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Fabric transitions in the Saxony granulite terrain

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Abstract—Quartz fabric transitions reported from the Saxony granulite terrain and from the nearby Ore Mountains are interesting because of the changes in the pattern types, and the variation in the opening angles of the fabric skeletons. A short summary is presented of salient features in research documented in the East German literature between 1961 and 1978.

The changes in fabric skeleton with decreasing metamorphic grade are proposed as mainly consequent to the deactivation of prism $\langle c \rangle$ glide systems as temperature decreases. Fabrics indicative of the appearance of the $\langle c \rangle$ Burgers vector might be diagnostic for deformation in regimes of comparatively high temperatures or low strain-rates, or for deformation under conditions such that there is a relatively high 'kinetically effective' hydroxyl content in the quartz structure.

INTRODUCTION

PROBABLY the most intensively studied high-grade metamorphic area with respect to quartz fabrics is the Saxony granulite terrain and the neighbouring Ore Mountains in Eastern Germany. In this paper we present a short summary of some of the results published between 1961 and 1978 by Behr (1961, 1964a, b, 1965, 1967, 1968a, b) and Hofmann (1974, 1975, 1978), and discuss some of the possible factors which could control the fabric variation in these rocks.

The Saxony granulite terrain comprises a granulite body surrounded by phyllites, schists and gneisses. Behr (1980) summarizes some important aspects of the geology and Fig. 1 (after Behr 1961) shows a block diagram of the body. Outcrops are sparse so it is not always possible to obtain as much information as might be desired, and this introduces some uncertainty into the interpretation of the complex metamorphic and deformational history.

The metamorphic history of the granulite involves an early high pressure granulite facies followed by an intermediate pressure granulite facies metamorphism. This later metamorphism produced migmatites in the outermost part of the granulite, where sufficient water was able to penetrate, while in the relatively dry core the effects of the retrogression can be seen in that kyanite was converted into sillimanite.

During or subsequent to this time the upper part of the granulite body was mylonitized. A well-developed stretching lineation can be found as well as sheath folds and other evidence of intensely deformed rock. Mylonites are developed in the surrounding schists and gneisses. The second metamorphism in the granulite and events in the surrounding rocks define a P/T sequence that fits a Barrovian facies series.

Behr (1961) mapped important fabric transitions passing upward from the granulitic core, through the mylonitized rim, into the surrounding strongly deformed schists and gneisses (see also Behr 1965, 1980). Figure 2 shows some of the spatial variation in *c*-axis fabrics.

The greenschist and amphibolite facies phyllites and schists are characterized by *c*-axis patterns with maxima and partial girdles orthogonal to the extension direction. Opening angles in the fabric skeletons are usually less than 30°. The fabrics include both type I and type II patterns (see Lister & Williams 1979) and maxima commonly develop at the (inferred) position of the Y-axis (orientation I in Fig. 3) and/or in the YZ plane (maxima in orientations II in Fig. 3).

The rim of the granulite body and the surrounding high-amphibolite facies inner schist mantle are characterized by *c*-axis fabrics with skeletal outlines that have larger opening angles (around 40–50°). A typical pattern (Fig. 4a) involves two girdles crossing at about 90°, with the intersection centred on the Y-axis. These patterns can be described as type II crossed-girdles with three mutually orthogonal maxima (in positions I and III in Fig. 3). The Y-axis maximum is usually best developed, and it is generally surrounded by four discrete submaxima (in positions IV in Fig. 3). Some patterns (e.g. Fig. 4b) may be regarded as asymmetric or partially developed variants of this pattern. However the existence of this type-fabric cannot be disputed, since synoptic plots of maximum orientations from several pole figures (Figs. 4c & d) demonstrate that there are discrete and distinct preferred maximum orientations. In addition the synoptic plots delineate exactly the same fabric skeleton.

Type I crossed-girdles with high opening angles are also found in the granulite rim, although the type II crossed-girdle (Fig. 4a) is the most commonly developed pattern. Figure 4(e) shows a synoptic plot of maximum orientations from type I crossed-girdle patterns developed in the northern rim. Maxima form in the *YZ* plane and at the *Y*-axes (positions I and II in Fig. 3). The fabric skeleton is defined by a small circle about *Z* (opening angle 40–50°) with a connecting girdle across the *Y*-axis.

Several different patterns have been developed in the granulite core. In areas that have suffered secondary migmatization the fabrics are weak or random. In other parts there are fabrics that have no well-defined skeletal elements, and most *c*-axes lie at high angles to the foliation normal. A synoptic plot of maximum orientations from this second type is shown in Fig. 4(f). Figure 4(g) shows one of the patterns to illustrate the lack of skeletal elements.

The fabrics that are most typical of the core are small-circle girdles of *c*-axes (opening angles 40–50°) commonly with a weak connecting girdle. A synoptic plot of maximum orientations from this fabric type is shown in Fig. 4(h). The almost orthogonal maxima in the *XZ* plane (position III) are strongly developed, and these with other weaker maxima (approximately in position IV) make the fabric skeleton appear as a small-circle girdle. However, apart from the strong *Y*-axis maxima which are not developed, the maximum orientations are the same as for the 90° crossed-girdle. Note that over a large part of the core, Behr (1980) shows "overprinted" patterns. These include for example small-circle girdles that have developed asymmetrically to the foliation (e.g. Fig. 4i).

The fabric transitions discussed above are documented graphically in Fig. 5 (after Behr 1964a) which shows quartz *c*-axis fabrics around a deformed gabbro body in the southwest part of the Saxony granulite. Fabrics change from those typical of the granulitic core and northern rim (small circles and type II crossed-girdles) to type I crossed-girdles typical of deformation under middle amphibolite facies conditions elsewhere in the terrain. Note however that the fabrics become markedly asymmetric as the gabbro contact is approached.

Fabric transitions as described above are not confined to the immediate vicinity of the Saxony granulite. Similar transitions have been reported by Behr (1964b, 1967) and Hofmann (1974, 1978) in the nearby Ore Mountains. Figure 6 shows a sequence described by Behr (1964b, 1967) from the Hermsdorf area in the southeast part of the Ore Mountains, near the German frontier with Czechoslovakia. A rapid transition in quartz fabrics over a few hundred metres is described in a section that passes from phyllites to garnet schists and then on to a migmatitic orthogneiss. The quartz fabrics change as a function of metamorphic grade but they also vary with lithology. Type I crossed-girdles with low opening angles are found in the phyllites, but type II crossed-girdles with high opening angles (40°–50°) are developed up-section, in the migmatitic orthogneiss.

ORIGIN OF THE FABRIC TRANSITIONS

Correlation with changing rheological response

The fabric variation discovered in the Saxony terrain and nearby Ore Mountains has so far been interpreted by attributing genetic significance to the two factors with which fabric transitions obviously correlate, that is changing metamorphic conditions and variation in lithology (e.g. Fig. 6). Behr (personal communication 1978) argues that different lithologies will have different rheological responses to the same applied conditions, so different fabrics in different lithologies can be taken as implying changing fabric response to changing rheological behaviour.

The factors which influence bulk rheological response will include intrinsic as well as extrinsic factors. Intrinsic factors include the rock mineralogy and whether or not

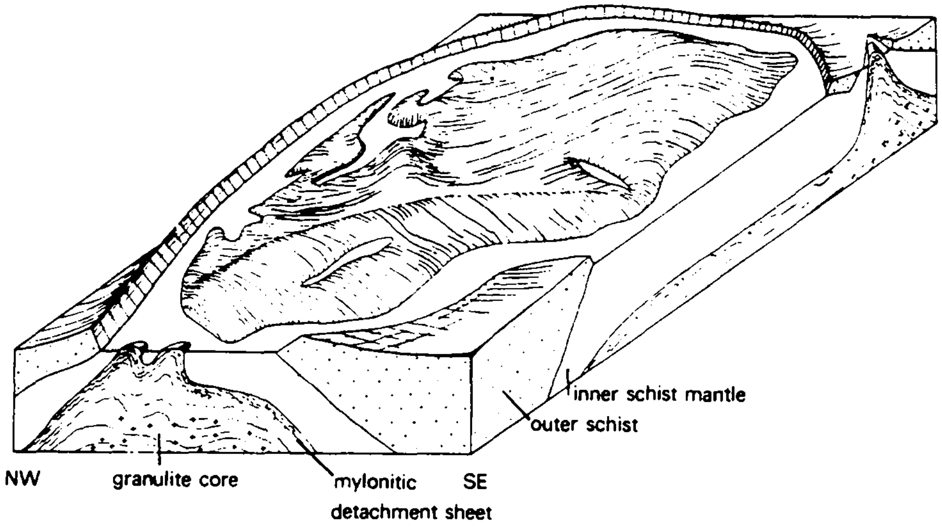

Fig. 1. Block diagram of the Saxony granulites (after Behr 1961).

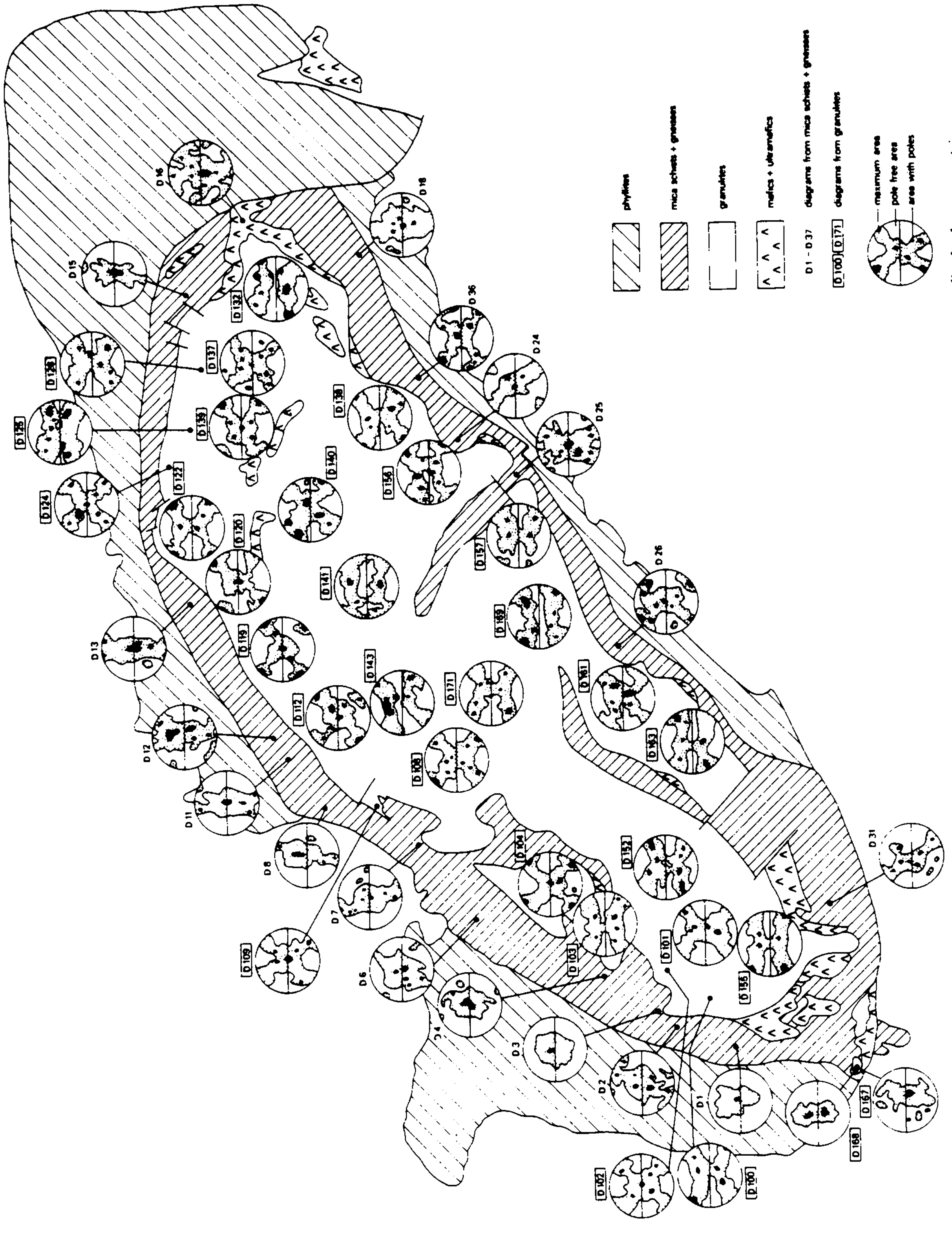

Fig. 2. Quartz c-axis fabrics in different parts of the Saxony granulite terrain. In the core of the granulite body asymmetric small-circle distributions are found. In the granulite rim a type II 90° crossed-girdle develops. In the mantling greenschist and amphibolite facies rocks single and double maximum fabrics are found. The opening angles in the skeletal outlines of the c-axis patterns increase suddenly as metamorphic grade increases (after Behr 1961 but simplified).

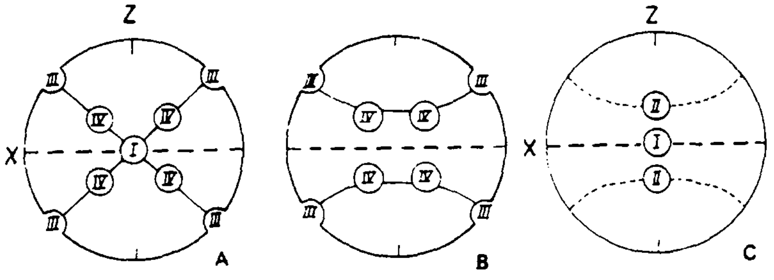

Fig. 3. Preferred maximum orientations in relation to the finite strain axes *X*, *Y* and *Z* (modified from Behr 1961 by relabelling axes).

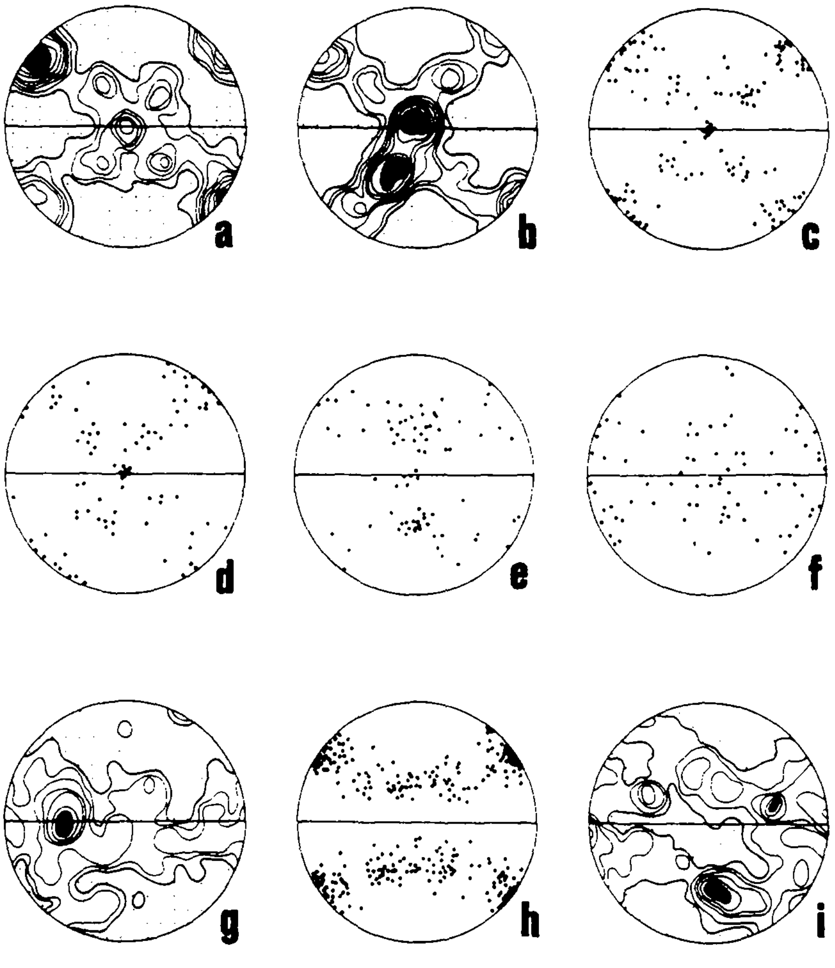

Fig. 4. Quartz *c*-axes fabrics from the high-grade zones of the Saxony terrain. Only patterns involving large opening angles in the skeletal outlines are shown (after Behr 1961). (a) *D*145 250 *c*-axes from granulite adjacent to garnetiferous gneiss. (b) *D*200 granulite mylonite, 200 *c*-axes. (c) *D*43 synoptic plot of 137 maxima from 18 pole figures, from the northern rim of the granulite body. (d) *D*44 synoptic plot of 89 maxima from 13 pole figure plots, from the inner schist mantle. (e) *D*41 synoptic plot of 81 maxima from 23 pole figure plots, from the granulite rim. Note the different maximum orientations. (f) *D*42 synoptic plot of 75 maxima from 26 pole figure plots from the main granulite body. (g) *D*245 200 *c*-axes from granulite (h) *D*40 synoptic plot of 137 maximum orientations from 47 pole figure plots, from the central granulite core. (i) *D*244 250 *c*-axes from a granulite adjacent to a lens of garnetiferous gneiss. Note the asymmetry. Also note different maximum orientations developed in these fabrics. See text for further discussion.

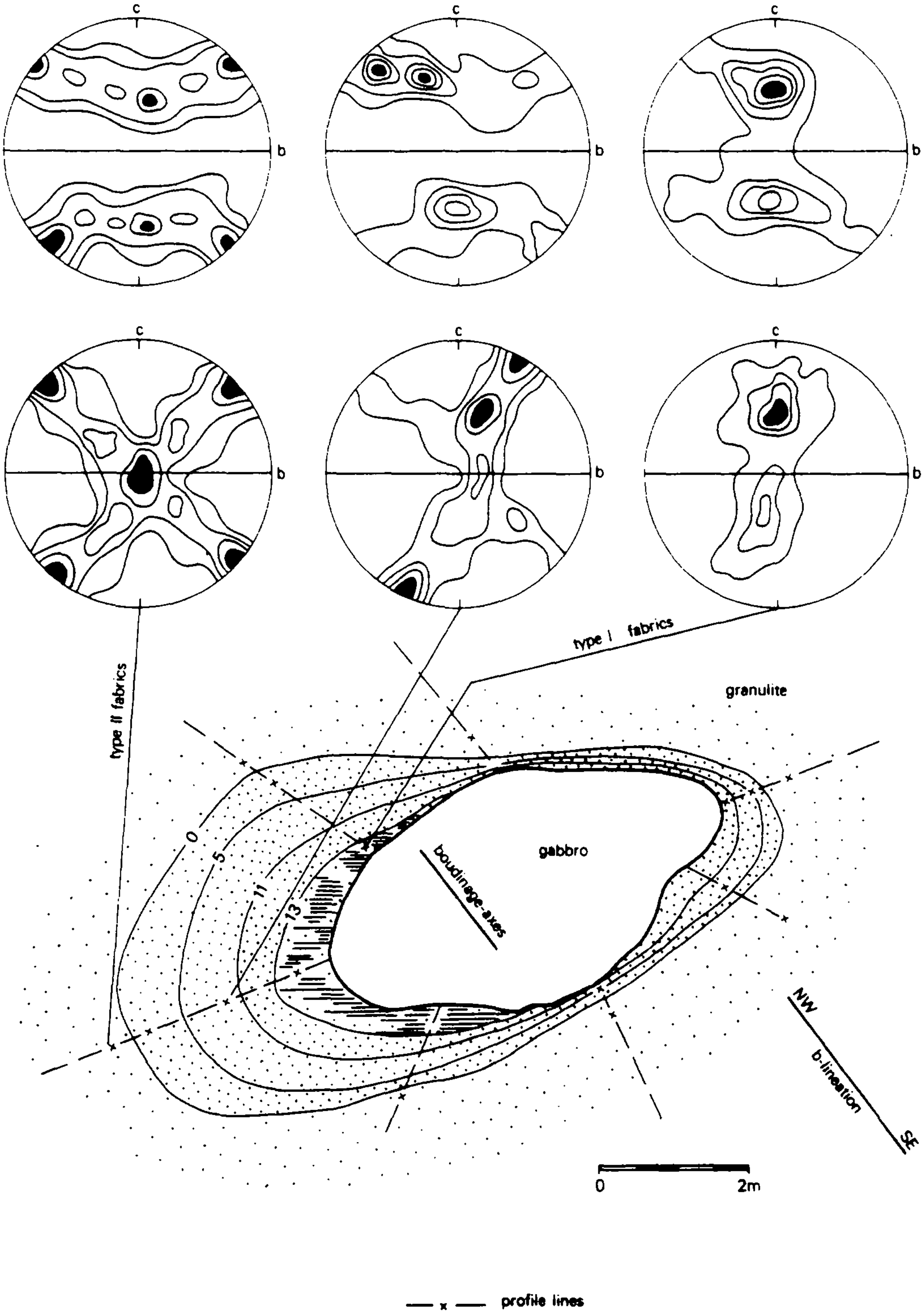

Fig. 5. Quartz *c*-axis fabrics around a deformed gabbro body in the southwest part of the Saxony granulite terrain. The fabrics typical of the granulite body give way to fabrics typical of deformation under lower grade conditions, and become asymmetric. The gabbro has probably been drawn or punched through the granulite in the solid state (after Behr 1964).

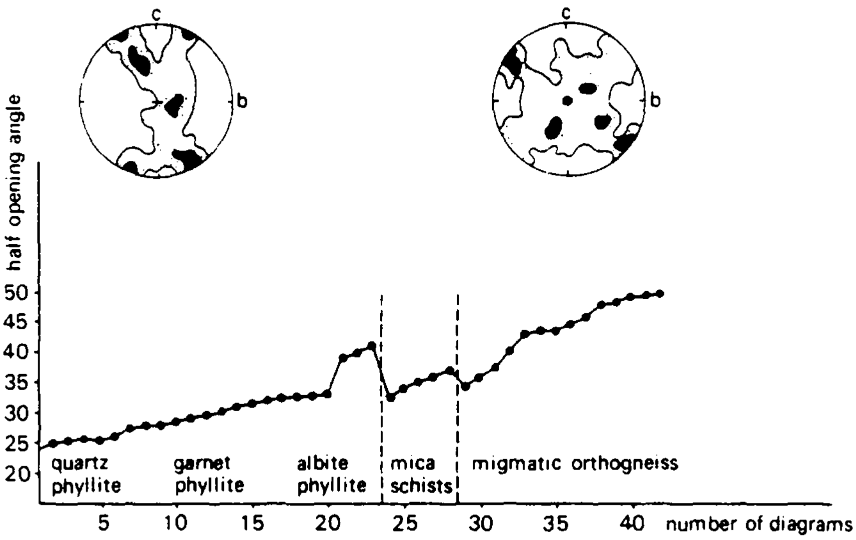

Fig. 6. Fabric transitions along a section in the Hermsdorf area of the Ore Mountains. There is a change in opening angle as metamorphic grade increases, and changes related to lithology (after Behr 1968).

penetrative anisotropy or heterogeneity exist. Additional factors might include whether or not H_2O and SiO_2 were components being released as a result of metamorphic reactions. Extrinsic factors include pressure, temperature, deviatoric stress intensity and strain-rate, and fluxes of H_2O or CO_2 if these are introduced externally to the system. However, because there are so many variables which influence rheological response it is rather difficult to determine which in particular are responsible for the observed fabric variation.

The effect of the deformation path

The effect of the deformation path is a factor that has not been taken into account in the existing literature concerned with the fabric transitions in the Saxony terrain. This is a problem, because fabrics develop differently according to whether strain is accumulated coaxially or non-coaxially, and depending on whether the deformation approximates plane strain, axial shortening or axial extension. There are some variations in fabric in the Saxony terrain that are probably related to variation in strain history from one part of the body to another.

For example, the change in fabric from the core to the rim of the granulite may be a change that is related to the type of strain history undergone, rather than to different conditions in the earlier high pressure granulite metamorphism compared to the conditions that applied in the granulite rim during the later overprinting metamorphism. It is true that fluid inclusions in the core are CO_2-rich and fabric transitions towards the rim correlate with an abrupt increase in the H_2O content of the fluid inclusions, so there may be some effects associated with different deformation and recrystallization behaviour from one metamorphic event to the other. However, the core seems also to be deformed during the later metamorphism and it is unlikely that early-formed fabrics will have survived without substantial modification. In any case the small-circle distributions in the core are typical of strain histories intermediate between axially symmetric shortening and plane strain, whereas the 90° crossed-girdle patterns at the granulite rim are typical for plane strain (Lister & Hobbs 1980, Lister 1981).

Other effects possibly related to the deformation path may be seen in the fabric transitions illustrated in Fig. 5, where development of asymmetric fabrics has taken place in an annular zone around a deformed gabbro plug. Unless there are effects related to initial variations in orientation distribution, this pattern of asymmetry suggests an annular zone of non-coaxial deformation (see review in Lister & Williams 1979). The gabbro was probably drawn or punched in the solid state through the granulite. The opening angles in the fabric skeleton suggest that this occurred under mid-amphibolite pressure–temperature conditions, but the rheological contrast between the gabbro and the surrounding rock may have caused sufficient increase in local deviatoric stress intensity to initiate a fabric transition under higher-grade conditions.

The effects of the operative deformation mechanisms

The dislocation glide systems that operate during crystal–plastic deformation of quartzite strongly influence the development of crystallographic fabric. The factors that determine which mechanisms operate include temperature, strain-rate, and trace impurity content (e.g. hydroxyl) in the quartz. Changes in these environmental variables from place to place, and with time, can induce mechanism transitions and thus alter the nature of a developing fabric. The major part of fabric variation in the Saxony terrain is likely to be related to effects such as these, for example, because the mechanisms allowing deformation of quartz under conditions applying in the high-amphibolite and granulite facies are different from those operating under lower grade conditions.

There is no way at present to be certain as to the nature of the lattice preferred orientation that will develop when particular deformation mechanisms operate. There are two factors which can be considered; namely the significance of: (a) preferred maximum orientations and (b) the skeletal outline of the fabric pattern (as defined by Lister & Williams 1979).

Schmidt (1927) argued that if the rhomb $\{10\bar{1}1\}$ was aligned in the foliation plane and the *a*-axis was aligned parallel to the *a*-kinematic direction, then the *c*-axis maxima in position III could be explained (the opening angle would then be 52°). Further (see Behr 1965) if the pyramid $\{2\bar{1}\bar{1}2\}$ was aligned in the foliation plane with the $[c + a]$ direction parallel to the *a*-kinematic direction the *c*-axis maxima in position II could be explained. In those days however the *a*-kinematic direction was placed parallel to what is now known to be the axis of intermediate strain (i.e. the *Y*-axis) in these rocks. It is a simple matter to reformulate the hypothesis made by Schmidt assuming the *a*-kinematic direction is close to the orientation of the stretching lineation, and to assume that the maxima arise because of effects of dominant slip on one easy glide system, as shown below.

(a) Maximum I (*c*-axis parallel to the *Y*-axis) might arise because one of the prism $\{10\bar{1}0\}$ $\langle a\rangle$ systems dominates deformation.
(b) Maximum II (*c*-axis in the *YZ* plane) might arise because one of the (+) rhomb $\{10\bar{1}1\}$ or (−) rhomb $\{01\bar{1}1\}$ $\langle a\rangle$ systems dominates deformation.
(c) Maximum III (*c*-axis in the XZ plane) might arise because one of the trigonal dipyramidal $\{2\bar{1}\bar{1}2\}$ $\langle c + a\rangle$ systems dominates deformation.

In the case of maximum orientations I and II a single *a*-axis should then line up close to the axis of extension, and in the case of maximum III a single $[c + a]$ axis should be so aligned. In the ideal case the two maxima in position II should subtend an angle of 76° across the *Y*-axis, and this is consistent with the angles between the type II maxima in Figs. 4 and 5. Similarly in the ideal case the angle between the two maxima in position III (measured in the *ZX* plane across the *Z*-axis) should be 95°. This is consistent with the angles between the type III maxima in Fig. 4, but as noted by Behr (1965) there is considerable spread in the opening angles in these patterns.

Maximum orientations formed during coaxial deformation histories commonly dispose two or three easy-to-activate glide systems symmetrically with respect to the axis of shortening, or a single easy-to-activate glide system in a position unfavourable to its continued operation. In contrast, maximum orientations formed during a non-coaxial deformation history, such as progressive simple shear, often apparently orient a dominant slip system in the orientation most favourable for its continued operation. In simple cases this involves alignment of the glide plane with the flow plane, and the slip direction with the flow direction.

There is considerable value in examining quartzites that display the type-patterns recognized by Behr (1961) and using X-ray techniques to obtain data to calculate a complete description of the lattice preferred orientation. From the orientation distribution figures obtained from such type-examples it would be possible to determine the crystallographic significance of the end-orientations that supposedly give rise to the maximum concentrations (see Siemes & Spangenberg 1980, Schmid *et al.* 1981).

Obviously the analysis of maximum orientations in terms of active deformation mechanisms is rather difficult if one is not certain of the movement picture that prevailed during deformation, nor the glide systems that can operate during crustal deformation of quartzite. Starkey (1979) analysed material from Saxony using X-ray techniques and then constructed inverse pole figures for the distribution of the foliation normal (and lineation where visible) relative to the crystal axes. Using the argument that a dominant glide system assumes a specific orientation with respect to the deformation axes Starkey was able to argue that the strong *Y*-axis maxima (in position I) were due to slip on the prism $\langle a\rangle$ systems. He attributed maxima in position III to the effect of slip on positive and/or negative rhombs, *r* $\{10\bar{1}1\}$ and *z* $\{01\bar{1}1\}$. However, because he assumed a deformation history involving axially symmetric shortening he could equally well have argued that maxima in position III result because during coaxial deformation active glide systems tend to reorient themselves so that they become symmetrically disposed with respect to the shortening axis. In this case the maximum in position III could result because basal $\langle a\rangle$ and prism $\langle c\rangle$ systems balanced each other so that eventually the lattice reached a compromise orientation with rhombs and dipyramids normal to the foliation plane. Note that during fabric simulations such compromise orientations also appear when basal systems are balanced by the steep trigonal dipyramidal systems $\{21\bar{3}1\}$ $\langle c + a\rangle$.

Deformation in greenschist up to mid-amphibolite facies conditions

The lower grade rocks display both type I and type II crossed-girdle *c*-axis patterns, and they are notable for *c*-axis maxima at the *Y*-axis (orientation I) and for symmetric double maxima in the *YZ* plane (orientation II). If the *a*-axes line up with the axis of extension the maxima can be explained as above, assuming that the rhomb and prism $\langle a\rangle$ glide systems were active under these conditions. There are also maxima commonly developed in the *XZ* plane with an opening angle (taken from *Z*) varying from 10 to 35°. These can be attributed to the effects of dominant slip on the basal $\{0001\}$ plane (see review in Lister & Williams 1979). Fabric simulations with the Taylor–Bishop–Hill analysis (Lister & Paterson 1979) show that when basal, rhomb and prism $\langle a\rangle$ glide systems are important during deformation, the *c*-axis fabrics that form involve skeletal outlines with opening angles between 25 and 35°. These are the opening angles commonly observed in the greenschist and mid-amphibolite facies rocks around the granulite.

The effect of the alpha–beta structural transition

When quartz changes from the hexagonal *beta* configuration to the trigonal *alpha* configuration as a result of decreasing temperature and/or pressure there are a number of dislocation glide systems that are no longer symmetrically equivalent. For example the (+) rhomb $\{10\bar{1}1\}$ $\langle a \rangle$ systems are no longer symmetrically equivalent to the (−) rhomb $\{01\bar{1}1\}$ $\langle a \rangle$ systems. If no distinction can be made between the preferred orientation of positive and negative forms it is possible that the fabric developed while the quartz was in the *beta* stability field. Otherwise the quartz deformed in the *alpha* field, or Dauphinée twinning has altered the distribution of positive and negative forms. Starkey (1979) discusses this point and Schmid *et al.* (1981) document evidence that suggests that some quartzites deformed while in the stability field of the *beta* structure. Some of the fabric variation in the Saxony terrain appears to be related to the effects of the *alpha–beta* structural transition.

The effect of the basal $\langle a \rangle$–prism $\langle c \rangle$ mechanism switch

Blacic (1975) described a transition from basal $\langle a \rangle$ to prism $\langle c \rangle$ dislocation glide systems as temperature increased or strain-rate decreased in sequences of experiments involving deformation of single crystals of quartz. This mechanism switch should be one of the most important factors affecting the nature of *c*-axis fabrics produced in plastically deformed quartzite. The reorienting tendencies of these two systems are more or less equal and opposite, and because of their geometrical relationship they compete directly against each other. We postulate that the basal–prism switch is responsible for the major part of the fabric variation around the Saxony granulite.

Tullis (1971) envisaged pattern concentrations formed as the result of a dynamic balance between the opposing reorienting tendencies of the basal vs the prism systems, and argued that the fabrics were reflecting the effects of the deformation process even though recrystallization and grain growth were increasingly important in determining the optically visible microstructure. She argued that the increases in opening angle (up to 40–50°) observed in the small-circle girdles of *c*-axes produced in her experiments with increasing temperature, decreasing strain-rate, or decreasing deviatoric stress intensity could be explained by the increasing importance of prism glide with respect to basal glide.

The fabric transitions discovered by Tullis *et al.* (1973) took place during axially symmetric shortening. The equivalent fabric transitions for other deformation histories are not known, although double-wedge patterns with low opening angles and 90° crossed-girdle fabrics have been produced during the few experiments imposing conditions approaching plane strain during pressure deformation of quartzite (Green *et al.* 1970, Tullis 1977, Kern 1977, 1979). Certainly, the fabric simulations documented by Lister (1981) suggest that these changes represent fabric transitions equivalent to the increase in opening angle of the small-circle *c*-axis patterns produced during axially symmetric shortening experiments.

Simulations of the effect of the basal $\langle a \rangle$/prism $\langle c \rangle$ mechanism switch on fabric development (Lister 1981) indicate that a 90° crossed-girdle centred on the Y-axis is an important element in the skeletal outline of the *c*-axis fabric for plane strain when basal $\langle a \rangle$ and prism $\langle c \rangle$ systems operate simultaneously, as long as prism $\langle a \rangle$ systems are relatively easy. A 40–50° small circle of *c*-axes around Z develops for axially symmetric shortening. When basal, rhomb and prism $\langle a \rangle$ systems operate without prism $\langle c \rangle$ systems double wedge patterns with low opening angles (25–35°) result for plane strain, and *c*-axis point maxima or 25–35° small-circle girdles around Z, for axially symmetric shortening.

Note that the Taylor–Bishop–Hill analysis does not successfully predict many of the common maximum orientations observed in naturally and experimentally deformed rocks, but it has accurately and consistently predicted variations to be expected in the fabric skeletons. It is therefore of considerable interest that the variation in skeletal outline predicted by the Taylor–Bishop–Hill analysis, as a consequence of the basal $\langle a \rangle$/prism $\langle c \rangle$ mechanism switch, mimics details of the variation in skeletal outline observed in natural fabric transitions in the Saxony terrain.

We suggest that most of the quartz in the core and rim of the granulite body deformed by involving simultaneous operation of basal $\langle a \rangle$ and prism $\langle c \rangle$ systems. The variation in fabric from 90° crossed-girdles of *c*-axes in the rim to 40–50° small-circle girdles in the core can be explained as due to a change in deformation path from plane strain to axially symmetric shortening. Fabrics such as those illustrated in Figs. 4(f) & (g) can be explained as a consequence of the operation of prism $\langle c \rangle$ systems without operation of basal $\langle a \rangle$ systems, because *c*-axes under these circumstances tend to cluster around the X-axis and in the XY plane (cf. granulite fabric from Galicia measured by Schmid *et al.* 1981).

Modification to fabric caused by the basal–prism switch

There will be marked modifications to already developed fabrics if the basal $\langle a \rangle$/prism $\langle c \rangle$ switch takes place at an intermediate stage in a deformation history. A number of the patterns measured by Behr (1961) look like 'compressed' versions of higher grade patterns, as would be the case if prism $\langle c \rangle$ systems deactivated at an intermediate stage in a deformation history after a strong pattern of preferred orientation had already developed. In such circumstances maxima and girdles of the existing pattern migrate toward new end-orientations and the skeletal outline is continuously transformed. Lister (1981) illustrates this sort of effect by showing the rapid modification of skeletal outline that takes place when prism $\langle c \rangle$ systems activate half-way through a deformation. In the simulations the opening angles in the fabric skeleton change by about $\frac{1}{2}^\circ$ for every additional 1% shortening after the mechanism switch. The 90° crossed-girdle typical of the mylonitized granulite rim (Fig. 7a) would be modified to look like the pattern in Fig. 7(b) if 30–40% additional shortening took place after prism ⟨*c*⟩ systems deactivated, assuming deformation in a regime of decreasing metamorphic grade.

Fabric transitions related to variation in rheological parameters other than pressure or temperature

Mechanism transitions are influenced by several factors other than mean stress and temperature. Other rheological parameters that play an important role are strain-rate, deviatoric stress intensity and trace impurity content. It is apparent that fabric transitions should correlate with factors other than metamorphic grade alone.

There are changes in developed fabric in the Saxony terrain that correlate with lithological variation (e.g. Figs. 5 and 6). It is not at all certain what the reason is. A gneiss body deformed adjacent to a schist body under similar metamorphic conditions will usually deform at a slower strain-rate. This may mean that, different mechanisms operate to allow deformation of the quartz in the schist compared with the quartz in the gneiss. Alternatively, the trace impurity content of the quartz (including kinetically effective hydroxyl) may be different from one body to another and this may be the cause of an observed fabric transition.

DISCUSSION

The effect of water content on the basal–prism switch

If the hypothesis we have made is correct and the basal ⟨*a*⟩/prism ⟨*c*⟩ mechanism switch is indeed responsible for most of the fabric variation around the Saxony granulite, then the mechanism switch apparently took place between 600 and 700°C at around 6 kbar mean stress. These temperatures are compatible with the experimental data for the first appearance of prism ⟨*c*⟩ systems (Blacic 1975) but the experiments involved strain-rates orders of magnitudes higher than those thought to apply to natural deformation. If the basal–prism switch does take place during crustal deformation of quartzite it allows comparison between conditions in experiments and conditions in the crust. It is therefore important to attempt to determine why the transition temperature is higher than would be predicted by extrapolating the data for the effect of decreasing strain-rate obtained by Blacic (1975).

The factors that affect the temperature at which the mechanism switch takes place in experiments are strain-rate pressure and initial 'water' content. The data concerning the effect of strain-rate and 'water' content come from Blacic (1975). Avé l'Allemant & Carter (1971) report a transition from basal to prismatic lamellae as a function of increasing temperature, but also a transition from prismatic to sub-basal lamellae as a function of increasing confining pressure. However, the stress–strain behaviour is not reported. Basal slip in general seems to be favoured by high deviatoric stress intensities.

The data concerning the effect of water are particularly ambiguous, and interpretation is made difficult by the demonstration (Paterson & Kekulawala 1979) that the kinetically effective hydroxyl in quartz is only a small part of the total OH content. These authors also argue that the kinetics of diffusion are extremely slow at low confining pressures, so that equilibrium concentrations of kinetically effective hydroxyl are not likely to be obtained in the time allocated to an experiment. Synthetic crystals used in experiments however contain grown-in 'water' and often have a relatively high content of kinetically effective hydroxyl. Blacic (1975) found lower transition temperatures for the basal–prism switch in sequences of experiments using synthetic quartz. These observations suggest that prism slip in the ⟨*c*⟩ direction is favoured by increasing the temperature, decreasing the strain-rate, and increasing the 'water' content.

Blacic (1975) performed some experiments with natural quartz, deforming the crystals above the transition temperature. Basal slip was reactivated when fluids (including water) released from the dehydrating talc-confining medium were able to penetrate the quartz. Blacic reported that in one crystal the central region deformed by slip on the $\{10\bar{1}0\}$ prisms while the exterior developed a 'rind' with basal and prismatic lamellae.

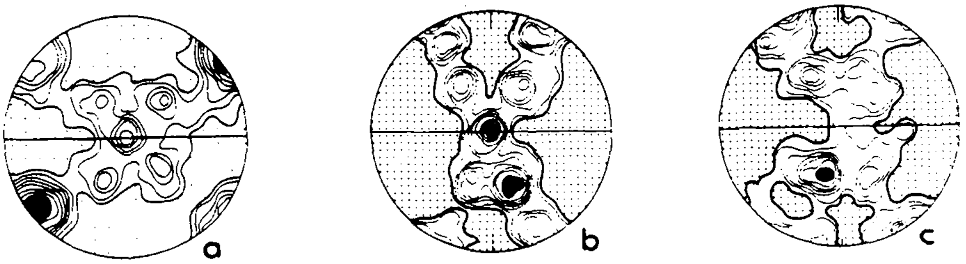

Fig. 7. The 90° crossed-girdle fabric (a) would be modified by a change in operating deformation mechanisms to look something like diagrams (b) and (c) if prism ⟨*c*⟩ systems deactivated half-way through the deformation history after a strong fabric had already formed. Diagram (a) is *D*145 (b) is *D*41 with 125 *c*-axes and (c) is *D*46 with 110 *c*-axes from Behr (1961). Diagrams (b) and (c) are from the outer schist mantle and were subjected to greenschist facies deformation.

Blacic suggested that the geometry of this 'rind' reflected the distribution of water released from the dehydration halo in the talc-confining medium. In addition he noted zones of basal slip around small cracks which could be related to diffusion haloes. These results suggest that basal slip is reactivated as a result of increasing the 'water' content while the crystal was deforming above the transition temperature, and apparently conflict with the statement made at the end of the previous paragraph.

However there are a number of uncertainties: (a) the fluids released from the dehydrating talc contain more than just water; (b) there are mechanical effects associated with the presence of mobile fluid at crack tips and interfaces, and these can lead to local increases in deviatoric stress intensity which may be of sufficient magnitude to reverse the mechanism switch and (c) the increased 'water' content may not imply an increased content of kinetically effective hydroxyl.

The comparison of data from synthetic crystals and natural crystals leads us to argue that the appearance of the $\langle c \rangle$ Burgers vector is diagnostic for regimes of comparatively low stress intensity during deformation, and this can be the result of deformation under low strain-rates, high temperatures or under conditions such that there is a relatively high kinetically effective hydroxyl content in the quartz structure.

The conjugate shear hypothesis and the significance of grain boundary alignment

This discussion of the fabrics of the Saxony granulite terrain would not be complete if some mention was not made of the conjugate shear hypothesis (Sander 1950) for the origin of crossed-girdle *c*-axis patterns of preferred orientation. According to this hypothesis (see Behr 1965), during coaxial deformation the rock develops a pervasive array of conjugate shears, and the fabric results because the quartz is realigned to have certain crystallographic directions parallel to the intersection of the shear planes and certain planes parallel to the shear planes themselves. This theory is tied up with the fracture hypothesis whereby Sander envisaged fracture of the quartz into needle-like shapes as an important precursor of the reorienting process.

Behr (1964a) examined deformed quartz lenses fron the southeast part of the amphibolite facies inner-schist mantle above the granulite body, and interpreted the grain boundary alignments shown in Fig. 8 as the result of the existence of conjugate shear surfaces. Fig. 8(a) illustrates the *c*-axis fabric measured from the quartz lens illustrated in Fig. 8(b). Behr (1964a) argues that it is significant that there is a correlation between the opening angles in the *c*-axis fabric and the angles between the interpreted shear planes.

The quartz lenses are 10–30 cm long and have been deformed so that they are parallel to the schistosity and elongate parallel to the stretching lineation. The illustrated microstructures are developed in sections cut parallel to the extension lineation, and they can be described as dove-tailed cross-mosaics of interlocking quartz grains, with marked grain boundary alignments at 40–50° to the external schistosity. Small muscovite grains with a spacing of 250–850 microns help define these cross-foliations. Note that the *c*-axis fabric is formed by three maxima approximately at right angles. Fabric mapping reveals that the *c*-axes tend to fall parallel to the long direction of the grains.

Cross-hatched microstructures are not rare in strongly deformed high-grade metamorphic rocks, but the conditions which lead to development of this microstructure remain conjectural. We envisage a possible deformation process where grain boundary sliding or localized shear takes place on surfaces oriented at 40–50° to the shortening axis (i.e. planes of high resolved shear stress). The process is likely to be

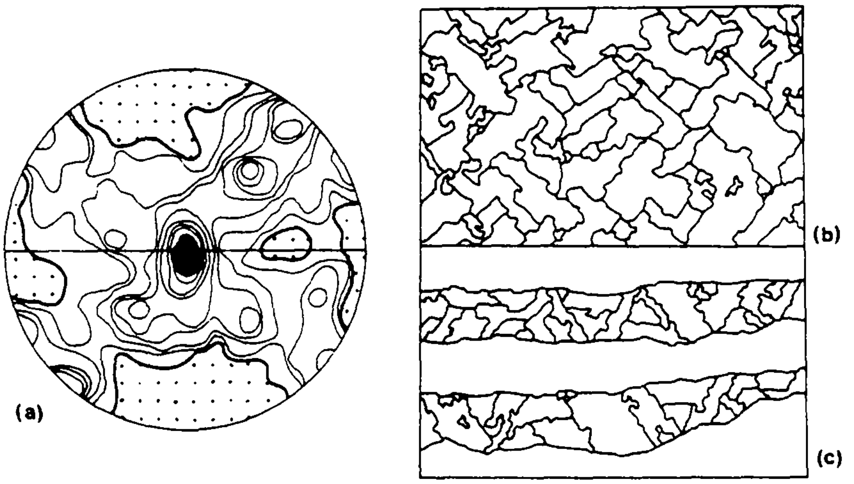

Fig. 8. (*D*22 after Behr 1961, 1964) Quartz knots in a mica schist from the Rossauer Forest south of Oberossau (between *D*24 and *D*36 on Fig. 7 in the inner schist mantle) develop the illustrated microstructure (b) and (c). There is an alignment of grain boundaries 40–50° to the principal schistosity and this conjugate cross-foliation is accentuated by a few small micas. Behr interprets this arrangement as the result of spaced shear planes. The *c*-axis fabric from (b) is shown (a). The opening angle of the crossed-girdle is about the same as the angle between the (interpreted) conjugate shear planes.

accompanied by shear of the adjoining crystals, and by diffusive mass transfer along the boundary. Slides may extend across two or three grain diameters by first introducing localized shear zones or discontinuities into grains lying astride the termination of the existing slide surface. Only small displacements need be involved. The effect of all this would be the same as slip at different times on individual members of a conjugate array of shear planes arranged in a cross-hatched pattern throughout the quartz knot. Assuming that extensive grain boundary migration was also taking place, the cross-hatched microstructure with characteristic hammer-shaped grains can be explained by calling on effects related to: (a) the existence of a strong *c*-axis fabric formed earlier during the deformation; (b) relatively rapid growth parallel to the *c*-axes and (c) partial impedance of grain boundary migration by some effect related to the existence of the shear surface, for example segregation of an impurity phase on the sliding surface which pins or poisons the migrating grain boundary.

It is difficult to illustrate precisely how this process could take place but this has been attempted in Fig. 9. Microslides and associated microshears of the adjacent crystalline material can be envisaged as taking place along suitably oriented grain boundaries. Under favourable circumstances (e.g. if the material rapidly strain softens) the microslide–microshear combination can propagate across several grain diameters. Adjacent grain boundaries are expected to migrate rapidly towards and along these microshears because the driving force for migration will be higher in these regions. It is interesting to note that a microstructure remarkably similar to that shown in Fig. 8(b) is developed near the pistons during high temperature deformation of Carrara marble (Schmid *et al.* 1980, pp. 259–262).

Sliding on discontinuities occurs over a wide range of metamorphic conditions during rock deformation. Cross-mosaic microstructures as described above may indicate that sliding on cross-hatched arrays of conjugate shears is an important aspect of high temperature plasticity of quartzites and carbonates in nature when bulk coaxial deformation is involved.

CONCLUSIONS

(1) Fabric transitions reported from the Saxony terrain may be explained by the effects of variations in deformation history, and by the effects of mechanism switches caused by changing metamorphic conditions. The most important variation could be related to the basal ⟨*a*⟩/prism ⟨*c*⟩ mechanism switch, with prism ⟨*c*⟩ systems activating in the high amphibolite facies between 600 and 700°C at around 6 kbar mean stress. Lister (1981) reports a distinctive change in the skeletal outlines of simulated *c*-axis fabrics related to this mechanism switch.

(2) The effect of variation in deformation path might be seen in the variation of fabric from the rim to the core. Fabrics in the core are typical of deformation in the flattening field whereas fabrics in the rim are typical for plane strain.

(3) Asymmetric *c*-axis fabrics around a deformed gabbro plug in the southwest part of the terrain may be related to an annular zone of non-coaxial deformation caused by movement of the gabbro relative to the granulite.

(4) The important variables affecting the basal–prism mechanism switch include temperature, strain-rate, deviatoric stress intensity, and trace impurity content of the quartz. The role of water is not clear. It is suggested that any increase in the kinetically effective hydroxyl lowers the temperature at which the mechanism switch is observed at any given strain-rate.

(5) Fabrics thought to be typical for operation of prism ⟨*c*⟩ systems, with or without basal ⟨*a*⟩ systems, are suggested as diagnostic for deformation in regimes of comparatively high temperature, low strain-rate, and low deviatoric stress intensity, or for deformation under conditions such that there is a relatively high kinetically effective hydroxyl content in the quartz structure.

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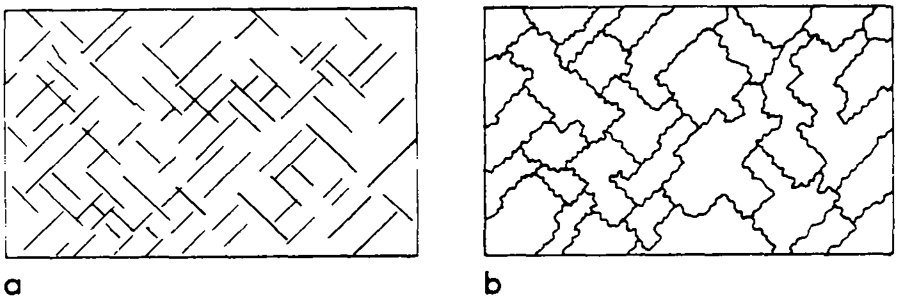

Fig. 9. The cross-hatched mosaic microstructure is interpreted as a result of rapid grain boundary migration during a deformation in which microslides and microshears initiate parallel to suitably oriented grain boundaries. Diagram (a) shows the cross-hatched network of microslides envisaged, showing all the microslides regardless of when they formed and regardless of whether or not a growing grain has subsequently consumed the volume where the microslide took place. Diagram (b) shows how we envisage the microstructure if rapid boundary migration and exaggerated grain growth was taking place during the deformation while the microslides and microshears formed. Pinning effects associated with some sort of impurity or second phase segregation along the microslides is suggested as the reason that the grain shapes achieve a characteristic hammer shaped form in this microstructure. Boundary migration allows growing grains to rapidly consume material between the microslides, but the boundary slows down or is stopped at the microslide location.

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