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Paleostress directions deduced from microcrack fabrics in KTB core samples and granites from the surrounding area.

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Summary. Detailed microcrack analyses on a gneiss sample from the KTB pilot drillhole and on granites from the surrounding area yield information about the paleostress directions during the Upper Carboniferous and for periods between the post-Paleocene and subrecent time. For the Upper Carboniferous the data points to a reorientation of the maximum horizontal normal stress (σ_H) from NW-SE to NE-SW, which is in good aggreement with the current tectonic models of the late-Variscan collision stage. For post-Paleocene to subrecent time the chronology of different crack generations indicates an anticlockwise rotation of σH of about 20° from NW-SE to WNW-ESE. At the surface level the youngest crack generation and the related σ_H-directions correlate well with in situ-stress measurements. In contrast, in situ-stress directions measured in the KTB-pilot drillhole deviate significantly from the surface data, which probably reflects local stress reorientations related to the close proximityof the Franconian Lineament.

Keywords: Paleostress directions - Microcracks - Crack mechanisms - Fluid inclusions - Variscan basement

Introduction

Microcrack analyses are of increasing interest in many fields of geoscience. Since microcracks usually display distinct preferred orientations ("textures"), they may significantly influence the petrophysical and mechanical properties of rocks, and hence, may also contribute to crustal-scale geophysical discontinuities. Moreover, microcrack networks may represent pathways for crustal fluids, and thus are of special interest in regards to the transport of matter in hydrothermal systems as well as convective heat transfer. The present investigations, however, focus on the reconstruction of paleostress directions in basement rocks of the extended KTB study area using different generations of microcracks as stress indicators. A topic of special interest are the relationships between stress directions deduced from microcrack patterns and in situ stress measurements.

The KTB site is located at the northwestern margin of the Bohemian Massif which represents the largest outcrop of Variscan basement in Central Europe (Fig. 1). The study area is interpreted as part of the late-Variscan collision zone between the Moldanubian terrane to the southeast and the Saxothuringian terrane to the northwest. The related rocks usually display complex fabrics due to polyphase deformation at different crustal environments. The whole area was intruded by large volumes of late- to post-Variscan granitoids, followed by several periods of intensified block faulting in different extensional as well as compressional regimes (e.g. Zulauf 1992). For comprehensive descriptions of the geological setting and related competetive tectonic models the reader is referred to, e.g., Behr et al. (1989), Behr (1992), Stettner (1993), Vollbrecht et al. (1989) and Weber (1992).

The investigated samples were taken from oriented cores from the KTB pilot well (paragneisses) and from outcrops in the extended surrounding area (granites) (Fig.1).

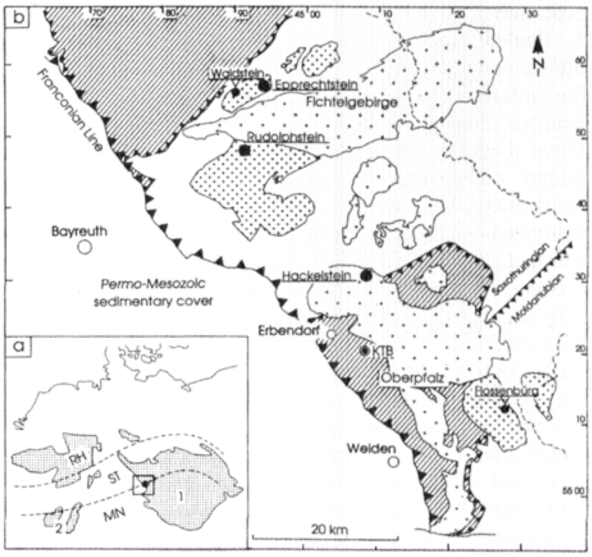

Fig.1. Geological sketch maps.
(a): Outcrops of Variscan basement in Mid-Europe with zones after Kossmat (1927); RH-Rhenohercynian, ST-Saxothuringian, MN Moldanubian; inset outlines study area as shown in (b).
(b): Study area with KTB location and sample sites within the granites.

Methods

The orientation of microcracks was determined by U-stage microscopy using 25-30 µm thick standard thin sections. In order to record all possible microcrack orientations, the measurements for each sample were carried out in three mutually perpendicular sections. The resulting data were plotted as composite crack pole figures for the horizontal plane (Schmidt net, lower hemisphere) reoriented with respect to the geographic directions. Spurious maxima in the composite pole figures, which might result from the overlap of Schmidt net areas of the three sections were statistically compensated (see Vollbrecht et al. 1991 for details). These composite crack pole figures were then used to define the orientation of the maximum horizontal normal stress σ_{H}, assuming that in a natural environment the cracks developed normal to the least normal stress σ_3. This assumption is confirmed by numerous investigations which indicate that the vast majority of natural microcracks are of the tensional (mode I) type, though crack initiation and further propagation may be related to different mechanisms and driving forces (see below). Offset patterns between different crack generations together with crack mineralizations and characteristics of fluid inclusions in healed cracks were used to define the relative chronology of crack formation and to relate it to certain P/T conditions or periods, respectively. The microthermometric investigation of fluid inclusions was carried out with a heating-freezing stage of the type Chaixmeca (Poty et al. 1976). The temperature of final melting (Tm) which defines the bulk salinity, and the temperature of homogenization (Th) were used to discriminate different generations of healed cracks and to calculate the inclusion densities (isochores) which yield information about probable P/T conditions during crack formation/healing. Inclusions suspected of secondary alterations like leakage or necking down were neglected.

Results

Microcracks in granites

Detailed analyses of granites from 5 localities (Fig. 1) have shown that two types of microcracks predominate which can be related to different stages of the post-magmatic evolution:

1. Healed cracks in quartz typically developed as two orthogonal sets which probably formed simultanously, since the microthermometric data of the related secondary aqueous fluid inclusions show no significant differences. Since these cracks are concentrated in quartz grains and seldom cross over into adjacent feldspars (Fig 2a), it is concluded that they formed in response to differential volumetric strains resulting from the strong thermal contraction of quartz within a framework of feldspar during cooling, as schematically illustrated by a bisphere model (Fig. 2b; for details see Vollbrecht et al. 1991). This model, here referred to as "thermal cracking", implies that in quartz-bearing rocks microcracks may generate even in deep crustal levels at high confining pressures and low external deviatoric stresses. The preferred orientation of these cracks over large rock volumes (see below) is explained by the superposition of an external stress field resulting in a first set of cracks normal to σ_3 (Fig. 2c; set I, long cracks). This first set causes a local uncoupling of the quartz core from the σ_3 direction, so that further thermal contraction of the now isolated quartz slices leads to a second set of cracks normal to σ_2 (Fig. 2c; set II, short cracks). This model offers the opportunity to determine all three principal normal stress directions (σ_1, σ_2, σ_3) related to the early cooling history.

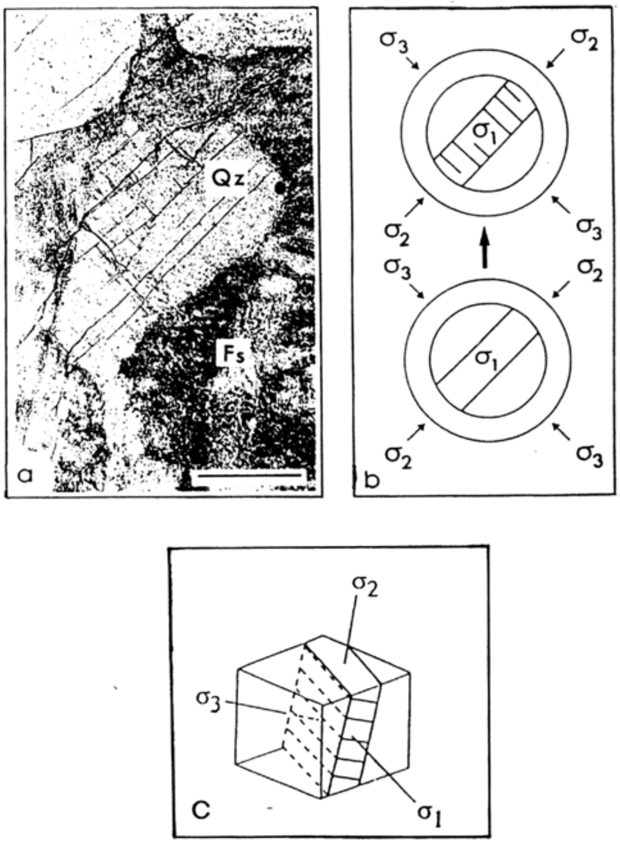

Fig.2. Concept of thermal cracking in quartz
a: Preferential cracking of quartz surrounded by feldspar indicating differential volumetric strain; typical ladder-shaped patterns formed by two crack sets (scale bar=0.25mm).
b: Interpretation in terms of a bisphere model with quartz-core and feldspar mantle; internal thermal stresses superposed by an external deviatoric stress field (for further explanation see text).
c: typical 3D pattern as observed by U-stage microscopy and inferred stress directions.

Rough P/T estimates based on fluid inclusion data suggest that thermal cracking in the granites started at about 500 ° C and 3 kbar (Vollbrecht et al. 1991) assuming related late-Variscan geothermal gradients between 40 and 60 ° C/km which are evident from several thermobarometric studies (for compilation of data see, e.g., Vollbrecht et al. 1990). Younger generations of similar healed cracks and related fluid inclusions indicate that thermal cracking continued during the further cooling and uplift ending at P/T conditions of about 150 °C and 0.8 to 1 kbar.

This paper concentrates on the first generations of thermal cracks and the related stress field for which the age can be roughly delimitated by geochronological data. According to Rb/Sr and K/Ar ages, which predominantly scatter between 320 and 290 Ma (e.g., Köhler et al. 1974; Besang et al.

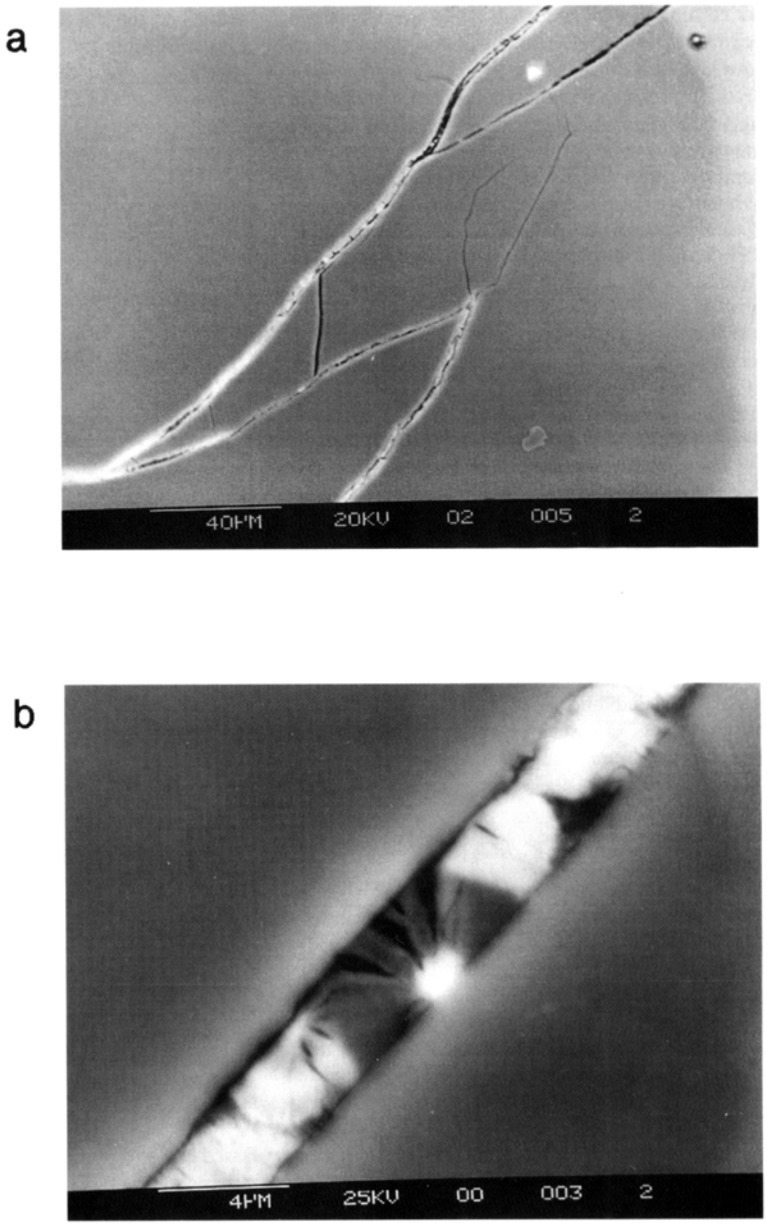

Fig.3. Open cracks partly coated or filled with Fe-oxides; scanning electron microscopy, back scattered electron images.
a: Overview with open and mineralized sections of cracks
b: Detail of (a) showing rosette-shaped aggregates of Fe-oxides.

1976; Wendt et. al. 1986; Wendt et al. 1988) there is only a short time span between the intrusion of the granites and cooling below temperatures of about 350 °C. Consequently, for the onset of thermal cracking at temperatures of about 500 °C and the related paleostress field an Upper Carboniferous age has to be assumed.

2. Open cracks often transsect quartz/feldspar phase boundaries and are usually developed as single sets. Sections of these cracks are often coated or completely filled with Fe-oxides indicating a natural origin (Fig. 3). Moreover, frequency and orientation of this crack type lack any geometrical relationship to the outline of the thin sections, so that crack formation during sample preparation can be largely excluded.

In contrast to the healed cracks, the open cracks don't yield any thermobarometric information which can be used for age estimates. However, they must have formed significantly later on the retrograde P/T-path than the youngest generation of healed cracks which formed at about 150 °C and 0.8 to 1 kbar. For this reason and microstructural similarities, these open cracks are correlated with open cracks met in the KTB borehole, for which better age relationships could be detected (see below).

A recent study on the crystallographic orientation of these two crack types in quartz (Vollbrecht et al. 1994) demonstrates that healed and open cracks originated by different mechanisms. However, both follow lattice directions which are extremely sensitive to thermal stresses in quartz.

Microcracks in paragneisses from the KTB drilling site

The microcrack patterns in paragneisses from KTB cores are more complex than those observed in the granites, probably due to the influence of the preexisting rock anisotropy (foliation and lineation defined by layering, shape- and lattice-preferred orientation of minerals). Microcrack analyses on samples from different depths and with varying attitude of the main foliation have shown that the orientation of healed microcracks is strongly related to the strike and dip of the foliation (Fig. 4). A comprehensive and satisfying model which can explain this phenomenon has not yet been developed. Another complication is, that in anisotropic rocks external horizontal stresses may be preferentially released by shearing or extension along the foliation as schematically illustrated in Fig. 5, so that crack growth is largely suppressed.

By taking these influences of preexisting rock fabrics into account, a core sample with approximately horizontal foliation was selected for the determination of horizontal normal paleostress directions, assuming that individual layers behaved mechanically nearly isotropic. This concept was confirmed by the measurements showing simple crack patterns for certain generations which can be used for paleostress determinations (see below). The interpretation of open cracks may be complicated by the fact that during core relaxation (strain recovery after core extraction; Zang et al. 1989) additional cracks may generate preferentially normal to the maximum in situ normal stress direction as illustrated in Fig. 6.

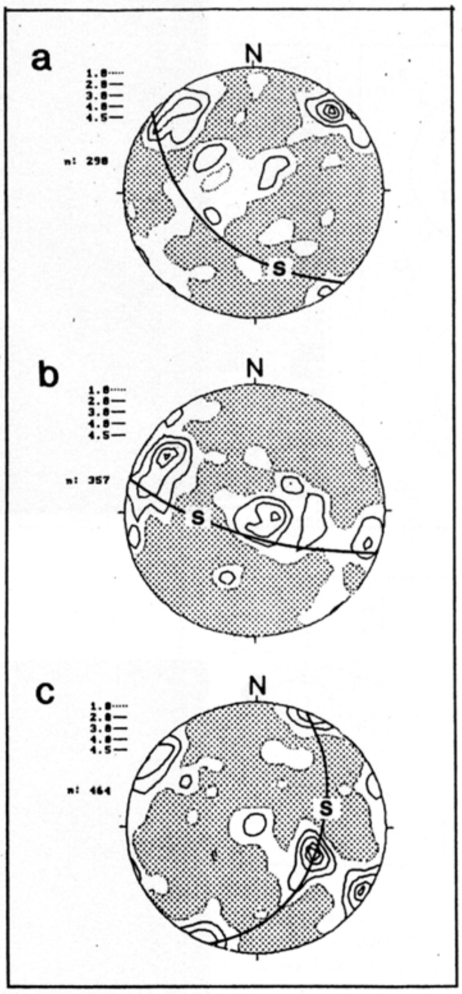

Fig.4. Microcrack pole figures of paragneisses from the KTB-pilote borehole; crack patterns (healed cracks in quartz) show strong geometric relationships to the strike and dip of the main foliation (s).
a: Sample 402J6q, 1790,5 m; b: Sample 588E5ac, 2425,9m; c: Sample 855C2nk, 3497,2m.

Based on microstructural characteristics and mineralizations (Fig. 7), together with geochronological data a polyphase crack development can be discerned which allows a very detailed reconstruction of stress directions for periods between upper post-Paleocene and recent time. The main features and decisive data (Fig. 8) can be summarized as follows; (for a more comprehensive description see Vollbrecht and Weber, 1992):

1. The oldest generation is represented by sericite-sealed cracks predominantly developed in plagioclase for which K/Ar data point to minimum ages of Lower Cretaceous (Wemmer 1991). These cracks show no distinct preferred orientation since they formed preferentially along cleavage and twin planes of plagioclase and hence are strongly texture-related.

2. The second generation is sealed with K-feldspar and is supposed to be correlated with larger K-feldspar mineralizations in subvertical dikes which are of Upper Cretaceous age, as also indicated by K/Ar data (Wemmer 1991).

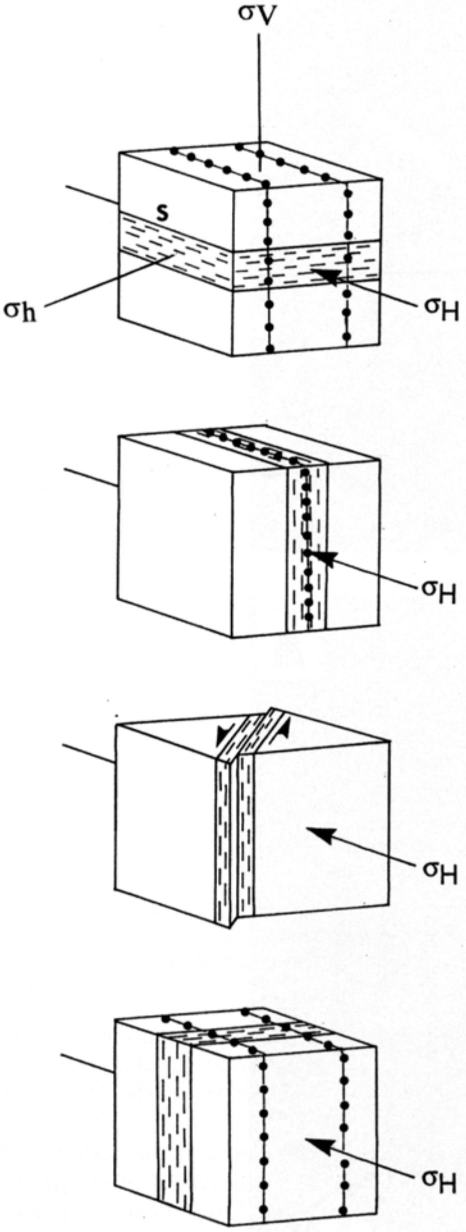

Fig.5. Mechanical activation of the s-plane in foliated rocks. If the s-plane is in suitable orientation with repect to the external stress field, stress release by shearing or extension along the s-plane may prevent the formation of microcracks which can be used as stress indicators (here illustrated for the case: $\sigma_H > \sigma_V > \sigma_h$); dotted lines: extensional (mode I) cracks.

3. The third generation, represented by healed cracks in quartz, partly displays genetic transitions to the second generation, in a way that they sometimes appear in the prolongation of K-feldspar-sealed cracks in adjacent plagioclase grains. The correlated secondary aqueous fluid inclusions are of high density and formed at temperatures around 100 °C. Therefore, apatite fisson track data indicating the age of cooling below 100 °C may be used to estimate the age of these cracks (e.g. Wagner et al. 1991). If fisson track ages of KTB samples taken from 172 m down to about 2000 m are extrapolated to the depth of the investigated sample (3145 m), an age of 60 Ma (Paleocene) can be assumed for the formation of the healed cracks.

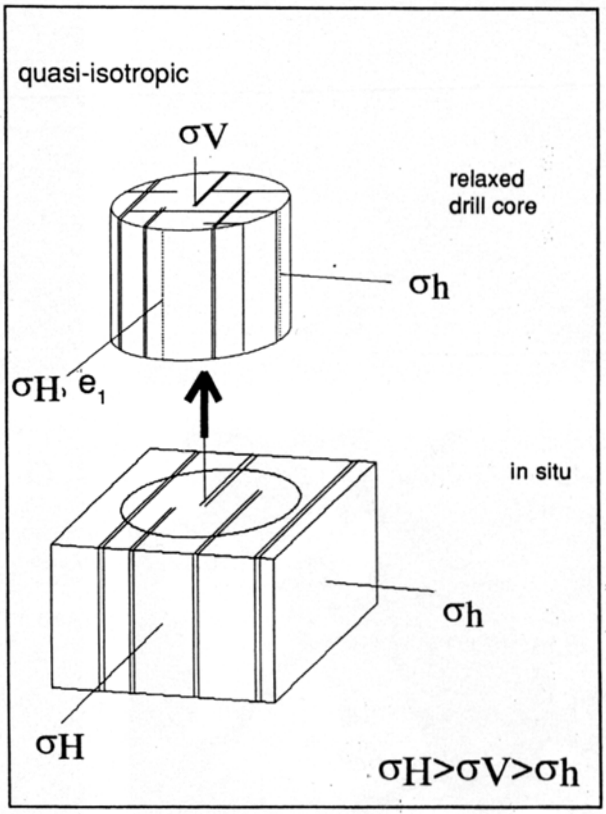

Fig.6. Superposition of natural cracks formed normal to paleo-σ_3 (here: σ_h) and cracks formed normal to σ_1 (here: σ_H) during core relaxation; e1 = direction of maximum extension. The sketch illustrates the crack formation for a quasi-isotropic rock and for paleostress directions which equal the present (in situ) configuration.

4. The pole figure of the open cracks shows a more complex pattern. As mentioned above, this probably results from the superposition of paleocracks (normal to paleo-σ_3) and cracks formed during core relaxation (normal to the recent in situ σ_1). The diffuse girdle of poles in the NE-SW-direction is attributed to paleocracks, probably reflecting a reorientation of σ_3 from a subhorizontal NE-SW direction (= σ_h) to a subvertical direction when approaching higher crustal levels during the latest stages of uplift. For these cracks Tertiary (? post-Paleocene) to subrecent ages are plausible. The submaximum of poles in the NNW-SSE direction can be attributed to core relaxation cracks, since

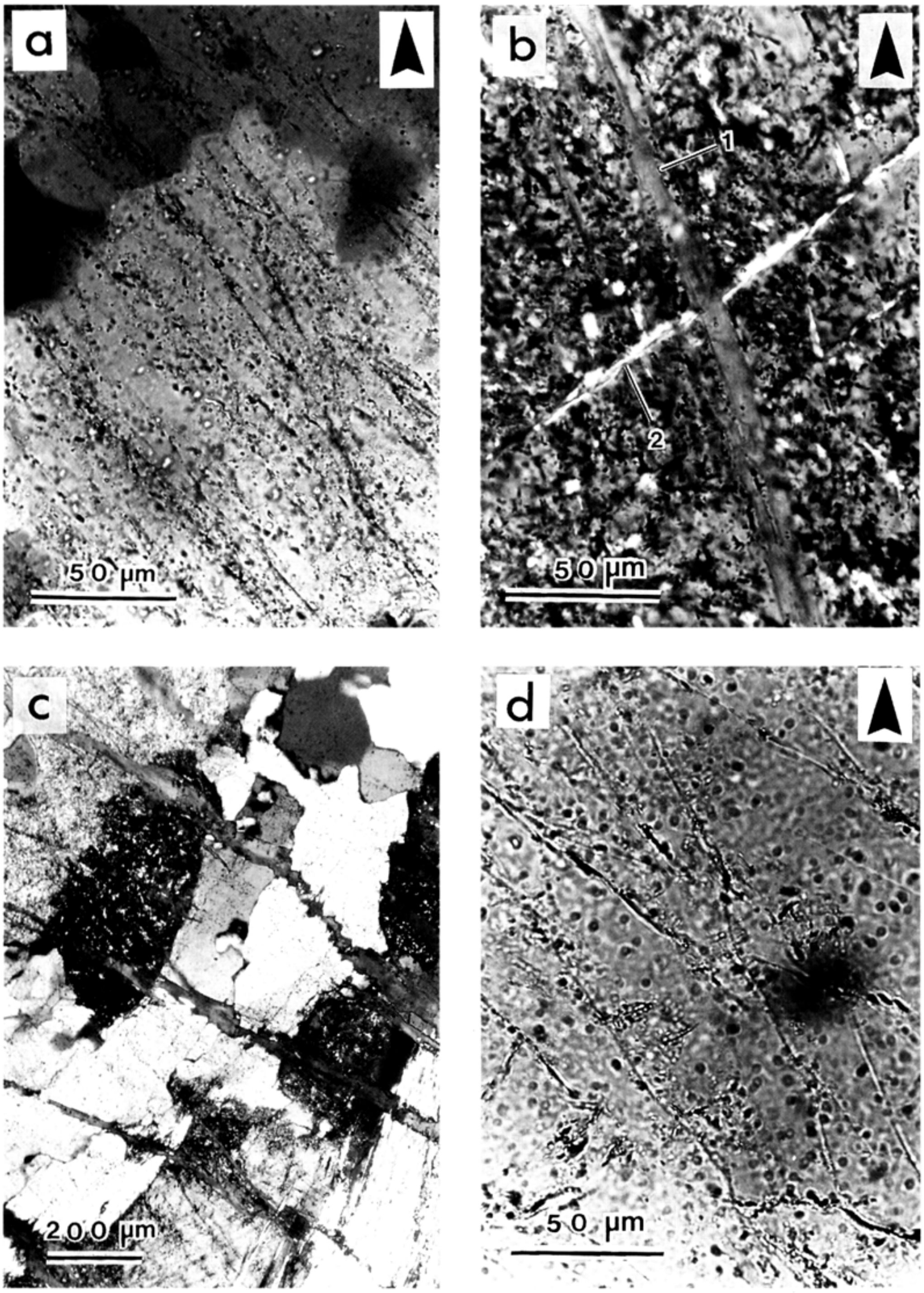

Fig.7. Microcrack generations in paragneiss from the KTB pilot drillhole (sample 767G3g; 3145m); arrows indicate N-direction in horizontal sections.

a: Healed cracks in quartz outlined by trails of secondary fluid inclusions

b: Crack with K-feldspar mineralization (1) within strongly altered plagioclase transsecting older cleavage cracks with sericite decoration.

c: Crack set with K-feldspar mineralization transecting grain and phase boundaries.

d: Anastomosing open microcracks in plagioclase.

their orientation agrees well with the medium value of the in situ maximum horizontal normal stress direction as defined for the KTB pilot hole (161° +/-14; Mastin et al. 1991).

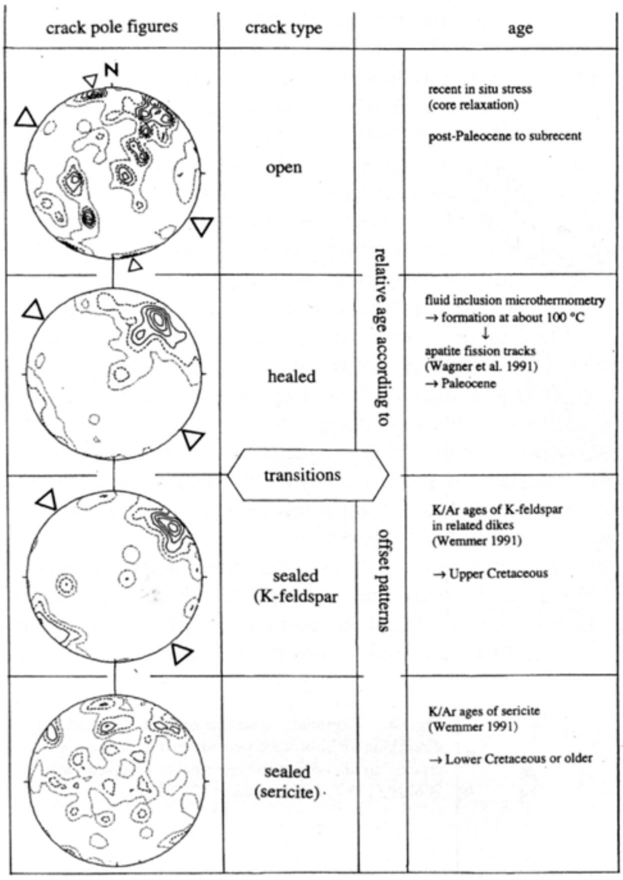

Fig.8. Temporal development of paleostress directions deduced from microcracks in a paragneiss from the KTB drillsite (sample 767G3g); big arrows= paleo-σ_H, small arrows= recent in situ-σ_H; for further explanation see text.

From generation 2 to 4, i.e. in a period between Upper Cretaceous and post-Paleocene/subrecent, a shift of the crack pole maxima is visible indicating an anticlockwise rotation of σ_H of about 20°(from NW-SE to WNW-ESE). With respect to these paleo-σ_H directions, the recent in situ-σ_H (160°, NNW-SSE) and the related core relaxation cracks point to a reversal of this trend.

Regional patterns of paleostress directions

As argued above, regional variations of paleostress directions can be represented for the Upper Carboniferous as indicated by the first generation of healed cracks in the granites, and for post-Paleocene to subrecent time periods as indicated by open cracks in granites and paragneisses from the KTB drillhole.

For the Upper Carboniferous (Fig. 9) NE-SW directions of σ_H predominate (35°+/- 10°; Waldstein, Hackelstein, Flossenbürg). At the Epprechtstein locality the σ_H direction scatters around 130°(NW-SE) which agrees with data from 3 localities in the Falkenberger granite (Maier & Stöckhert 1992), based on two-dimensional crack analyses. Therefore, according to the present data, two preferred σ_H directions can be assumed for the considered period. However, the question arises, whether these two directions reflect local variations of the paleostress field or a temporal development, i.e., a switch of σ_H during the Upper Carboniferous. Both σ_H-directions correlate well with successive stages of the late-Variscan collision tectonics as inferred from macroscopic structures: NW-SE-directed compression indicated by thrusting, backthrusting and related folding (e.g., Vollbrecht et al. 1989), followed by a NE-SW-directed compression (e.g., Zulauf 1992). A complex interference between these two main directions of compression as well as temporal transitions may be interpreted in terms of a transpressional tectonic model (Weber 1992). Accordingly, the σ_H direction (80°) at the Rudolphstein locality may represent a transitional stage of this stress reorientation.

The paleostress directions deduced from open cracks in granites are in good agreement with in situ-stress measurements in the surrounding field of the KTB site NW-SE to WNW-ESE; Fig. 10), which argues in favor of a subrecent age of the open cracks. A local deviation from this regional pattern is only observed around the Epprechtstein locality. This probably reflects a local reorientation of the stress directions in the vicinity of a fault zone. At three localities offset relationships between successive generations of open microcracks with different orientations may be used to determine the temporal reorientation of σH (clockwise at Epprechtstein and Hackelstein, anticlockwise at Flossenbürg).

In contrast to the surface data, the results from the borehole show a significant discrepancy between the in situ-stress and the paleostress directions related to open cracks. The paleostress direction (σ_H, open cracks) agrees with the regional configuration at the surface, the in situ-σ_H, however, deviates by about 40° in a clockwise sense (see also Fig. 8). Vertical variations can be ruled out as a suitable explanation, as shown by constant in situ-stress directions met in the KTB pilot drillhole along a continuous profile between 900 and 3800m depth (e.g., Mastin et al. 1991). Therefore, it is more likely that local variations of the in situ-σ_H direction are probably influenced by the stress configuration along the Franconian Line and related fracture zones, which are met in the deeper sections of the KTB profile (e.g., Hirschmann 1992).

Conclusions

The present study demonstrates that detailed analyses of microcracks are a suitable tool for the determination of paleostress directions in crystalline rocks. For this, an

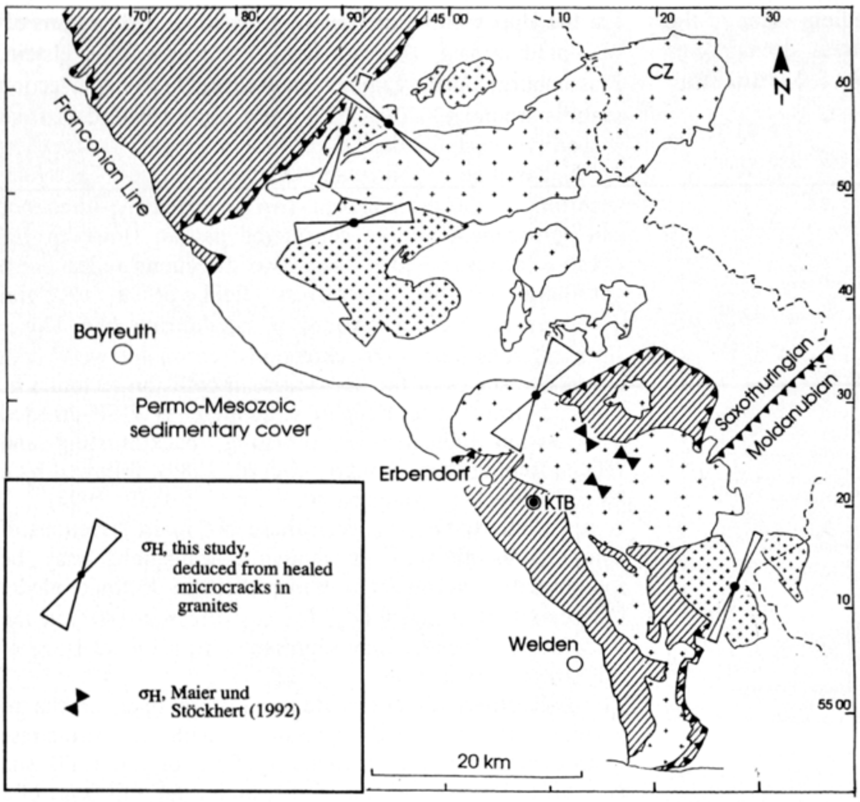

Fig.9. Regional distribution of paleostress directions during the Upper Carboniferous, deduced from healed cracks in granites; data for the Falkenberg granite after Maier and Stöckhert (1992); for further explanation see text.

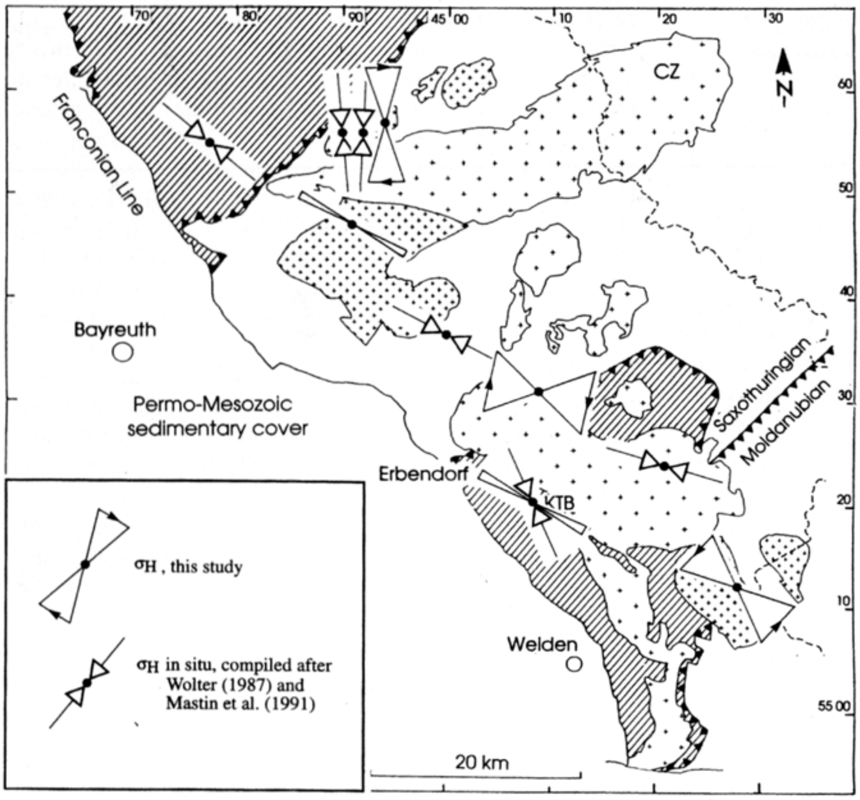

Fig.10. Regional distribution of paleostress directions for subrecent periods deduced from open cracks; in situ-stress measurements compiled after Wolter (1987) and Mastin et al. (1991).

essential prerequisite is the isotropic behavior of rocks in response to external stresses. Rocks with distinct anisotropic fabrics have to be in a suitable orientation with respect to the external stress directions so that planes of anisotropy remain mechanically inactive. Otherwise, stress release can be achieved by, e.g., slip on the planes of anisotropy (foliation) or extension normal to them.

The consistant orientation of the detected paleostress directions at different localities and the good correlation with in situ-stress directions confirm, that microcrack patterns of small rock volumes may be representative for areas at regional scale. The advantages of this methods are (1) that it can be applied to small rock specimens like drill cores and (2) that in the case of thermal cracking paleoconfigurations can be detected even for deviatoric paleostresses which are far below the critical value for macroscopic failure. Mineralizations and fluid inclusions in healed cracks may offer an opportunity for thermobarometric estimates which enables one to relate different crack generations to certain segments of the p/T/t paths. Since ductile deformation and neomineralizations usually destroy preexisting crack fabrics, microcrack analyses in orogenic belts mainly yield information about the late- to post-orogenic uplift history and the related stress fields. Moreover, the observed microcrack patterns obviously reflect only parts of the stress history between Upper Carboniferous and recent time, since deviating paleostress configuration were deduced for other periods by anlyses of macrostructures (e.g., Malkovsky 1987).

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