virtually absent. A mineral lineation parallel to the fold axis is constituted by alignment of ribbon-like quartz grains and micas. Individual minerals show no deformation or recovery structures.

At specific K-feldspar boundaries myrmekite rims are found. Their occurrence is related to the presence of independent quartz adjacent to K-feldspar. Myrmekite is only found at those K-feldspar interfaces that terminate in a triple point junction of two feldspar crystals and quartz. In some cases, the occurrence of myrmekite is restricted to a small domain adjacent to such a triple point (Fig. 3).

Most myrmekites display a zonal structure. Near the interface of K-feldspar and myrmekite a continuous, finely structured vermicular network of quartz in plagioclase matrix is found (Fig. 4). This network is in crystallographic continuity with the adjacent quartz crystal at the triple point. Away from the boundary, quartz constitutes individual blebs (Fig. 4). Crystallographic orientations of blebs and network-quartz are similar.

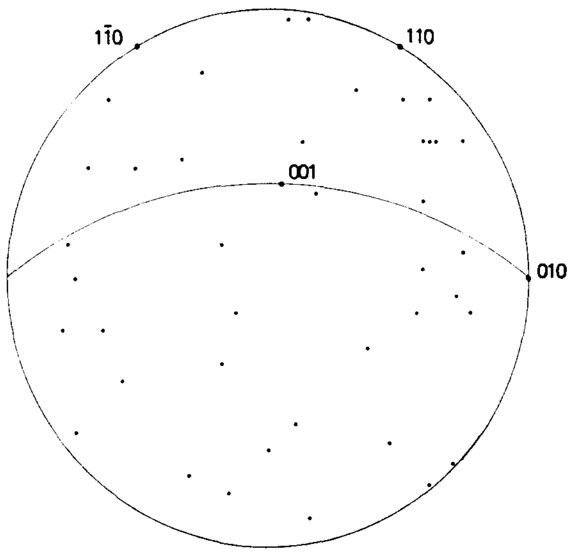


Fig. 5. Fabric diagram showing orientation of myrmekitic quartz relative to the crystallography of plagioclase host. Small dots represent c-axes of quartz, poles to crystallographic planes of plagioclase are indexed and are represented by larger dots. Great circle represents the zone 100 of plagioclase.

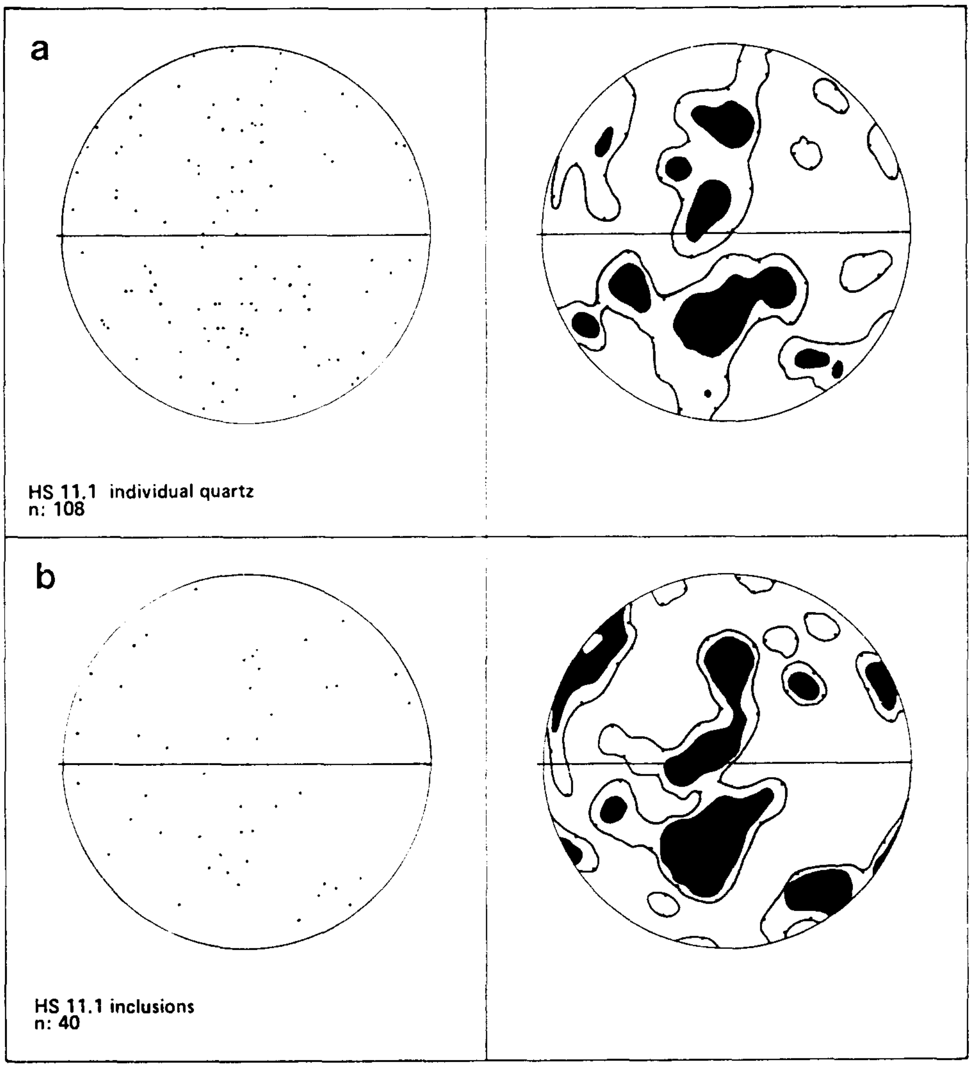


Fig. 6. Fabric diagram of granitic vein, showing the relation between (a) independent quartz grains and (b) myrmekitic quartz. Note similarities of location and shape of the maxima in both diagrams. Dots represent c-axes of quartz. In contoured diagrams the 1 and 2 times uniform distribution contours are drawn; areas with distribution density >2 times uniform are black.

The crystallographic orientation of quartz 'worms' in myrmekite appears to be independent of the orientation of the host feldspar. This is illustrated in Fig. 5, which shows the orientation of *c*-axes of quartz relative to the crystallography of the plagioclase host. The crystallographic orientation of myrmekite quartz appears to be strongly related to that of adjacent, independent quartz crystals. This phenomenon is observed on a small scale (Fig. 4) and it can also be shown on the scale of a thin section where the orientation pattern of myrmekitic quartz and independent grains are almost identical (Fig. 6). The crystallographic orientation patterns of folded veins are diffuse type I girdles (Lister 1977), symmetrical with respect to the lineation.

RIBBON GNEISSES, MICROSTRUCTURES AND LATTICE PREFERRED ORIENTATION PATTERNS

A microstructural study of ribbon-bearing gneisses from the oldest structural element of the Antskog shear zone reveals the possible use of myrmekite as a fabric-memory. The mineral composition of the gneisses is 30% feldspar, 15% biotite, 25% hornblende and 30% quartz.

The gneisses have a strong lineation, defined by quartz ribbons with aspect ratios of *ca* 20:3:1 (cf. Figs. 7a & b). Some ribbons are mono-crystalline, others are composed of three or four extremely elongate grains (Fig. 7a). Longest dimensions of quartz grains vary between 1 and 10 cm. Quartz grain boundaries are lobate and ribbons have highly irregular outlines ('amoeba shaped'). Quartz crystals have inclusions of feldspar and mica grains. The ribbons are comparable with "type 3" in the terminology of Boullier & Bouchez (1978) and "Plattenkvartsen" described by Behr in Saxony granulites (Behr 1961, 1980). The quartz ribbons are embedded in a feldspar-rich matrix composed of plagioclase (An 39%), brown biotite, hornblende, small quartz grains and a minor amount of microcline. Plagioclase crystals are subhedral, some crystals show zonation parallel to their outline. Myrmekitic rims occur at plagioclase–microcline interfaces. Locally, completely myrmekitic grains are found. Quartz grains in these domains are relatively small (<1 mm) and strain-free.

LATTICE PREFERRED ORIENTATION (LPO) PATTERNS

c-Axis fabrics of gneisses containing quartz ribbons show weak patterns to near-random distributions. Composite diagrams from two or three thin sections of one hand-specimen show weak maxima. The position of maxima is consistent in composite diagrams from different specimens, with a maximum parallel to the *Y* axis and two peripheral maxima located 30–45° from the *Z* axis of the shape fabric (compare Figs. 8a–g).

Myrmekitic quartz grains in feldspar-rich domains in

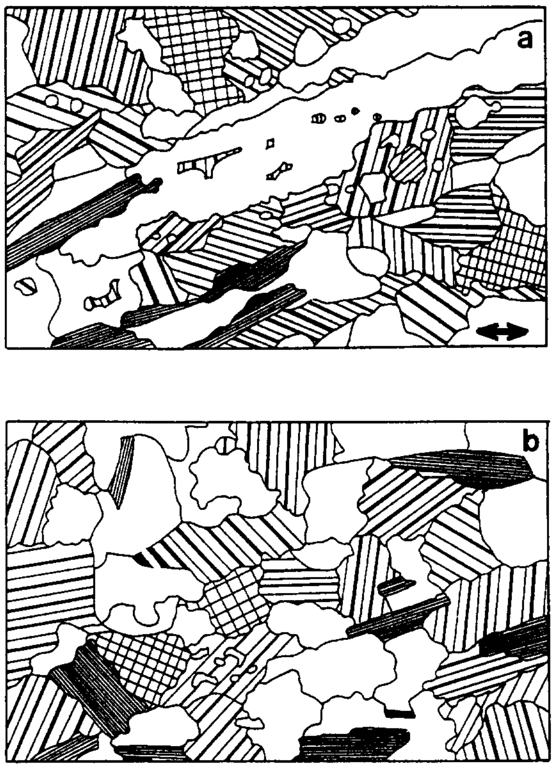


Fig. 7. Line drawing of photomicrograph of ribbon-bearing gneiss. White = quartz; finely hatched = biotite; coarsely hatched = plagioclase; cross hatched = K-feldspar. (a) Section parallel to the *XZ*-plane of the shape fabric, (b) section parallel to *YZ*. Note shape fabric of quartz ribbons (*ca* 20:3:1), feldspar inclusions in quartz, and lobate quartz–feldspar boundaries. Scale bar 0.5 cm.

these rocks show strong crystallographic fabrics (Figs. 9 and 10). The *c*-axes form two small girdles at 40° from the *Z* axis, and a maximum parallel to the *Y* axis of the shape fabric. This pattern can be classified as "type I crossed girdles" (Lister 1977). In individual thin sections, *c*-axis orientations of myrmekitic quartz in feldspar-rich domains fall well within the orientation-distribution of ribbon quartz *c*-axes. In all the cases, the locations of the *c*-axis maxima of myrmekitic quartz are located in the centre of diffuse maxima of the LPO patterns of the ribbons.

INTERPRETATION AND DISCUSSION

The origin of myrmekite and of its crystallographic orientation are discussed here in order to evaluate the occurrence of LPO patterns in myrmekitic quartz.

In recent literature it is reported that in granitic rocks, deformed at low- to medium-grade metamorphic conditions, K-feldspar is (partly) transformed to plagioclase (Hanmer 1982, Simpson 1985, Stel 1986). Stel (1986) reports that under these conditions K-feldspar may crystallize as a stable phase in veins, while the mineral is unstable once the veins are deformed ductilely. This stability–instability alternation may be related to buffering of the metamorphic fluid when a vein is closed. Alternatively, transformation of K-feldspar to plagioclase may be related to a decrease of the stability field of

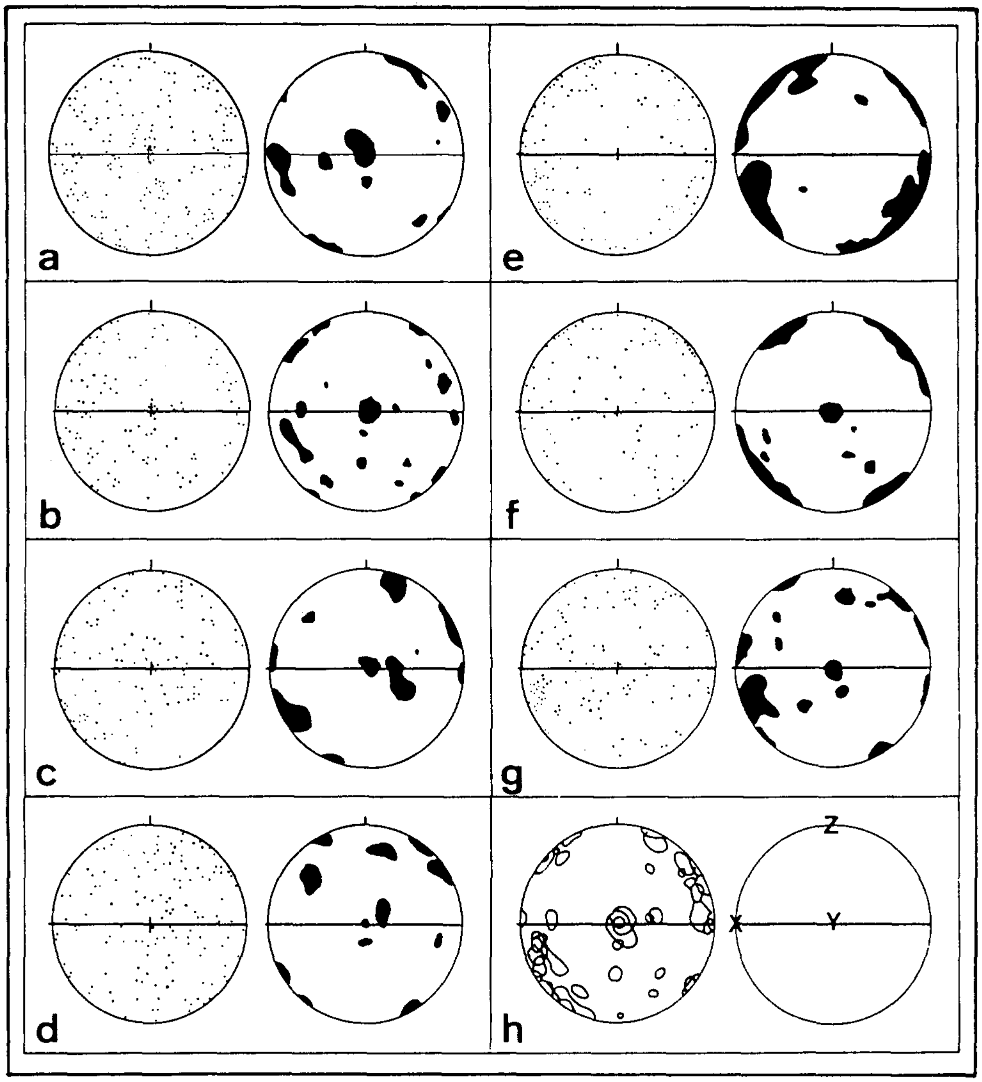


Fig. 8. Fabric diagrams of typical ribbon-bearing gneisses from oldest structural element of the Antskog shear zone. Symbols and contour lines for (a)–(g) are as Fig. 6. (a)–(g) Composite diagrams of two to three thin sections of one hand specimen. Number of data (*n*) for (a) 200, (b) 127, (c) 120, (d) 13, (e) 116, (f) 100 and (g) 140. (h) Composite diagram of maxima >3 times uniform of (a)–(g); the diagram on right indicates the orientation of all diagrams with respect to the shape fabric axes ($X > Y > Z$) of the rocks. Note that in each rock specimen X, Y and Z axes constitute an internal reference frame, which has no fixed relation to the geographical co-ordinate system.

the former as a result of a high dislocation density generated during deformation (Stel 1986, Simpson & Wintsch 1989). Simpson (1985) reports that myrmekite is located at sites of high strain, i.e. K-feldspar boundaries aligned with the local foliation.

The microstructural setting of myrmekite in deformed pegmatitic veins described here is similar to that reported by Simpson (1985). We follow the interpretation of Simpson (1985) and Simpson & Wintsch (1989) that myrmekite structure is a result of a syntectonic transformation of K-feldspar to plagioclase which can be written as

$$KAlSi_3O_8 + xCa^{2+} + (1-2x)Na^+ = (CaAl_2Si_2O_8)_x\cdot(NaAlSi_3O_8)_{(1-2x)} + 2xSiO_2 + K^+ \quad (x \leq 0.5)$$

(generalized after Simpson & Wintsch 1989).

The mechanism of myrmekite formation is deduced from the microstructures. There is crystallographic continuity between myrmekitic quartz networks and adjacent, independent quartz crystals. Moreover, the presence of an independent quartz crystal at the triple-point junction of plagioclase, K-feldspar and quartz appears to be of critical importance for the development of myrmekite. Only when such a triple point is present, does myrmekite at K-feldspar interfaces occur. From these interrelations we interpret that myrmekitic quartz was generated by epitaxial nucleation on an adjacent grain (cf. Spry 1969, Vernon 1974). The zonal structure of myrmekite, vermicular network at the boundary and individual blebs in the inner part of the host plagioclase, is interpreted as a nucleation stage followed by a coarsening recrystallization stage. This interpretation explains the consistent relation of LPO patterns of independent quartz grains and the myrmekitic inclusions in plagioclase from granitic veins. The coarsening stage of myrmekite resulted in the formation of individual quartz blebs, which are completely enclosed by plagioclase. Because these blebs are isolated, they will not be affected by grain-boundary migration processes which may take place in the quartz grains in the bulk rock. So, when the crystallographic fabric of a rock

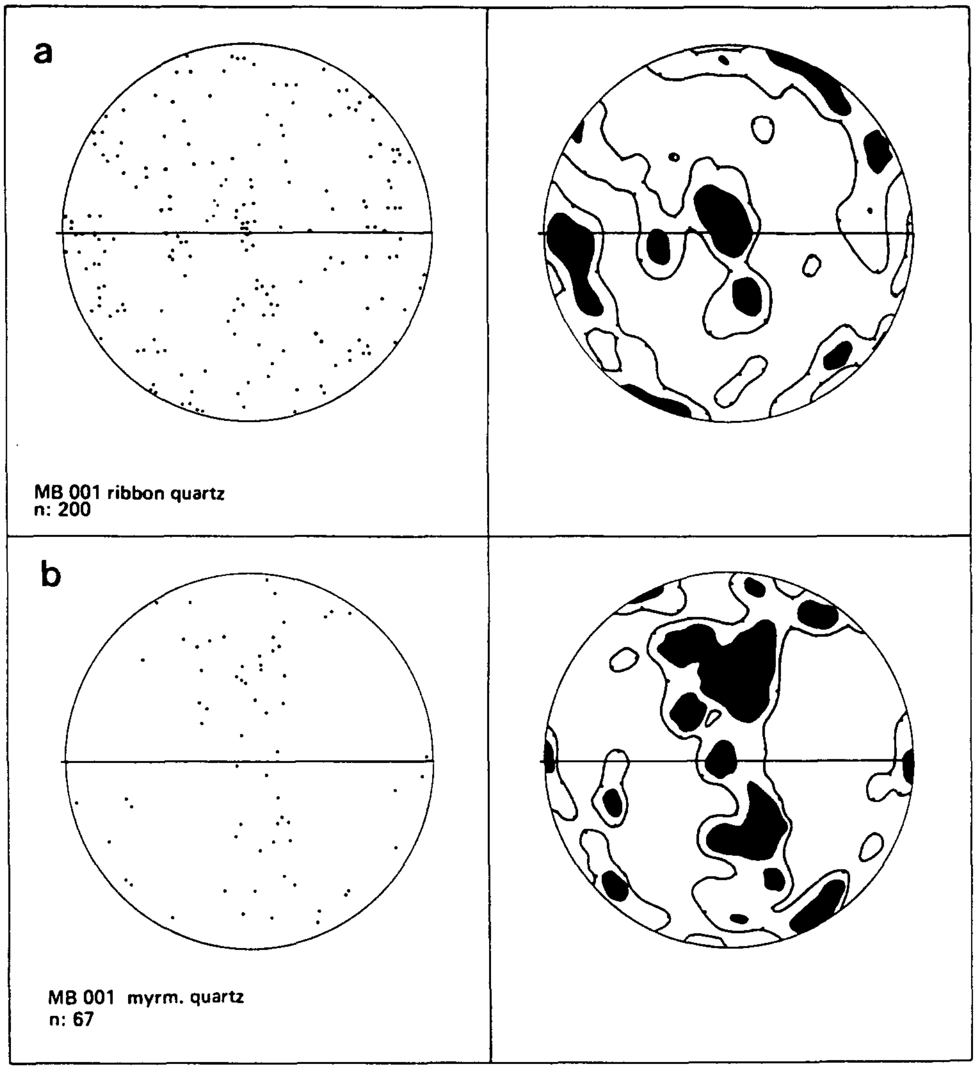


Fig. 9. Synoptic fabric diagram of (a) *c*-axis fabrics of ribbons and (b) myrmekitic inclusions of specimen MB 001. (a) Corresponds to Fig. 8(a). Pattern of myrmekitic quartz is a type I crossed girdle, while the pattern of ribbon quartz is much more diffuse. The location of the maxima is similar.

is altered by this type of recrystallization, myrmekitic inclusions in plagioclase will not be affected and will retain their original orientation. Since this orientation is inherited from independent crystals during epitaxial nucleation, it can be applied as a fabric memory. Accordingly, the LPO patterns of myrmekitic inclusions in plagioclase in ribbon-bearing gneisses are interpreted as relicts from a fabric in the bulk rock that was randomized at a later stage.

In a recent paper Blom (1988) compared fluid inclusions in myrmekitic quartz with those in independent quartzes from migmatites of the same gneiss belt that we discuss here. Blom (1988) noted that myrmekitic quartz in plagioclase represents an older crystallization phase than independent quartz, and concluded that the latter underwent a pervasive recrystallization phase. These findings are in agreement with the results of the present study.

The fabric history of ribbon bearing gneisses

We suggest that LPO patterns in myrmekitic quartz represents a fabric memory in ribbon-bearing gneisses. So, at the moment of myrmekite formation, a type I crossed girdle fabric was present in the rocks. We conclude that post-kinematic processes largely destroyed such a fabric in non-myrmekitic quartz grains. The microstructures suggest that two processes took place: grain growth involving the movement of quartz–quartz grain boundaries, and growth of quartz at the expense of K-feldspar and mica.

Grain growth involves migration of grain boundaries and the consumption of several grains by another. It is difficult to imagine how such a process (reduction of the number of different crystallographic orientations) can scatter a given fabric. Indeed, *in situ* experiments on recrystallization (Urai & Humphreys 1981) show that grain growth processes strengthen a crystallographic distribution pattern.

We suggest that in the present case, quartz overgrowth over feldspar, mica and hornblende caused a profound scattering of the fabrics. Investigations into the details of this process are the subject of current research.

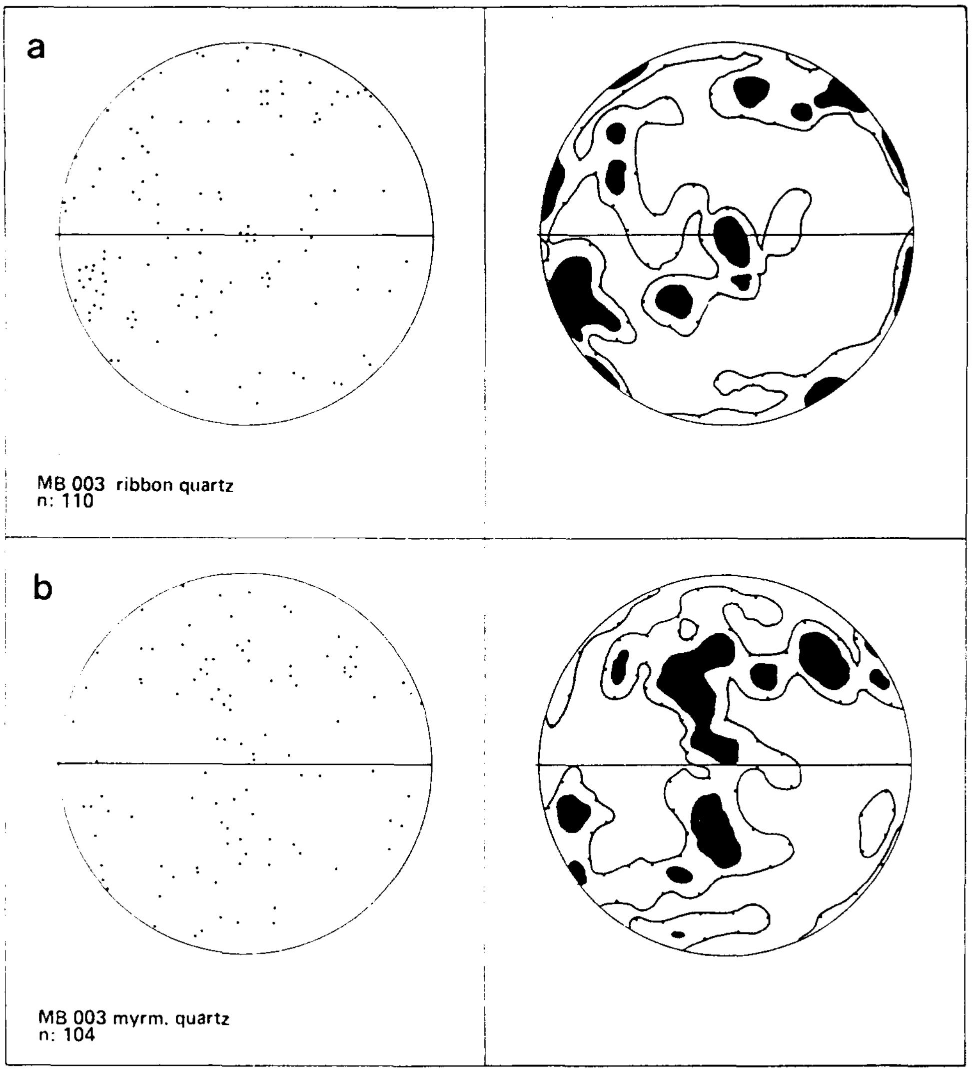


Fig. 10. Synoptic fabric diagram of *c*-axis fabrics of (a) ribbons and (b) myrmekitic inclusions of specimen MB 003. (a) corresponds to Fig. 8(g). Pattern of myrmekitic quartz is a type I crossed girdle, while the pattern of ribbon quartz is much more diffuse.

CONCLUSIONS

The crystallographic orientation of myrmekitic quartz in plagioclase is determined by the orientation of an independent quartz crystal.

In this way, fabrics in myrmekite reflect the fabrics in the bulk rock at the moment of myrmekite formation. These fabrics may be preserved during post-kinematic alteration of the host rock fabric. As such they provide valuable indices for the deformation history of a given rock and can be applied as a 'fabric-memory'.

Acknowledgements—The authors wish to thank Dr L. Westra who introduced us to the field area. Dr E. Campbell and Dr S. A. P. L. Cloetingh read the manuscript and suggested improvements. Dr C. Simpson and two anonymous reviewers are thanked for helpful suggestions.

REFERENCES

Behr, H. J. 1961. Beiträge zur petrographischen und tektonischen Analyse des Sächsichen Granulitgebirges. *Freiber. Forsch.-H.C.* **215**, 9–146.

Behr, H. J. 1980. Polyphase shear zones in the granulite belt along the margins of the Bohemian Massif. *J. Struct. Geol.* **2**, 249–254.

Blom, K. A. 1988. Subsolidus migmatization in high grade metatuffs (Kurkijärvi, southwest Finland). *Lithos* **21**, 263–278.

Boullier, A. M. & Bouchez, J. L. 1978. Le quartz en rubans dans les mylonites. *Bull. Soc. geol. Fr.* **22**, 253–262.

Culshaw, N. G. & Fyson, W. K. 1984. Quartz ribbons in high grade granite gneiss: modifications of dynamically formed *c*-axis preferred orientation by oriented grain growth. *J. Struct. Geol.* **6**, 663–668.

Front, K. & Nurmi, P. A. 1987. Characteristics and geological setting of syn-kinematic Sveco-Karelian granitoids in southern Finland. *Precambrian Res.* **35**, 207–224.

Gaal, G. & Gorbatschev, R. 1987. An outline of the Precambrian evolution of the Baltic shield. *Precambrian Res.* **35**, 15–52.

Hanmer, S. K. 1982. Microstructure and geochemistry of plagioclase and microcline in naturally deformed granite. *J. Struct. Geol.* **4**, 197–215.

Hobbs, B. E., Means, W. D. & Williams, P. F. 1976. *An Outline of Structural Geology*. Wiley, New York.

Lister, G. S. 1977. Discussion. Crossed-girdle *c*-axis fabrics in quartzites plastically deformed by plane strain and progressive shear. *Tectonophysics* **39**, 51–54.

Lister, G. S. & Paterson, M. S. 1979. The simulation of fabric development during plastic deformation and its application to quartzite: fabric transitions. *J. Struct. Geol.* **1**, 99–115.

Lister, G. S. & Hobbs, B. E. 1980. The simulation of fabric development during plastic deformation and its application to quartzite: the influence of deformation history. *J. Struct. Geol.* **2**, 355–370.

Lister, G. S. & Dornsiepen, U. F. 1982. Fabric transitions in the Saxony granulite terrain. *J. Struct. Geol.* **4**, 81–92.

Rutter, E. H. & Rusbridge, M. 1977. The effect of non-coaxial strain paths on crystallographic preferred orientation development in the experimental deformation of marble. *Tectonophysics* **39**, 73–86.

Sander, B. 1950. *Einführung in die Gefügekunde der Geologischen Körper*. Springer, Vienna.

Schmid, S. M. & Casey, M. 1986. Complete fabric analysis of some commonly observed quartz *c*-axis patterns. *Geophys. Monogr.* **36**, 263–286.

Schreurs, J. & Westra, L. 1986. The thermotectonic evolution of a Proterozoic, low pressure granulite dome, West Uusima, SW Finland. *Contr. Miner. Petrol.* **93**, 236–250.

Simonen, A. 1980. The Precambrian in Finland. *Bull. geol. Surv. Finland* **304**.

Simpson, C. 1985. Deformation of granitic rocks across the brittle–ductile transition. *J. Struct. Geol.* **7**, 503–511.

Simpson, C. & Wintsch, R. P. 1989. Evidence for deformation-induced K-feldspar replacement by myrmekite. *J. metamorphic Geol.* **7**, 261–275.

Spry, A. 1969. *Metamorphic Textures*. Pergamon, Sydney.

Stel, H. 1986. The effect of cyclic operation of brittle and ductile deformation on the metamorphic assemblage in cataclasites and mylonites. In: *Internal Structure of Fault Zones* (edited by Wang, C). Birkhauser, Basel, 289–307.

Tuominen, H. V. 1957. The structure of an Archean area Orijärvi, Finland. *Bull. Comm. Geol. Finland* **177**.

Urai, J. L. & Humphreys, F. J. 1981. The development of shear zones in polycrystalline camphor. *Tectonophysics* **78**, 677–685.

Vernon, R. H. 1974. *Metamorphic Processes. Reactions and Microstructure Development*. Allen & Unwin, London.

Wenk, H.-R. 1985. *Preferred Orientation in Deformed Metals and Rocks: An Introduction to Modern Texture Analysis*. Academic Press, New York.

Wilson, C. J. L. 1982. Texture and grain growth during the annealing of ice. *Textures & Microstruct.* **5**, 19–31.

Wilson, M. R., Hamilton, P. J., Fallick, A. E., Aftalion, M. & Michard, A. 1985. Granites and early Proterozoic crustal evolution in Sweden: Evidence from Sm–Nd, U–Pb and O isotope systematics. *Earth Planet. Sci. Lett.* **72**, 376–388.