Ninth Indian Expedition to Antarctica, Scientific Report, 1994
Department of Ocean Development, Technical Publication No. 6, pp. 173-187

Microstructural Variation in Mylonites of the Schirmacher Hills, East Antarctica

SUDIPTA SENGUPTA

Department of Geological Sciences, Jadavpur University, Calcutta-700 032

Abstract

Development of ductile shear zone in the Schirmacher Hills took place under amphibolite facies conditions. The microstructures of the sheared quartzofeldispathic rocks differ in many respects with the common mylonites of the green schist facies. The Antarctic mylonites show characteristic features typical of high temperature mylonitization. Feldspar has undergone a drastic grain refinement through crystal plastic processes and quartz shows long single-grain or polycrystallirte ribbons even in a very advanced stage of mylonitization. The absence of significant optical strain in quartz ribbons is explained by syntectonic grain growth.

Introduction

The Precambrian basement rocks of the Schirmacher Hills, Queen Maud Lands, East Antarctica show different episodes of metamorphism, migmatization, folding and ductile shearing (Sengupta 1986, 1988 a & b, 1991,1993). The E-W trending hill range is traversed at a low angle by nearly parallel mappable units of (i) banded gneiss, (ii) garnetiferous alaskite, (iii) garnet biotite gneiss, (iv) interlayered calc gneiss, khondalite, basic granulite, charnockite and granite gneiss, (v) augen gneiss and (vi) streaky gneiss.

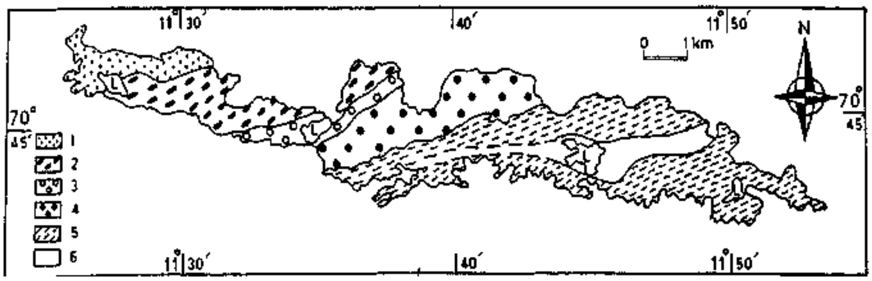

Fig. 1. Geological map of Schirmacher Hills, 1 - streaky gneiss, 2 - augen gneiss, 3 - interlayered calc gneiss, khondalites, basic granulites, charnockite and granite gneiss, 4 - garnet- biotite gneiss, 5 - banded gneiss and 6 - alaskite, L - lakes.

The rocks of Schirmacher Hills have undergone two phases of granulite i'acies metamorphism (M_1 and M_2) followed by a phase of amphibolite facies (M_3) metamorphism (Sengupta 1993). The M_2 event is associated with charnockitization while M_3 is broadly synchronous with regional granitization. The earliest deformation (D_1) can be recognized in some enclaves and is represented by a foliation marked by pyroxene grains. The second and third deformations (D_2 and D_3) are the most dominant deformations in this region and are broadly synchronous with M_2 and M_3 metamorphism, respectively. The D_2 foliation has often rotated to become sub parallel to D_3 foliation although a low foliation and a low angle discordance are preserved in many places. During D_3 deformation rocks were intensely deformed into two sets of coaxial isoclinal folds (F_{3A} and F_{3B}) with axes plunging moderately towards southwest. The dominant foliation (D3) is axial planar to this group of folds and strikes roughly E-W, with a moderate southerly dip. There are two other generations of later folds with steep axial surfaces. One set of these late folds is coaxial with the F_3 group of folds but with sub vertical axial surfaces while the other set has sub horizontal E-W axes with steep northerly dipping axial surfaces.

Ductile shear zones ranging from a few mm to more than a km occur throughout the area. The shearing mostly took place under amphibolite facies conditions and is broadly synchronous with D3 deformation. The sheared rock of this area shows microstructures characteristic of high temperature mylonitization. The present study concentrates on the mylonites of the area, with a detailed description of microstructural variations of quartzofeldspathic and other types of mylonites.

Fig. 2. Augen gneiss sheared by the first type of ductile shear zone, dissected again by the second type of ductile shear.

Ductile Shear Zones of the Schirmacher Hills

The Schirmacher Hills show a number of megascopically visible ductile shear zones and discrete shear fractures. These can be grouped into three main categories:

(1) The most widespread shearing movement occurred during or in continuation of the development of the F_3 folds. These ductile shear zones may range in width from a few millimetres to several metres and run parallel to the D_3 foliation (Fig.2). Anastomosing shear zones with characteristic C and S surfaces are fairly common. The mylonitic foliation within the shear lenses are sigmoidally curved and become parallel to the bounding C surfaces (Berthe *et al.,* 1979). The shear zone foliation is parallel to the moderate to gently, southerly dipping axial surfaces of the F3 folds and the mylonitic lineation is parallel to the hinges of the F3 folds plunging moderately towards SW. In large thin sections perpendicular to F3 hinges it is often seen that the isoclinally folded form surface is represented by an early mylonitic filiation while in the quartzose layers a new mylonitic foliation has developed axial planar to the folds (Fig. 3). Such a transposition of an early mylonitic foliation and development of a new axial planar mylonitic foliation is fairly common in these shear zones.

(2) The quartzofeldspathic gneisses and the associated metamorphic rocks often show shear zones at a high angle to the D3 foliation and also to the F3 axial surfaces (Fig. 2). These shears are steep and show some variation in strike. From either side the foliation of the country rock swerves to become parallel to the shear zone walls. Although these narrow discordant shear zones or shear lenses show a variation in the attitude of planar surfaces

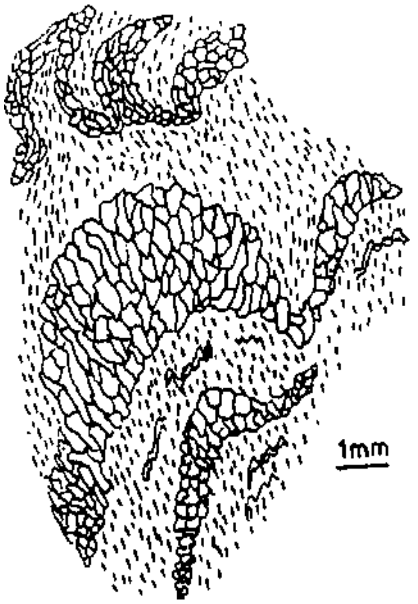

Fig.3. Development of second generation foliation axial planar to F_{3B} folds in mylonitised calc gneiss. The quartzose bands have undergone pinching and swelling during the development of F_{3A} folds.

similar to those of C and S surfaces, these two types of surfaces did not develop simultaneously as in cases recorded by Berthe *et al.,* (1979). The planes of *cissaillement* in the present case are distinctly superimposed on a pre-existing foliation or S surface. Such non-synchronous shear foliations (Lister & Snoke 1984) are likely to occur where the shear lenses develop in foliated rocks or where shear lenses of successive generations are superimposed on one another (Ghosh & Sengupta 1987).

(3) In certain places the rocks are dissected by close-spaced sub parallel discrete shear fractures which cut across all the earlier surfaces. These are later than the ductile shear zones.

Microstructural Variation of Quartzofeldspathic Gneisses in Ductile Shear Zones

General

The microstructural studies indicate that mylonitization is much more widespread than what appears from the rocks of the megascopically recognizable ductile shear zones. Apart from the clearly recognizable mylonites, quartzofeldspathic gneisses of megascopically non mylonitic appearance often show relics of a mylonite microstructure. Depending on the intensity of shearing and the relative importance among the processes of intra crystalline deformation, subgrain formation, dynamic recrystallization and grain growth the gneisses within the ductile shear zones show a wide range of microstructural variation.

With increasing intensity of shearing, the gneisses pass through the stages of protomylonite, mylonite or orthomylonite (Wise *et al.,* 1984) and ultramylonite (Fig.4). This division is made on the basis of the ratio between the porphyroclasts and the matrix material.

Initial stage of ductile shearing

The very first stage of mylonitization (Fig.4a) is shown by rocks in which the deformation is mainly achieved by intracrystalline strain associated with elongation of grains, without much grain size reduction. The fine grained matrix in such rocks forms less than ten percent of the total volume and is mostly confined to a few thin anastomosing zones (Fig.5a). The large K-feldspar grains in the XZ sections show an average aspect ratio of about 2. The average aspect ratio of quartz is distinctly larger than this, The textural changes in both quartz and feldspars have been brought about by crystal plastic processes. Some of the strongly deformed plagioclase and microcline megacrysts have narrow aprons of fine polygonal subgrains associated with fine recrystallised grains with sharp optical divergence among them.

Protomylonitic stage

With further increase in deformation the rock passes to a typical lenticular protomylonite (Wise *et al.,* 1984) with a characteristic mortar structure consisting of a more or less continuous fine grained matrix within which occur isolated porphyroclasts (Figs 4b, 5b). More than 50 percent of the rock is composed of porphyroclasts. Among the porphyroclasts both quartz and feldspars are present, the porphyroclasts of quartz being more elongate than those of feldspars. Many of the residual microcline megacrysts are subdivided into fairly large subgrains with less than ten degrees among the extinction positions. Both recrystal-

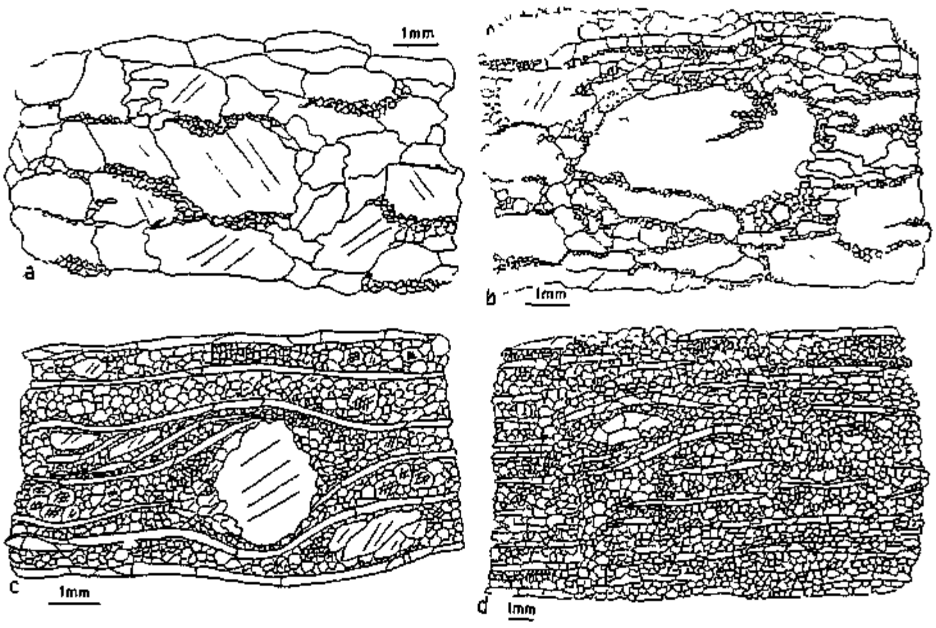

Fig.4. Different stages of mylonitization of quartzofeldspathic gneiss. (a) Initial stage, (b) protomylonite, (c) orthomylonite or mylonite and (d) ultramylonite. Note that the quartz ribbons and micro banding are best developed in the orthomylonitic stage.

lized grains and subgrain structures are present in the matrix. The matrix also contains some irregular medium sized strongly undulant residual grains of feldspar. An initial stage of a crude banding of long quartz ribbons is noticed in some cases (Fig.4b).

Orthomylonitic and ultramylonitic stages

With increasing intensity of shearing the ratio of porphyroclast to matrix decreases and the rock passes into orthomylonites and ultramylonites (Figs. 4c & d). Beyond the protomylonitic stage the sheared quartzofeldspathic rocks develop a microscopic banding of alternate thin quartz bands and feldspar-rich bands (Fig.5c). This kind of banding has been produced only after a certain stage of mylonitization, when the megacrysts of feldspar have been greatly reduced in number. The feldspar porphyroclasts form less than twenty per cent of the area of the feldspar-rich bands. In greatly sheared rocks the porphyroclasts of feldspar are almost entirely absent within these bands. The feldspar-rich bands may also contain some amount of fine-grained quartz. With increase in the intensity of shearing, the feldspar rich bands pass from the orthomylonitic to an ultramylonitic microstructure. The fine grained material within these bands is generally composed of equant grains, although in

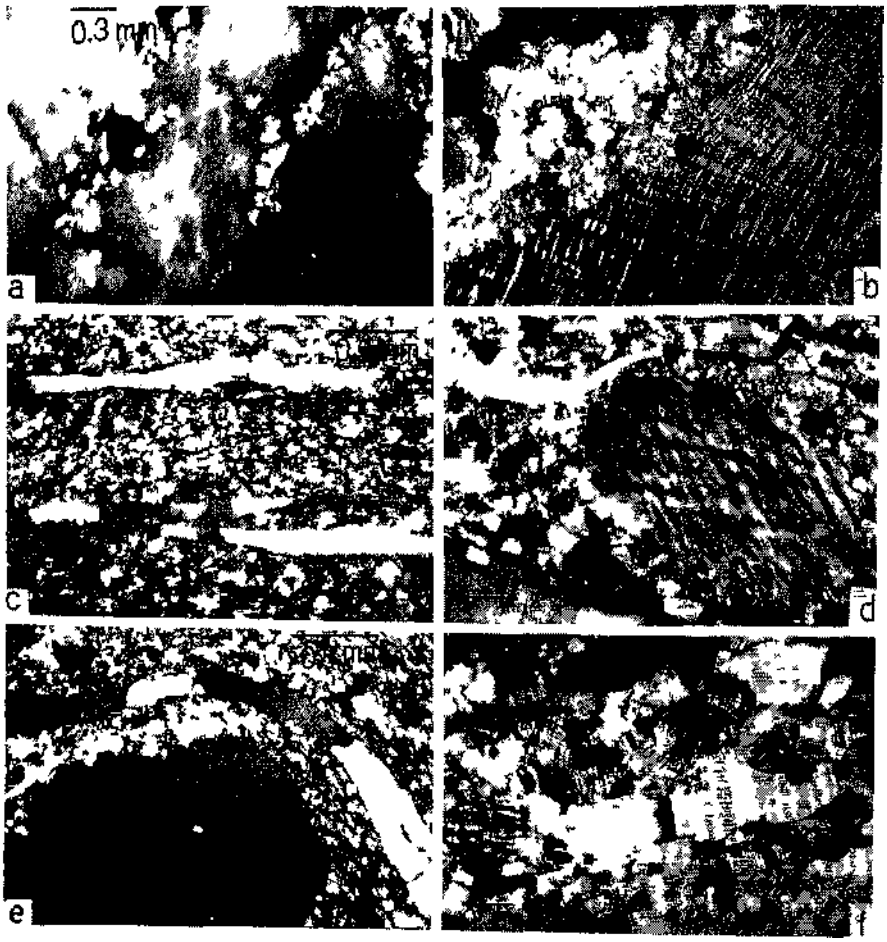

Fig 5 (a) Initial stage of mylonitization. A large undulose quartz grain is subdivided by thin discontinuous zones of grain refinement (b) Part of a large strained porphyroclast of microcline in protomylonitic augen gneiss. Fine grains of myrmekite from the matrix embay into the porphyroclat. (c) Quartz ribbons in granite mylonite. The ribbons consist of very long grains with smooth subparallel border. Some parts of the ribbons are subdivided into shorter grains and subgrains. (d) In certain cases, a single grain of quartz ribbon may curve around a perphyroclast and still be free from strain as in the curving ribbon in the lower right. Quartzofeldspathic mylonite. (e) Quartz ribbon segmented into shorter pieces are commonly strain free. When the ribbons swerve around the porphyroclasts, as in figure, the individual pieces may show optical strain. (f) Lenticular grains of quartz (long white portions) in a granite mylonite. These grains with sinuous borders are either unstrained or weakly strained and are several times larger than the recrystallized feldspar grains of the matrix.

some of the rocks a slight elongation of the grains can be seen. Recrystallized grains of high angle boundaries and medium sized subgrains of feldspars are present. The extent of recrystallization is considerably greater than in the protomylonite. There are rare instances of late brittle fracture of feldspars with two optically continuous parts of an elongate porphyroclast separated by a narrow transverse fissure filled with randomly oriented muscovite.

The variation from a protomylonitic to an ultramylonitic microstructure often takes place within a short distance and can sometimes be seen in alternate bands of different scales. Figure 6 shows a central band of pegmatite which has been reduced to a protomylonite with megascopically visible clasts upto a diameter of several centimeters. Along the length of the same band the rock has been converted to a mylonite and ultramylonite. Above this band we can see a zone of mylonite with residual clasts of an average diameter of a few millimetres. The two zones are bordered on either side by zones of ultramylonite Similar association of protomylonite, mylonite and ultramylonite is often seen in the scale of thin sections.

The quartzofeldspathic mylonites show a large variation in microstructure both with respect to the megacrysts and with respect to the matrix. These are described separately.

Megacrysts

Feldspars: The megacrysts of quartz and feldspar have quite different appearances. The feldspar megacrysts mostly of K- feldspar are generally oval in appearance (Fig 5d) with the aspect ratios in XZ sections hardly exceeding 2.5. Globular porphyroclasts are present but are rather rare. The foliation in the matrix swerves past the oval or globular porphyroclasts (Fig. 4c). The longer porphyroclasts are essentially parallel to the foliation and micro banding. Porphyroclasts of relatively small axial ratios show rotations upto 90 degrees. The mylonitic foliation sweeps past them and forms asymmetrical drag patterns (Ghosh & Ramberg 1979). The presence of large porphyroclasts must have made the rocks mechanically inhomogeneous. Hence, the borders of the megascopically visible porphyroclasts are also often the sites of localization of asymmetrical folds on the mylonitic foliation.

The porphyroclasts of feldspar are usually strongly undulant (Fig.5b) and show various stages of destruction As indicated earlier, because of the high temperature of mylonitization, the destruction of the feldspar megacrysts was very rarely by brittle fracturing, it was mostly achieved by subgrain formation and dynamic recrystallization. The grain refinement of the feldspar megacrysts starts mostly around the periphery. In the orthomylonitic and ultramylonitic stages the core region of the megacrysts (White 1976) may be subdivided into clusters of polygonal subgrains/grains. The subgrains/grains produced from the core are generally larger than those from the mantle. The matrix of orthomylonites and ultramylonites may also contain medium sized remnant porphyroclasts. These extremely undulant grains do not retain the oval shape but have very irregular grain borders.

Quartz: The quartz megacrysts belong to several different types The residual megacrysts in protomylonites appear as strongly undulant elongate grains with serrated borders and with peripheral grain refinement. However, not all the megacrysts of quartz are remnants of a coarse grained pre-mylonitic rock It is well known that during mylonitization of quartzofeldspathic rocks, feldspar behaves as a more resistant mineral than quartz. Hence in

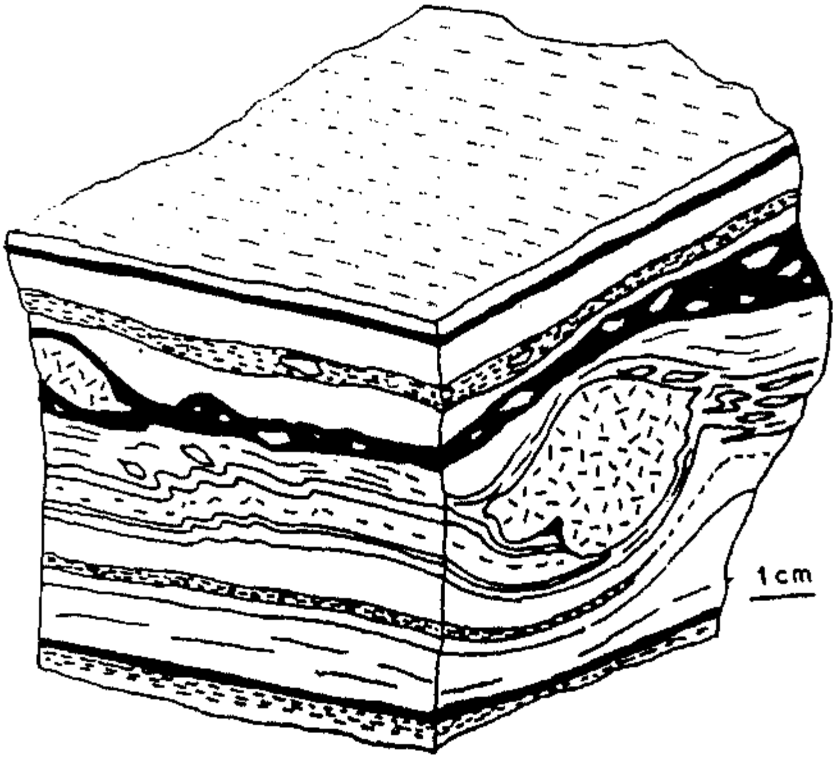

Fig.6. Hand specimen of quartzofeldspathic mylonite. The dashes on the upper surface are parallel to the mylonitic lineation. The two lateral surfaces are perpendicular to the foliation. The specimen shows different intensities of mylonitization in the different bands. A central band of pegmatite has been reduced to protomylonite with megascopically visible clasls in certain parts while elsewhere the same band has been converted to an ultramylonite with very rare porphyroclasts even in the microscopic scale. The rotational character of the deformation is indicated by the asymmetric drag around porphyroclasts. The white clasts in the dark layer also represent fragmentation of a thin pegmatite vein.

mylonites it is expected that quartz megacrysts would become much fewer than the feldspar megacrysts. However, such a progressive reduction in the volume of the quartz megacrysts is not apparent among the sheared rocks of the present area. At a fairly advanced stage of mylonitization the quartz megacrysts in these rocks may belong to the following two types, (i) quartz ribbons with nearly straight or parallel edges (Figs. 7a, b) and (ii) elongate grains with somewhat sinuous borders but with an overall lenticular appearance (Fig.5e). Unless affected by a later deformation, both types of the megacrysts are either unstrained or weakly strained and do not show any marginal grain refinement.

Quartz ribbon: In the orthomylonitic stage a microscopic quartz band may consist of (i) a very long ribbon made up of a single grain and with an aspect ratio ranging between 10 to 20 in the XZ sections (Figs. 5c & 7a), (ii) a single ribbon subdivided into shorter subgrains with aspect ratios of less than 6 in the XZ sections and with less than 5° difference in extinction positions (Fig.5e) and (iii) a single ribbon subdivided into shorter segments but with clear optical divergence among the different parts of the same band (Fig.7b). The individual grains of all types of ribbons do not generally show strong undulatory extinctions and are often optically unstrained. The very long ribbons have sometimes remained optically strain free even when they curve round a globular porphyroclast of feldspar (Fig.5d) or bend around an isoclinal fold.

The occurrence of quartz megacrysts in the mylonites does not readily fit into the general scheme of evolution of a low temperature mylonitic microstructure. The presence of such a large amount of strained or weakly strained quartz megacrysts alternating with ultramylonitic feldspathic bands strongly suggests that these quartz megacrysts have developed by grain growth (White *et al.,* 1980, Culshaw & Fyson 1984, Boulier & Bouchez 1978). Since these ribbons and the lenticular megacrysts are parallel to the gneissic foliation and show trails of inclusions of fine mica flakes parallel to the ribbons, it is likely that the initiation of grain growth was syntectonic with reference to the mylonitization, with crystallization outlasting deformation.

Matrix

General: The large variation in microstructure of the quartzofeldspathic mylonites may be described in terms of two extreme types. (1) In certain rocks we get a fine grained equigranular texture with highly serrated grain borders, strong optical strain and frequent development of subgrain structures. (2) On the other extreme the matrix shows polygonal or rounded grains with smooth grain borders and less frequent subgrain structures. These extreme end members are separately seen in comparatively small number of rocks. The majority of the mylonites show an association of clusters of these two types of matrix microstructure. The proportion between them varies strongly from rock to rock. The rocks in which equant unstrained grains with smooth borders dominate, are similar to those which were earlier described as blastomylonites.

Grain size variation: There is a small range of grain size within the fine grained in which the dominating microstructure is of the first type. On the other hand, microstructure of the second type shows a large variation of size of the matrix grains. Rocks in which the second type of grains dominate often show different domains within their matrix. Within each domain the grain size is fairly uniform. However, the grain size varies strongly from domain to domain with an average of 0.02 mm for the domains with the finest grains and an average of 0.2 mm in domains with the coarsest grains. Apart from these two typical mylonitic fabrics there is a third type, transitional between mylonitic and non-mylonitic rocks. These retain a mylonitic microstructure in certain parts; elsewhere the rocks show a strong variation from very fine to medium grains with sinuous grain borders but with very little sign of optical strain and subgrain structures.

The size frequency plots of the quartzofeldspathic matrix are shown in Fig.8. Some of the graphs have clear unimodal distribution of the matrix grain size, with a very strong

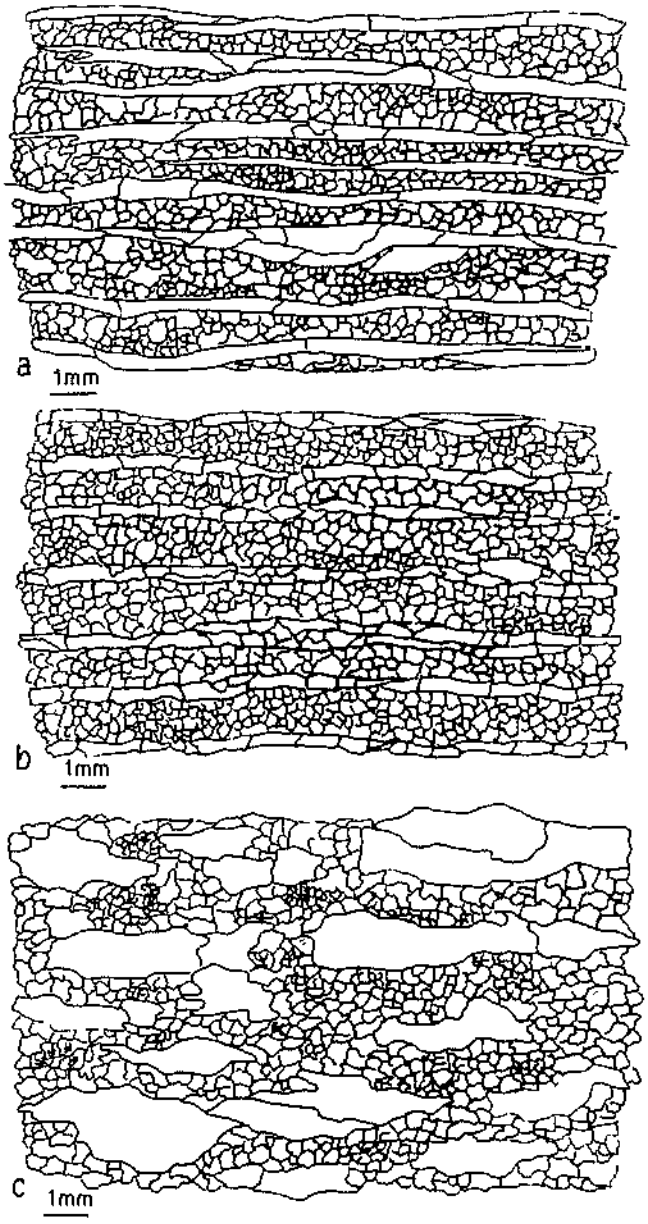

Fig.7. Three types of quartz megacrysts. (a) Quartz ribbon with long grains, (b) Quartz ribbons subdivided into a number of smaller grains. (c) Lenticular quartz megacrysts with sinuous grain boundaries. The equigranular matrix is composed mostly of feldspars with little quartz.

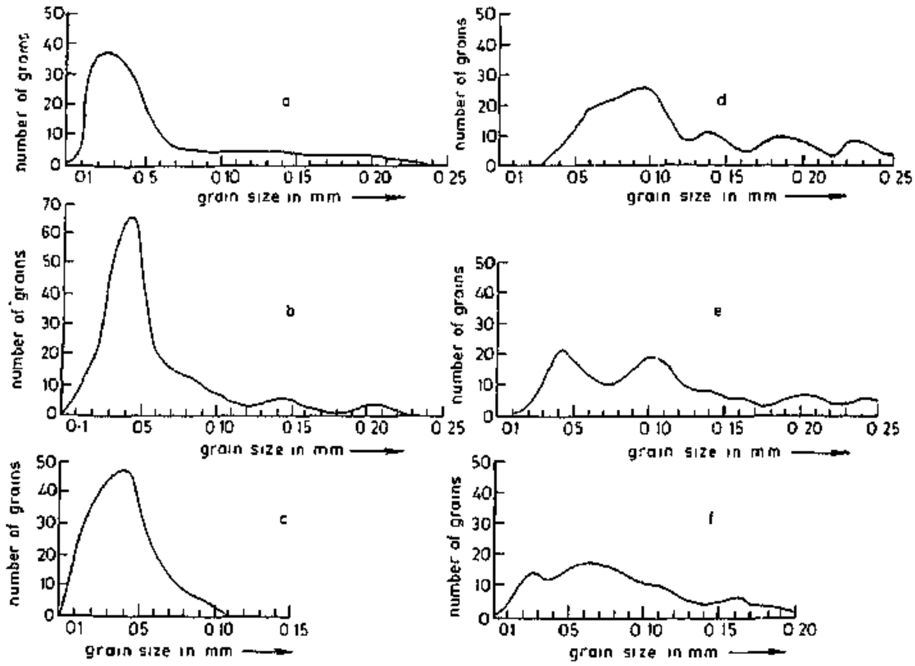

Fig. 8. Grain size-frequency graphs of quartzofeldspathic mylonites with different types of microstructures.

maximum between 0.02 mm and 0.04 mm (Fig.8 a, b, c). In such rocks the matrix shows the first type of microstructure with mostly serrated grain borders and with frequent preservation of optical strain and subgrain structures. However, this type of matrix microstructure does not depend on the intensity of ductile shearing. The matrices of protomylonites, orthomylonites and ultramylonites may show the same type of size frequency distibution. The second type of mylonitic matrix (Fig. 8 d, e, f) shows a larger size of the matrix grains and more than one weak minimum. The larger matrix grain size in these rocks and the absence of a very strong maximum are clearly related to the dominance of recrystallization and grain growth. Thus Fig. 8d is of mylonite with a few porphyroclasts of microcline. Although the rock retains a mortar structure in some parts, the matrix grains of feldspar are thoroughly recrystallized. Moreover, there is a wide range of grain size variation. Certain recrystallized feldspar grains show a grain size distinctly larger than what is commonly encountered in mylonites. The maxima in the comparatively higher ranges in Fig. 8e have resulted mostly from recrystallization of the matrix quartz grains. The size frequency in Fig. 8f is a result of association of two different types of structures. In certain narrow zones the texture is very fine grained with serrated grain borders and frequent subgrain structures. These alternate with the zones in which the feldspar grains are more thoroughly recrystallized and the quartz grains have grown to fairly large size.

The rocks showing the second type of mylonitic matrix often grade into gneisses with microstructures transitional between a mylonitic and non-mylonitic gneiss. The mylonitic percentage ot these rocks is shown by the preservation of rare porphyroclasts and domains ot fine grains in a second type matrix.

The microstructures of some of the quartzofeldspathic gneisses bear the imprint of repeated mylonitization, with narrow anastomosing shear zones superposed on and cutting across an earlier mylonitic foliation or with folding of the earlier foliation and development ot a new axial planar mylonitic foliation. In such rocks the long grains ot quartz ribbons of an earlier generation are optically strained and are replaced in part by smaller lecrystallized grains. Along the shear zones the second type of matrix texture may be replaced by the first type.

Summarizing, larger than average grain size of recrystallized grains in mylonites may develop in different ways. In certain cases, somewhat larger grains are clearly derived from the cores of the residual megacrysts while the periphery has given rise to finer grains. This is likely to be related to the difference in the strain distribution in the core and the mantle of residual megacrysts (White 1976). In some of the mylonites the average size of the recrystallized grains is distinctly larger than what is normally in low temperature blastomylonites. A similar dependence of grain size on the metamorphic conditions of mylonitization was also observed by Simpson (1985). Lastly, the size of some matrix grains is too large to have been produced by any of the above mentioned processes. Clusters of such large and medium sized strain free grains would not normally be encountered in a mylonitic microstructure. It is likely that these clusters of fairly large grains are products of syn- to post-mylonitic grain growth.

Ductile Shearing in Rocks Rich in Pyroxene or Amphibole

Ductile shear in the mesoscopic scale are often seen in the enderbites, pyroxene granulites, calc-granulites and amphibolites. The shear zones are particularly well developed in the calc-granulites. In all these rocks the intensity of mylonitization varies from layer to layer and the transition from a protomylonite to an ultramylonite may sometimes be seen within a single band specimen or even on a microscopic scale. The increase in the intensity of mylonitization is invariably associated with an increase in the amount of biotite in the rock. The biotite is clearly derived from pyroxene or hornblende. In some protomylonite patches ot calc-granunites where neomineralization of biotite is minimum, the grains of diopside may form a mortar texture with a few strongly undulant porpyroclasts occurring in a matrix of fine, equant strain free recrystallized grains of diopside (Fig 9). Along the shear zones of calc-granunites the grains of scapolite and plagioclase have also undergone a grain refinement. The occurence of recrystallized grains of diopside in the matrix suggests that the ductile shearing took place in upper amphibolite facies conditions. In the fine grained matrix of some of the mylonites there are small equant grains of garnet without any sign of fracturing or peripheral grain refinement. It is likely that these isolated fine grains of garnet have grown during or after mylonitization. The Fe-Mg partitioning of the neocrystallised garnet and biotite in mylonites indicates that the temperature of mylonitization was about 550°C.

With increasing mylonitization almost all of the pyroxenes have undergone biotitization. Small residual grains of hypersthene or diopside may occur within the biotite clots. Elsewhere the rocks have been converted to a phyllonite which shows very fine flakes of

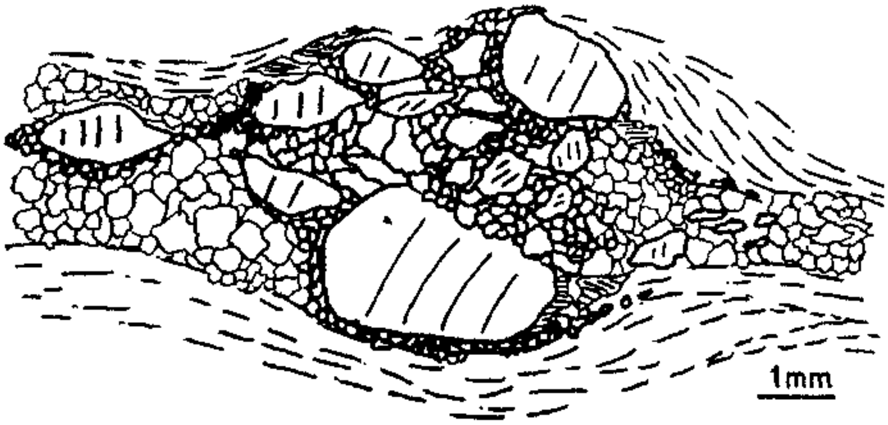

Fig.9. Mylonitised calc-gneiss with pinch-and-swell of a diopside rich layer. Diopside (with bold outlines) shows a mortar structure with weakly strained lenticular porphyroclasts set in a mosaic of fine recrystallized grains of diopside. The equant grains with fine outlines are scapolite, quartz and plagioclase. A mylonitic foliation marked by fine flakes of biotite wraps around the pinch-and-swell.

biotite running through a mosaic of fine grained feldspar and quartz. Thus Fig. 10 shows the specimen of a pyroxene granulite, one part of which has been invaded by a granulite facies pegmatite with very coarse crystals of plagioclase, hypersthene and garnet. The crystals of garnet and hypersthene in the pegmatitic part range in size from about 5mm to about 3cm in diameter. Along a border between pyroxene granulite and pegmatite runs a narrow shear zone and both parts of the rock have been affected by shearing. Away from the shear zone, both the pyroxene granulite and the pegmatite show only a granulite facies assemblage (hypersthene-plagioclase-garnet-quartz). The average diameter of the plagioclase grains in the pyroxene granulite is 0.5mm. In thin sections close to the shear zone both pyroxene and plagioclase show a weak undulatory extinction. The grains of pyroxene are partly replaced by randomly oriented large flakes of biotite with an average width of 0.2mm. The rock in the shear zone is a phyllonite where the foliation is marked by very fine flakes of biotite. Plagioclase and quartz in the shear zones form a mosaic of small grains with an average of 0.4mm diameter. There may also be medium or small sized residual grains of hypersthene with very strong undulatory extinction. Since the amount of biotite rapidly increases from the border towards the middle of the shear zone, the time of biotitization is clearly related to ductile shearing.

Narrow microscopic mylonite zones are also found in the amphibolites. Such sheared rocks show very fine recrystallized grains of plagioclase without any porphyroclasts and mortar structure with large strained porphyroclasts of hornblende surrounded by a lenticular mosaic of small recrystallized grains. Both porphyroclasts and the matrix are partially

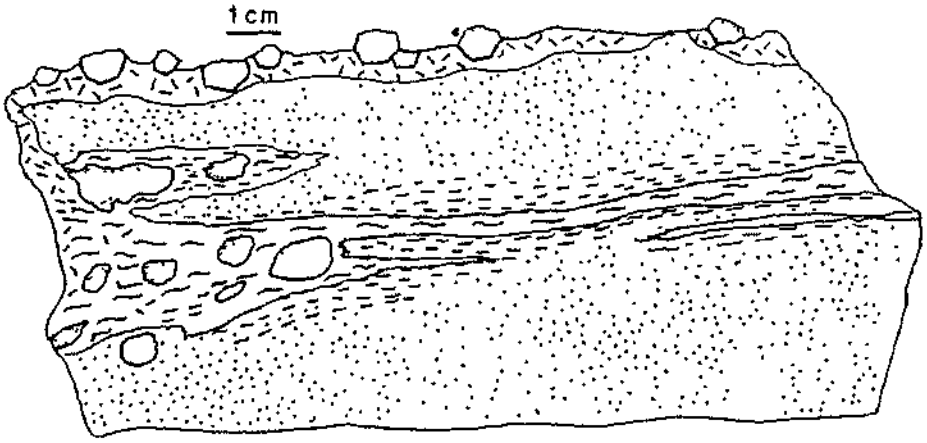

Fig. 10. Hand specimen of a pyroxene granulite invaded by a pegmatite with very coarse crystals of garnet, Inpersthene and feldspar. The lower band of pegmatite coincides with a narrow shear zone. The mylonitised part of the pegmatite is shown by short wavy lines and the mylonitised part of the pyroxene granulite is shown by dashes.

replaced by biotite. The recrystallization of hornblende and plagioclase (oligoclase/andesine) in the matrix implies that the ductile shearing took place in amphibolite facies conditions.

Conclusions

There is a large variation in the microstructure of the mylonites in the Schirmacher Hills of East Antarctica. The variation is partly due to the heterogeneity of the intensity of ductile shearing from domain to domain. This has given rise to the well known categories of protomylonites, orthomylonites and ultramylonites. However, a large part of microstructural variation has resulted from post-to syntectonic recrystallization and grain growth. Syntectonic grain growth is most clearly seen in high temperature mylonites with very long quartz ribbons without an optical strain even when they swerve past remnant megacrysts. The other type of grain growth has produced medium sized equant, optically strain free grains of quartz and feldspar which occur in isolated domains within a typical mylonitic microstructure. With increase in grain growth these domains have been enlarged and in most places the mylonitic microstructure has been obliterated leaving behind a few isolated microscopic pod.

Acknowledgement

I thank the Department of Ocean Development for facilities of field work in Antarctica

References

Berthe, D., Choukroune, P. and Jegouzo, P. (1979): Orthogneiss, mylonite and noncoaxial deformation in granites: the example of the South Armorican Shear Zone. *J.Struct. Geol,* 1, 31-42.

Boullier, A.M. and Bouchez, J.L. (1978): Le quartz en rubans dans les mylonites. *Bull. Soc. Geol. Fr.,* 7, Ser. 20, 253-262.

Culshaw, N.G. and Fyson, W.K. (1984): Quartz ribbons in high grade granite gneiss; modifications of dynamically formed quartz c-axis preferred orientations of oriented grain growth../. *Struct. Geo!.,* 6, 663-668.

Ghosh, S.K. and Ramberg, H. (1979): Reorientation of inclusions by combination of pure shear and simple shear. *Tectonophysics,* 34,1-70.

Ghosh, S.K. and Sengupta, S. (1987): Progressive development of structures in a ductile shear zone, *J. Struct. Geol* 9, 277-287.

Lister, C. and Snoke, A.W. (1984): S-C mylonitcs. J. Struct. Gcol.,6, 617-638.

Sengupta, S. (1986): Geology of Schirmacher-Range (Dakshin Gangotri) East Antarctica. Scientific Report of Third Indian Expedition to Antarctica. Department of Ocean Development, Technical Publication., 3, 187-217.

Sengupta, S. (1988 a): History of successive deformation in relation to metamorphic-migmatic events in Schirmacher Hills, East Antarctica. *Jour. Geoi. Soc. Ind.2,* 295-319.

Sengupta, S. (1988 b): Precambrian rocks of Schirmacher Range, East Antarctica. Z.Geol. Wiss. Berlin,16(7), 647-660.

Sengupta, S. (1991): Structural and petrological evolution of basement rocks in the Schirmacher Hills, Queen Maud Land, East Antarctica. (Eds. Thomson, M.R.A.,Crame, J.A. and Thomson, J.W.) Cambridge University Press, 95-97.

Sengupta, S. (1993): Tectonothermal history recorded in mafic dykes and enclaves of gneissic basement in the Schirmacher Hills, East Antarctica. Precambrian Research,Vol. 63, No. 3/4. 273-292.

Simpson, C. (1985): Deformation of granitic rocks across the brittle-ductile transition. *J. Struct, Geo!.,* 7,503-51.

White, S. (1976): The effects of strain on the microstructures, fabrics and deformation mechanism in quartzites. *Phil. Trans. Roy. Soc. Land.,* A283, 69-86.

White, S.H., Burrows, S.E., Carreras. J., Shaw, N.D. and Humphreys, F.J. (1980): On mylonites in ductile shear zones. *J. Struct. Geol., 2,* 175-187.

Wise, D.V., Dunn, D.E., Engelder, J.T., Geiser, P.A., Hatcher, R.D., Kish, S.A., Odom, S.A. and Schame, S. (1984): Fault related rocks: suggestions for terminology. *Geology,* 12, 391-394.