Journal of Structural Geology, Vol. 2, No. 1/2, pp. 249 to 254.
Pergamon Press Ltd. 1980. Printed in Great Britain

0191–8141/80/0601–0249 $02.00/0

Polyphase shear zones in the granulite belts along the margins of the Bohemian Massif

H. J. BEHR

Geologisch-Paläontologisches Institut, Goldschmidt-Str. 3, D–3400 Göttingen, W. Germany

(*Received* 17 *May* 1979; *accepted in revised form* 7 *September* 1979)

Abstract—Along the NW and SE borders of the Bohemian Massif prominent shear belts are developed. The areas are characterized by basement nappes, parautochthonous gneiss wedges, thrusts, medium and high pressure granulites, garnetiferous ultrabasic mantle rocks and specific sedimentary and magmatic sequences. In the Saxonian Granulite Mts for example, there are slices of rocks preserved with relics of blastomylonitic deformations which took place at different *P/T*-levels ranging from the mantle to the upper crust. A comparison between the quartz microstructure, quartz lattice orientation patterns, tensional microcracks and fluid inclusions allow the reconstruction of polyphase retrograde shearing through all its stages. From the core to the border of the granulite body, successive generations of fluid inclusions in quartz show decreasing salinity, decreasing volume and density of CO_2 and decreasing temperatures. There is a positive correlation between the *P/T*-data from fluid inclusions and the quartz fabric. Changes in viscosity caused by hydrolytic weakening of quartz and by the formation of anatectic gneisses along the margins of the granulite body are of major importance when considering the development of the shear belts. Their formation is related to the process of intracontinental subfluence (A-subduction) during the development of ensialic orogenic belts by Cadomian, Caledonian and Variscan events.

INTRODUCTION

PROMINENT shear belts are developed along the NW and SE borders of the Bohemian Massif (Fig. 1). While the central part of the Massif is characterized by predominantly autochthonous tectonics with gneiss dome structures, the shear belts are marked by the following features:

1. Basement nappes and thrust structures in the south east (Fuchs & Matura 1976, Fuchs & Scharbert 1979). These nappes contain granulites which are developed as voluminous lenses and platy bodies interlayered with migmatites and gneisses of amphibolite facies.

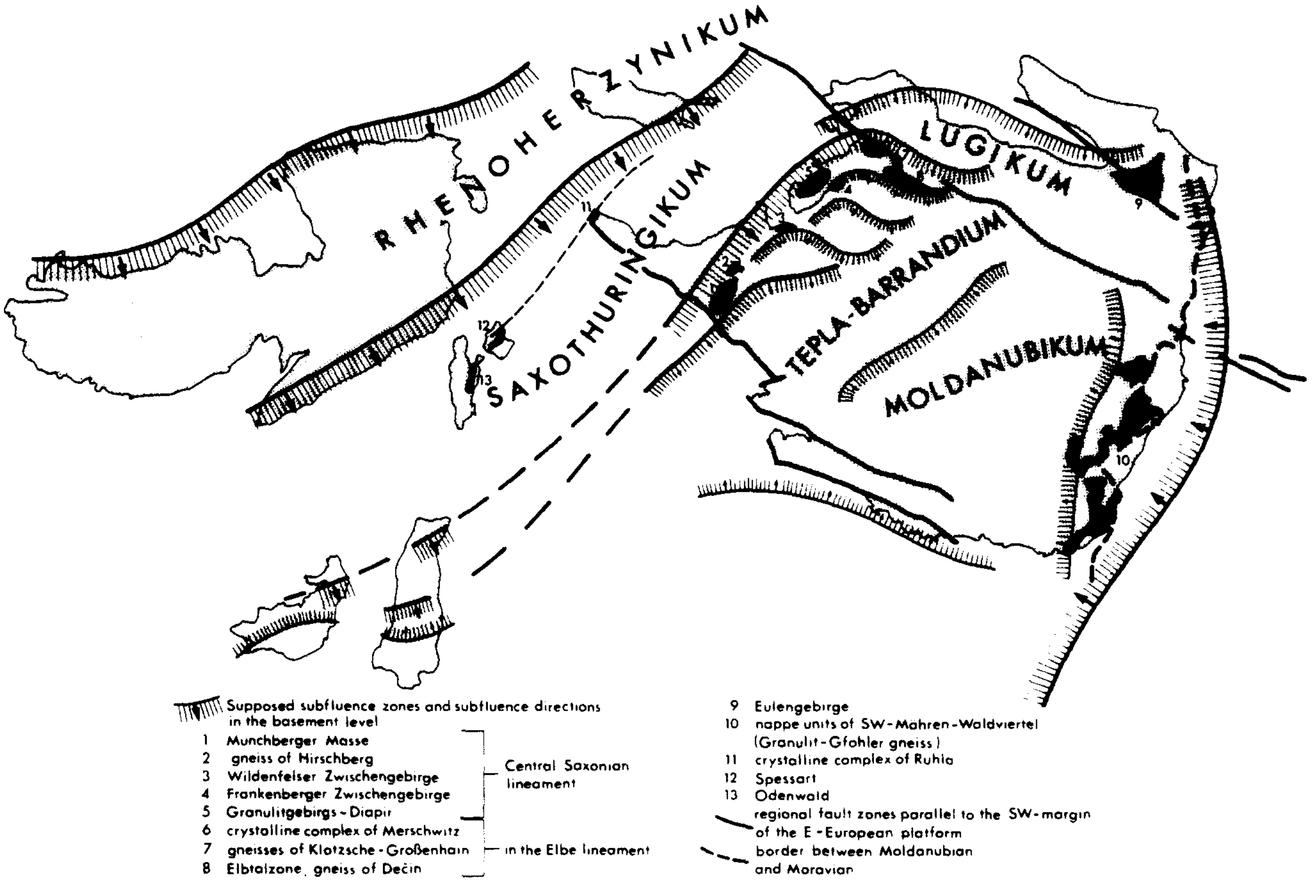

Fig. 1. Supposed subfluence zones in the basement level of the Moldanubian, Saxothuringian and Rhenohercynian.

The NW border is characterized by allochthonous or by parautochthonous gneiss wedges imbricated in a nappe-like manner and by thrusts, abnormal sedimentary facies of the Palaeozoic with gravity tectonics and olistostromes and specific magmatic sequences (Central

Saxony Lineament) (Schwan 1974). This zone includes the brachyanticlinal diapiric body of the Granulite Mts.

2. Medium pressure and high pressure granulites with two-pyroxene assemblages, pyroclasites and mantle derived garnetiferous ultrabasics are developed in the north west (Saxony Granulite Mts — according to Mathé 1969, Behr 1978) and in the south east (Waldviertel, Lower Austria — according to Scharbert & Kurat 1974).

3. Besides the granulites, kyanite bearing leptynite gneisses are abundant, occurring as thin mylonite horizons in thrust planes along both borders.

In contrast to the shear belt granulites, those described from the central part of the Bohemian Massif are not real granulites, since critical two-pyroxene-parageneses, high-pressure granulites, voluminous bodies of incorporated mantle derivatives and prograde kyanite bearing granulites are missing. They should be called leptynite gneisses and they occur within an autochthonous, probably stratigraphical sequence of rocks (Vesela 1967).

The shear belts have been active during the Cadomian, Caledonian and Variscan events. In some incorporated slices of basement rocks, relics of blastomylonitic deformation are preserved which took place at different *P/T*-levels from the mantle up to the upper crust and at different times. These different stages of the polyphase mylonitization and recrystallization can best be studied in the Saxonian Granulite terrain. In this area a comparison has been made between the metamorphic paragenesis, the morphology and the preferred lattice orientation of the quartz and the *P/T*-data from fluid inclusions, the results of which are reported below.

Finally, the Saxony Granulite terrain has a concentric layered structure made up of medium pressure granulites in the core which also contain lenticular tectonic relics of high pressure granulites (Mathé 1969). Towards the margins, there is an increase of mylonitization and overprinting by an amphibolite facies metamorphism.

FLUID INCLUSION DATA

A detailed investigation of fluid inclusions showed that all granulite types contain groups of primary inclusions filled with pure CO_2 (Fig. 2). However, while the number of CO_2-inclusions and the CO_2-densities decrease rapidly from the core towards the margin of the granulite body, the total volume of fluid inclusions increases in the same direction with the CO_2 gradually being replaced by H_2O-solutions.

The salinity of the solutions decreases from high- to

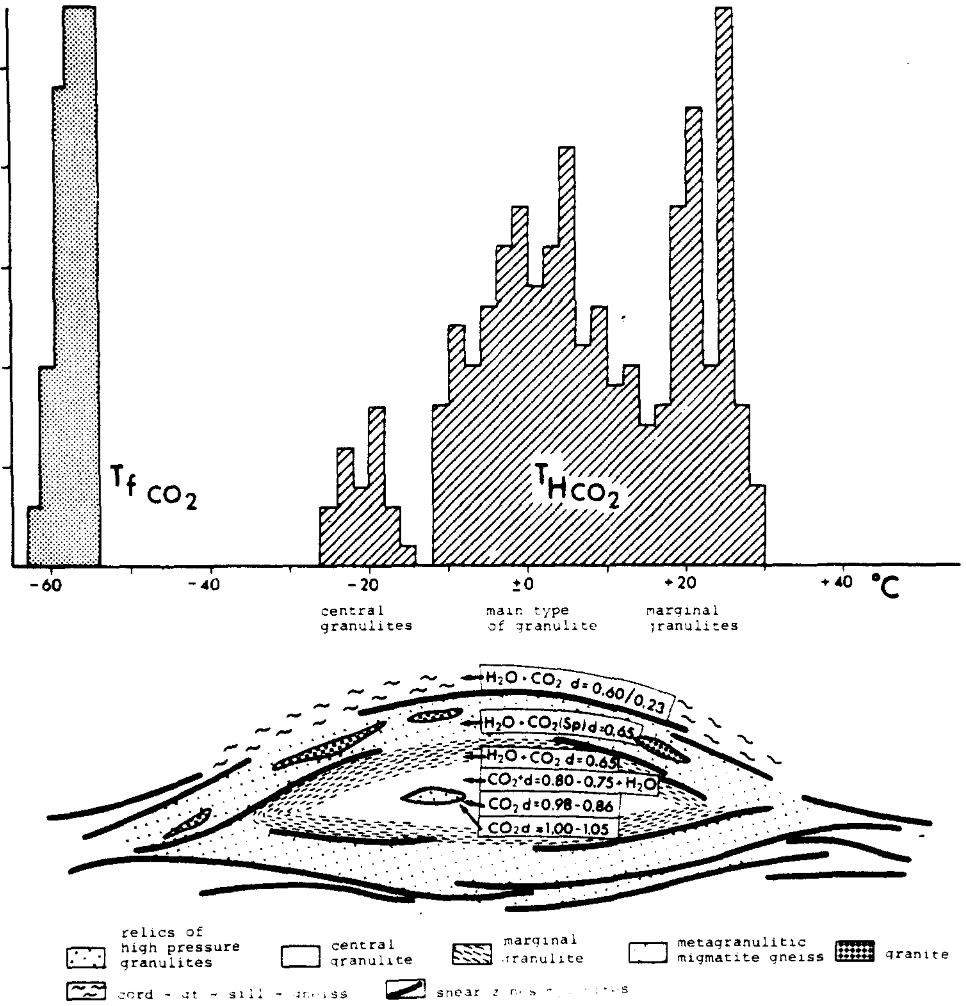

Fig. 2. CO_2-inclusions in Saxonian granulites. Temperatures for final melting T_f°C, temperatures of homogenization T_H°C, CO_2-densities d ($g \cdot cm^{-3}$).

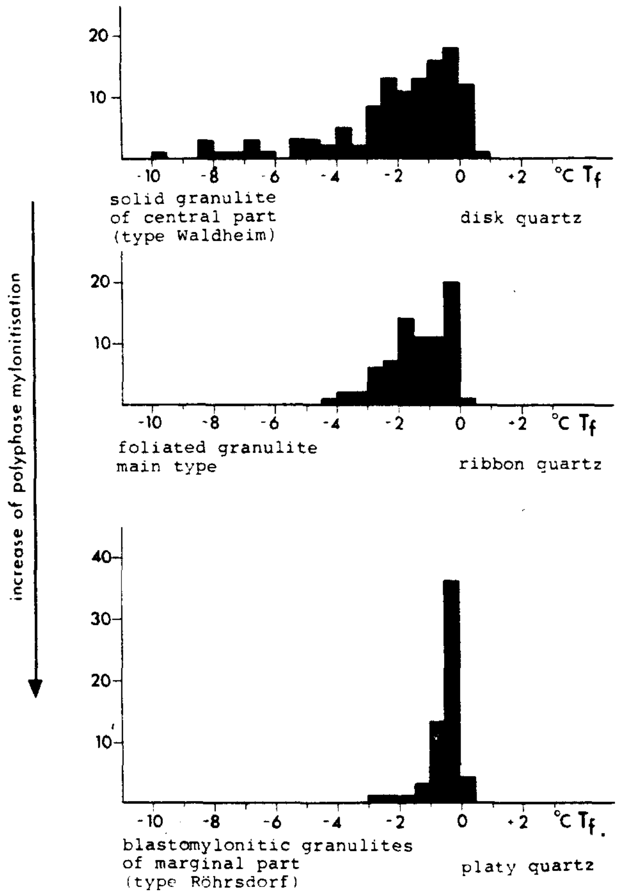

Fig. 3. Temperatures for final melting of aqueous inclusions within granulites exhibiting different stages of mylonitization.

low-grade metamorphism (Fig. 3). The homogenization temperatures of the CO_2-free inclusions have their maxima at 180°, 240°, 300° and 400°C for the different types of deformation. Due to the cogenetic occurrence of pure CO_2- and H_2O-inclusions in the different stages of deformation, P/T-data may be constructed from the isochore intersections. Figure 4 shows the average results for 16 different granulite occurrences which underwent deformation at different depths.

FABRIC DATA

The *c*-axes pole diagrams of the quartz fabric are characterized by small circles parallel to the foliation, *s*, in the central granulites, by cross girdles with an angle of 90° in the marginal granulites and by a maximum I/II in the marginal mylonitic granulites (Fig. 5). All these orientation patterns are connected by gradual transitions. This continuous change of the orientation patterns is very well documented in the borehole section of Fig. 5. A map showing the distribution of the different orientation patterns is presented in Fig. 6 (see also Behr 1961).

In the weakly deformed central granulites, the quartz porphyroblasts have a cauliflower-like appearance with a single-grain fabric, a lattice orientation with small circles parallel to *s*, and P/T-data of 5–7kb/600–850°C from fluid inclusions. With increasing amphibolite facies overprinting, single grains attain disc-like shapes forming a ribbon texture with a cross-girdle preferred orientation pattern with an opening angle of 90° and P/T-data of 4–6kb/600–700°C. Carpets of perfectly parallel oriented platy quartz grains with a lattice orientation pattern between cross girdle and maximum I/II and P/T-data of 2.5kb/500–650°C follow in the sequence. In the marginal mylonitic granulites, the platy quartz carpets recrystallize to a subgrain-like texture with maximum I or II and P/T-data of 1–2kbar/250–400°C (Fig. 4).

All quartz patterns are orientated strictly symmetrically to the cleavage and to a well developed stretching lineation. In the area which is free from overprinting or weakly overprinted the granulites with small circle patterns have a stretching lineation striking NE–SW, while in the roof region, where cross girdles are developed and the amphibolite facies overprinting increases, the lineation turns into a NW–SE direction. Furthermore in the roof region intrafolial folds, boudinage, rotated phacoids and sheath-folds on a metre scale are developed.

MICRORUPTURE DATA

The different deformation types are accompanied by specific and typical microrupture fabrics. Except for the type with subgrain-like recrystallization, the quartz grains are pervaded by microruptures of $<1\ \mu m$ size which are tension cracks following the cleavage of the quartz in $\{10\bar{1}1\}$ and $\{01\bar{1}1\}$ planes. The number of the ruptures per volume increases from the central to the marginal granulites by more than 10 times. These ruptures are filled with fluid inclusions. The 4.55 vol% contraction of the quartz below the inversion point is the reason for the unusual intensity of the rupturing. A rapid ascent of the granulite into higher crustal levels may have caused thermal stresses and the ruptural opening of the cleavage planes. With increasing numbers of microruptures, the density of the rock decreases. The densities of the Saxonian granulites have been studied by Kopf (1968, 1976). The density of the central granulite is 2.74–2.69 ($g{\cdot}cm^{-3}$), of the transitional type 2.69–2.65 ($g{\cdot}cm^{-3}$) and of the marginal granulite 2.65–2.63 ($g{\cdot}cm^{-3}$). The decrease in density is partly due to retrograde phase transition and partly to microrupturing.

DISCUSSION

The data summarized in Fig. 4 lead to the following conclusion. The metamorphic paragenesis of the granulites follows a path from field A to B and C. The oldest generation of fluid inclusions form between B and C within tourmaline and quartz. This group of inclusions lies on a geothermal gradient of 40°C/km. The granulite types with transitions of *c*-axis pole orientations with small circles parallel to s or with cross girdles to maximum I/II patterns, and the granulites with subgrain-like

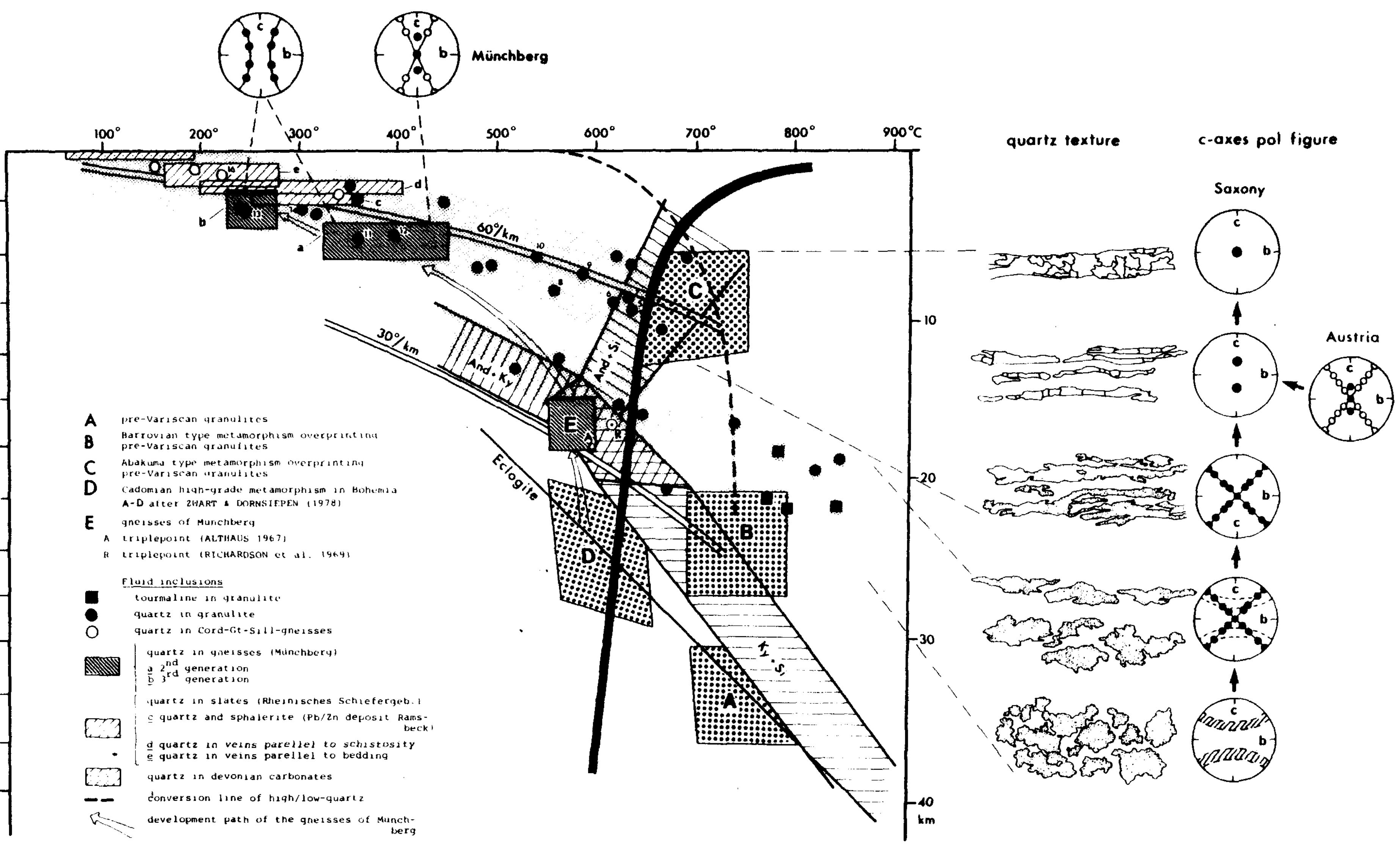

Fig. 4. *P/T* grid for Saxonian granulites and gneisses of Münchberg, based on data of metamorphic parageneses, fluid inclusions, quartz textures and *c*-axes pole figures.

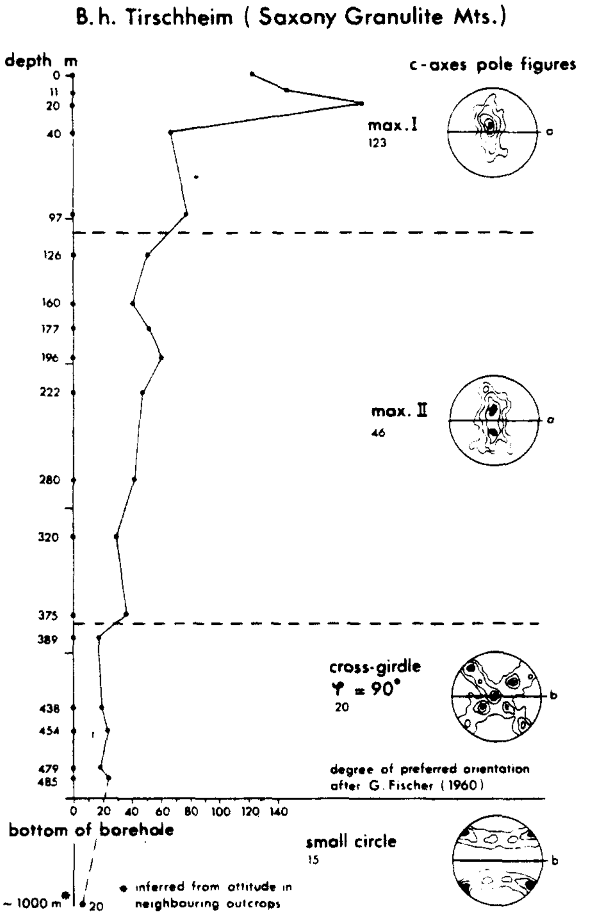

Fig. 5. c-axes pole figures for a borehole section, drilled into granulites which had been deformed at different levels in the crust.

recrystallization are situated on a gradient of 60–70°C/km between 700°C/2.5 kbar and 300°C/1 kbar. On the same steep gradient are also situated the quartz fabrics of the gneisses of Münchberg with their field of metamorphic paragenesis at E. Two different fossil geothermal gradients can be distinguished. The synkinematically produced quartz fabrics recrystallized subsequently under decreasing *P/T*-conditions after the peaks of two successive metamorphic events. The first overprinting located in field B strongly affected the whole granulite body, while the second overprinting was limited to the marginal horizons. The fluid inclusion studies show convincingly that H_2O entered the dry granulite from the neighbouring paragneisses. Supposedly, the H_2O enhanced the tectonic mobility of the quartz by hydrolytic weakening and has produced thick zones of metagranulitic migmatite gneisses with relict kyanite along the margins of all the granulite bodies.

The diapiric upwelling of the granulite body was initiated by plastic flow in the shear belt, probably in consequence of hydrolytic weakening and promoted by the density difference of the granulite and the surrounding paragneisses. The paragneisses, also investigated by Kopf (1968), yielded densities of 2.71 – 2.78 ($g \cdot cm^{-3}$). Thus there is a negative difference of up to 0.15 ($g \cdot cm^{-3}$) between the granulite and the paragneiss. The comparatively low densities of the granulites are explained by the low content of mafic minerals and the low proportion (*ca* 5%) of basic granulite types. It can be shown that the light-coloured low-density granulites are derived from rhyolitic and alkali-rhyolitic volcanics and clastics of graben zones. All the age data for the granulites indicate ages between *ca* 500–338 Ma (Arnold & Scharbert 1973, Watznauer 1974) and those for the Münchberger Masse between 483–370 Ma (Söllner 1978, Gebauer & Grünenfelder 1979).

Our present knowledge indicates that the granulites were formed during the Cadomian or Caledonian event (*ca* 460 – 480 Ma) and were continuously overprinted by metamorphism and mylonitization with distinct peaks during the Middle Devonian (Acadian, 384 Ma in over-

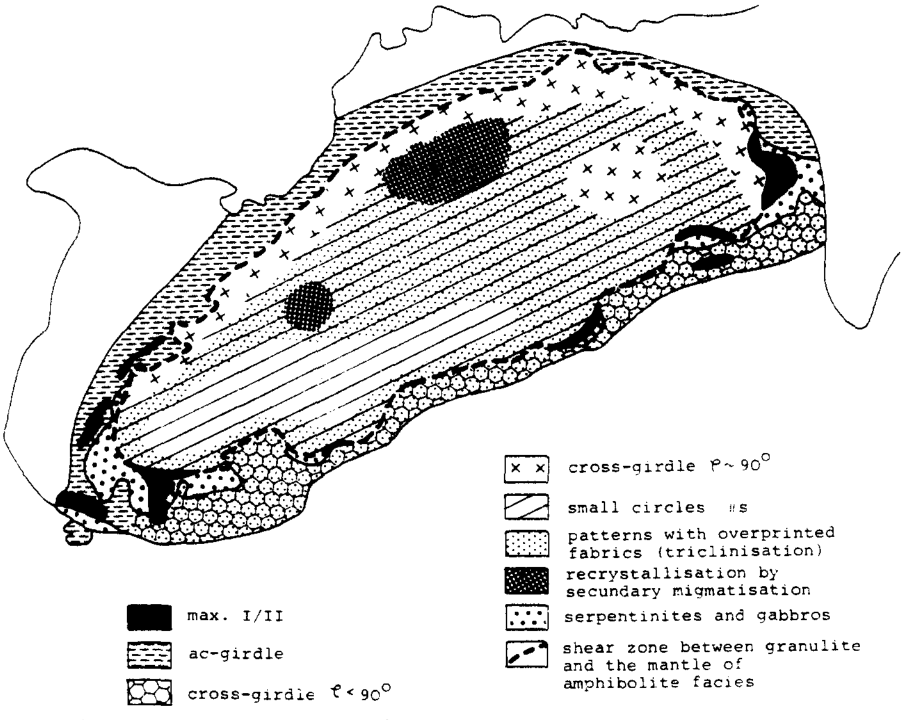

Fig. 6. Regional distribution of the different quartz fabrics in the Saxonian Granulite Mts.

printed granulites) and between Lower and Middle Carboniferous (Sudetic–Asturian). Both shear belts along the NW and SE margins of the Bohemian Massif are regarded as prominent subfluence zones which developed during Cadomian, Caledonian and Variscan intracontinental A-subduction processes (Behr 1978, Behr & Weber 1979). The northern belt may be traced into the Black Forest and the Vosges, while the southern one continues as far as to the basement nappes of the Central Massif (Burg & Matte 1978) though locally covered and overprinted by the northern margin of the Alps.

REFERENCES

Arnold, A. & Scharbert, H. G. 1973. Rb–Sr-Altersbestimmungen an Granuliten der südlichen Böhmischen Masse in Österreich. *Schweiz. miner. petrogr. Mitt.* **53**, 61–78.

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

Behr, H. J. 1978. Subfluenz-Prozesse im Grundgebirgsstockwerk Mitteleuropas. *Z. dt. geol. Ges.* **129**, 238–318.

Behr, H. J. & Weber. K. 1979. The structural and metamorphic development of the Variscides with special regard to the Rhenohercynian and Saxothuringian zones. In: *Intern. Geodynamic Project*, Deutsche Forsch. Gemeinschaft, Bonn.

Burg, J. P. & Matte J. P. 1978. Cross section through the French Massif Central and the scope of its Variscan geodynamic evolution. *Z. dt. geol. Ges.* **129**, 429–460.

Fischer, G. 1960. Über die Auswertung von Gefügediagrammen. *Abh. Dtsch. Akad. Wiss.* **3**, 283–299.

Fuchs, G. & Matura, A. 1976. Zur Geologie des Kristallins der Böhmischen Masse. *Jb. Geol. B. — A. Wien.* **119**, 1–44.

Fuchs, G. & Scharbert, H. G. 1979. Kleinere Granulitvorkommen im Niederösterreichischen Moldanubikum und ihre Bedeutung für die Granulitgenese. Verh. *Geol. B. — A. Wien.* **2**, 29–49.

Gebauer, D. & Grünenfelder, M. 1978. U–Pb zircon and Rb–Sr mineral dating of eclogites and their country rocks. Example: Münchberg Gneiss Massif, Northeast Bavaria. *Earth Planet. Sci. Lett.* **42**, 35–44.

Kopf, M. 1968. Zur petrophysikalischen Untersuchung und Abgrenzung von metamorphen Para- und Orthokomplexen. 23rd *Int. geol. Congr. Praha* **4**, 237–251.

Kopf, M. 1976. Zur Anwendung der Petrophysik in der Petrographie. *Z. geol. Wiss. Berlin* **4**, 1049–1067.

Mathé, G. 1969. Die Metabasite des Sächsischen Granulitgebirges. *Freiberger Forsch. - H. C.* **251**, 1–130.

Scharbert, H. G. & Kurat, G. 1974. Distribution of some elements between coexisting ferromagnesian minerals in Moldanubian granulite facies rocks, Lower Austria. *Tscher. miner. Petr. Mitt.* **21**, 110–134.

Schüller, A. 1954. Die kristalline Scholle von Wildenfels, ihr Stoffbestand und ihr tektonischer Bau im Rahmen des varistischen Gebirges. *Z. Geol.* **3**, 707–749.

Schwan, W. 1974. Die Sächsischen Zwischengebirge und Vergleiche mit der Münchberger Gneismasse und anderen analogen Kristallinvorkommen im Saxothuringikum. *Erlanger geol. Abh.* **99**, 1–189.

Söllner, F. 1978. Rb/Sr-Altersbestimmungen an Gesteinen der Münchberger Gneismasse, NE-Bayern. *Inaugural-Dissertation, Ludwig-Maximilians-Universität München.* 1–125.

Vesela, M. 1967. On the stratigraphical position of granulites in the Moldanubikum. *Krystalinikum* **5**, 137–152.

Watznauer, A. 1974. Beitrag zur Frage des zeitlichen Ablaufes der Granulitgenese (Sächsisches Granulitgebirge). *Krystalinikum* **10**, 181–192.