Mitt. Österr. Geol. Ges.	ISSN 0251-7493	**90** (1997)	11-29	Wien, Dezember 1999

Keywords
Bohemian Massif
strike-slip shear zones
fluid inclusions
microfabric analyses
mineral rheology

Contrasting P-T conditions during conjugate shear zone development in the Southern Bohemian Massif, Austria

BRANDMAYR M.[1], LOIZENBAUER J.[2], WALLBRECHER E.[2]

13 Figures and 3 Tables

Content

Kontrastierende P-T Bedingungen während der Entstehung konjugierter Scherzonen in der südlichen Böhmischen Masse

Zusammenfassung

Aufgrund von gefügekundlichen Untersuchungen und Analysen von Flüssigkeitseinschlüssen von Scherzonen der Südlichen Böhmischen Masse wurde ein Modell entwickelt, in dem die große Variation an abgeleiteten Druck-Temperatur-Bedingungen, die in beiden Blattverschiebungssystemen (sowohl in den NW-SE streichenden dextralen, als auch in den NE-SW streichenden sinistralen Scherzonen) abgeleitet werden können, Berücksichtigung finden. Generell kann zwischen höher temperierten Myloniten im Westen (Pfahl und Donau Scherzonen) und höher krustalen, tiefer temperierten Myloniten bzw. Kataklasiten im Osten (Vitiser und Diendorfer Scherzonen) unterschieden werden. Großregionale Transpressionstektonik, bei der ein spätproterozoisches Terrane von einem frühpaläozischen Terrane überschoben wird, führt zu beträchtlichen Krustenverdickungen in den Internzonen des variszischen Orogens. Spätvariszisch intrudieren große Mengen an Plutonen, die eine erhebliche regionale Aufheizung des Krustenstapels mit sich bringen. Postintrusiv kommt es zur Ausbildung des konjugierten Scherzonensystems. Mikrothemometrische Analysen an Flüssigkeitseinschlüssen aus zwei Scherzonen zeigen, daß die Störungen unter verschiedenen P-T Bedingungen und damit in unterschiedlichen Krustenniveaus gebildet wurden. Die Fluiddaten weisen auch auf ungleiche Hebungsgeschichten für die Scherzonen im Osten zu denen im Westen hin. Dabei führt eine variszische Krustenverdickung zu regional unterschiedlichem Aufstiegsverhalten innerhalb der südlichen Böhmischen Masse und ist der Grund dafür, daß heute Hochtemperaturmylonite der westlichen Scherzonen und kataklastische Gesteine der östlichen Scherzonen aufgeschlossen sind. Während des Aufstiegs setzt sich die Scheraktivität weiter nach Norden fort, und öffnet dadurch die permischen pull-apart Becken von České Budějovice und Blanice.

Abstract

Microfabric analysis and fluid inclusion studies were carried out on a NW-SE striking dextral, and a NE-SW striking sinistral system of conjugate strike slip shear zones in the southern Bohemian Massif. A large variety of pressure-temperature conditions was found in both fault zone sets. Generally, "higher" temperatures of >650°C were typical for the westernmost shear zones (Pfahl and Danube Shear Zone) whereas

Adress of the authors

[1] Ingenieurgemeinschaft Dr. Garber – Dr. Dalmatiner, Leechgasse 37, A-8010 Graz
[2] Institut für Geologie und Paläontologie der Karl-Franzens-Universität, Heinrichstraße 26, A-8010 Graz

"lower" temperature conditions and higher crustal positions were typical for the eastern shear zones (Vitis and Diendorf Shear Zones). The data give rise to a model explaining the geological evolution of the fault systems: Crustal thickening occurs due to large-scale northeastward transpression of an Early Paleozoic terrane onto a Late Proterozoic terrane during the Variscan orogeny. In the very late stages of the orogeny a large mass of plutonic bodies intruded both terranes and led to a high heat flow in all crustal levels. This was immediately followed by begin of shear in the west which produced the conjugate shear system. Microthermometric analyses on fluid inclusions reveal contrasting P-T conditions for two of the strike slip shear zones. Furthermore fluid inclusion data indicate an asymmetric exhumation in the southern Bohemian Massif caused by Variscan crustal stacking. This led to the exposion of deep-crustal high-temperature mylonites in the West and upper-crustal cataclastic rocks in the East. Simultaneously shearing propagated towards the north, opening the Permian pull-apart basins of České Budějovice and Blanice.

1. Introduction

Studies of shear zones aim at the evaluation of shear senses, of timing of deformation, and of conditions at which deformation took place. Whereas shear senses of shear zones sometimes are easily determined, the exact P-T conditions often remain unclear, because many other parameters concerning the behaviour of minerals, like strain rate or confining pressure are often unknown. Although experimental data from natural rocks (TULLIS et al., 1973; TULLIS & YUND, 1985; KRONENBERG et al., 1986; JAOUL et al., 1984; KRONENBERG & TULLIS, 1984; KRONENBERG & WOLF, 1990; GREEN et al., 1970; MAINPRICE, 1981) can only suggest how rocks might have deformed under natural conditions, general trends can be derived.

Ductile behaviour of various rock forming minerals is believed to be controlled mainly by temperature and strain-rate (e.g., TULLIS et al., 1973; TULLIS & YUND, 1985). A high temperature and a low strain rate induce diffusion by dislocation creep and produce crystallographic preferred orientations of minerals different from those produced at a low temperature and a high strain rate.

The effect of water on the rheologic behaviour of a mineral phase and/or rock is interpreted controversially (TERZHAGI, 1923; GRIGGS & BLACIC, 1965; BLACIC, 1975; HOBBS, 1985; MAINPRICE et al., 1986; DEN BROK & SPIERS, 1991). On the one hand, ductile deformation is enhanced by the presence of at least some amounts of a hydrous fluid, an effect known as hydrolytic weakening (GRIGGS & BLACIC, 1965), although high confining pressures do not necessarily give evidence for ductile deformation (DEN BROK, 1992). On the other hand such high fluid pressures trigger brittle deformation of a rock as a whole, and Coulomb style faults lead to cataclastic deformation. In most cases fluid inclusions are the only evidence of a paleofluid present at the time of deformation. These fluid inclusions preserve information on P-T conditions which prevailed during deformation and, in many cases, also on mineral reactions that took place during deformation and metamorphism. Recently, fluid inclusion studies have also been applied to solve tectonic problems such as reconstructing the exhumation history of geological units and fault zones (e. g. HODGKINS & STEWART, 1994).

The purpose of our fluid inclusion studies was to gain information about the fluid regime predominant during deformation history of the strike-slip fault system. The advantage of fluid inclusion thermobarometry is that successive entrapment of fluid generations may be correlated with appropriate deformation phases and each of the individual fluid generations define a specific deformation event. This is based on the assumption that secondary fluid inclusions trapped either within trails which opened in direction of smallest principal stresses, sub-parallel to highest principal stress, or along conjugate fracture systems. Therefore, orientation of FI trails can be correlated to the general deformation regime during syntectonic entrapment. Deformation related changes in fluid composition and in fluid density from early deformed host rocks to late-tectonic extension gashes provided the reconstruction of clockwise P-T paths for two strike-slip faults. The combination of microthermometric analyses on fluid inclusions with mineral rheology reveals not only the P-T conditions of strike-slip faulting but also information on the exhumation history of the two shear zones.

In most cases interpretations of microstructural data, including observations of mineral behaviour, the development of preferred crystallographic orientations, knowledge of active glide systems, and knowledge of deformation and annealing mechanisms, which are important tools for evaluating conditions under which rocks might have been deformed, can only be suggested on the basis of far-reaching assumptions. A combination of these data with investigations on fluid inclusions which were trapped during or after major tectonic events with petrographic observations often give a very consistent picture.

In this paper we present a model for the formation of the conjugate shear zones within the southern Bohemian Massif. Structural and textural data are linked with microthermometry of fluid inclusions.

2. Geological setting

The southern and central parts of the Bohemian Massif are formed by the Tepla-Barrandian Zone, the Moldanubian Zone and the Moravo-Silesian (or Moravian) Zone (Fig. 1).

The *Tepla-Barrandian Zone* is composed of metasediments and metavolcanics of Proterozoic age which are overlain by Cambrian to Devonian sedimentary and volcanic rocks. In the *Moldanubian Zone,* which underlies the Tepla-Barrandian Zone, three main tectonostratigraphic units can be distinguished: (1) the Monotonous and Variegated Series, (2) the ophiolitic Letovice and Raabs complexes and (3) the Gföhl gneiss and granulite nappe representing the highest tectonic subunit (e.g. DALLMEYER et al., 1992; FRITZ & NEUBAUER, 1993; FRITZ, 1994; HÖCK et al., 1997). The *Moravo-Silesian* (or Moravian) *Zone* is composed from bottom to top of the Pleißing nappe and the Bittesch Gneiss. Locally the Moravian units are underlain by the late-Proterozoic Brno batholite (Fig. 1). For further general geologic relations within this area the reader is referred to FRASL (1970), FUCHS & MATURA (1976), THIELE (1976), SCHARBERT & FUCHS (1981), FRANKE (1989), MATTE et al. (1990), CARLSWELL (1991), SCHULMANN et al. (1991), DALLMEYER et al. (1992), and SCHULMANN et al. (1994).

According to FRITZ & NEUBAUER (1993), and FRITZ et al. (1996), the Moravo-Silesian Zone and the Variegated and Monotonous Series are part of a distinct Late Proterozoic terrane which is separated from an Early Palaeozoic terrane, consisting of the Gföhl and granulite nappes, by the ophiolitic

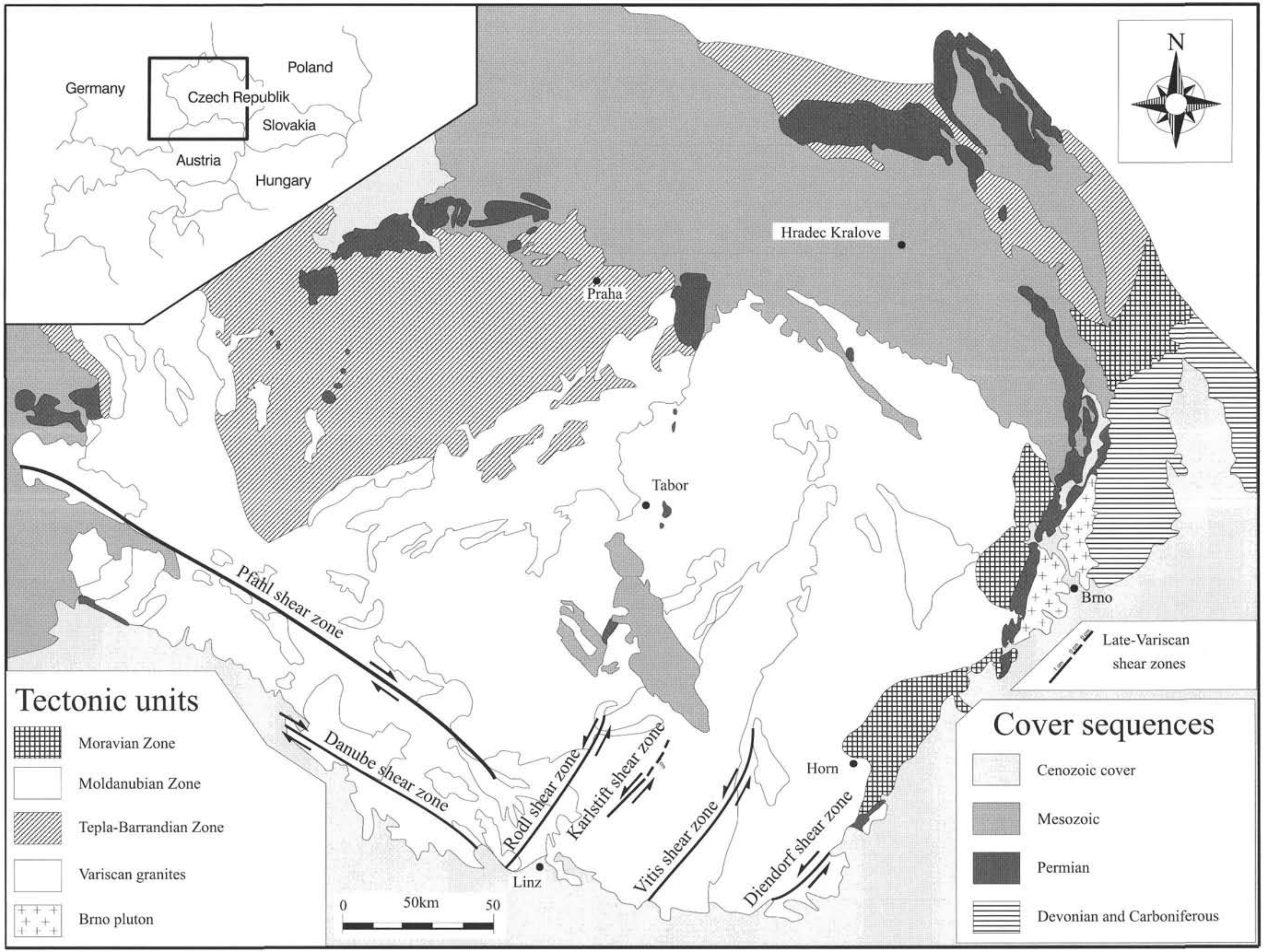


Fig. 1
Geological sketch map of the Southern Bohemian Massif (modified after FUSAN et al., 1967).

Letovice and Raabs units. The Moldanubian-Moravian boundary, as described by SUESS (1908, 1912), is interpreted as a deep crustal décollement which developed during NE-directed foreward propagation of thrusts (FRITZ, 1994).

Large parts of the Bohemian Massif include Late Paleozoic plutons (Fig. 1), e.g., the Rastenfelder granodiorite, the Weinsberger granite and the Freistadt granodiorite. U/Pb age data on monazite give post-orogenic intrusion ages of c. 330 to 300 Ma (Rastenberger granodiorite 323 ± 2 Ma; Weinsberg granite 318 ± 4 Ma; Freistadt granodiorite 302 ± 2 Ma; FRIEDL et al., 1993; KLOETZLI, 1993; KLOETZLI & PARRISH, 1996).

The southern part of the Bohemian Massif is crosscut by two sets of conjugate shear zones (Fig. 1), a NW-SE trending system with a dextral shear sense (Pfahl Shear Zone and Danube Shear Zone) and a NE-SW trending system with a sinistral shear sense (Rodl, Karlstift, Vitis and Diendorf Shear Zones). These shear zones are thought to have formed simultaneously during a late stage of the Variscan orogeny (WALLBRECHER et al., 1990, 1991; BRANDMAYR et al., 1993; BRANDMAYR et al., 1995) based on the indenter model of TAPPONNIER & MOLNAR (1976). An upper age limit for the shear zone formation is given by the intrusion ages of the Late Variscan granites (e.g., SCHARBERT, 1987; FRIEDL et al., 1993; KLOETZLI, 1993; KLOETZLI & PARISH, 1996), since all shear zones crosscut various granite bodies. Lower age limits for the major shear deformation are in fact much more difficult to give since even recent activity has been recorded in the Diendorf Shear Zone (SCHEIDEGGER, 1976).

3. Microstructures and textures

Textures of the fault-related rocks were studied using an optical microscope. Quartz and feldspar are the dominant minerals in all of the rocks studied, volumetrically as well as for the rheological behaviour during deformation.

The host rocks affected by shearing are anatectic and diatectic gneisses (e.g., perlgneiss, perldiatexite), migmatites, and late Variscan granitoids. Typical mineral assemblages in the high temperature metamorphic rocks are: Pl + Qtz + Bt ± Ms or Qtz + Kfs + Pl + Bt + Sil + Crd. The textures are discussed in detail in WALLBRECHER et al. (1990) and BRANDMAYR et al. (1995).

3.1 Pfahl Shear Zone

The Pfahl Shear Zone exhibits mylonites which are strongly overprinted by subsequent brittle deformation. As one of the major dextral shear zones the foliation dips steeply to the NE with a subhorizontal stretching lineation.

On a macroscopic and a microscopic scale, the mylonites are developed as highly deformed rocks comprising a fine-grained matrix flowing around large feldspar clasts (Fig. 2a). The feldspar grains generally underwent brittle deformation although remnants of recrystallized feldspar grains can sometimes be observed, pointing to an earlier high temperature deformation stage. Fig. 3a shows a large feldspar grain which partly recrystallized due to subgrain rotation recrystallization. Quartz most commonly occurs as recrystallized grains forming bands which are several millimetres thick alternating with biotite-rich layers. Crystallographic preferred orientations of quartz grains show, in most cases, clusters arranged in the vicinity of the Z-axis in the [XZ] kinematic frame, although the X-axis parallel clustering also has been observed, (WALLBRECHER et al., 1990, BRANDMAYR et al., 1995).

3.2 Danube Shear Zone

The Danube Shear Zone actually comprises two parallel dextral shear zones with completely different microstructural and petrographic features (cf. WALLBRECHER et al., 1990; PLATZER & WALLBRECHER, 1993).

One of the shear zones comprises high temperature amphibolite facies mylonites with recrystallized equidimensional quartz and feldspar grains (Fig. 3b) forming bands which are several millimetres thick and orientated parallel to the foliation. Quartz fabric analysis reveals crystallographic preferred orientations with <c>-axes arranged in oblique single girdles and clusters at ca. 45° to the [XZ]-kinematic plane (WALLBRECHER et al., 1990).

The other shear zone is developed as a low-temperature shear zone (Fig. 2b) formed within greenschist-facies conditions and dominated by a very pronounced S-C-fabric. Petrographically the rocks are dominated by lower temperature mineral assemblages with high amounts of chlorite. Whereas the feldspar grains underwent entirely brittle deformation, the quartz grains suffered ductile deformation, as can be seen by the occurrence of equidimensionally recrystallised grains. Quartz <c>-axes plot either as oblique single girdles or as single clusters between 0 and 45° to the [XZ] kinematic frame (WALLBRECHER et al., 1990).

3.3 Rodl Shear Zone

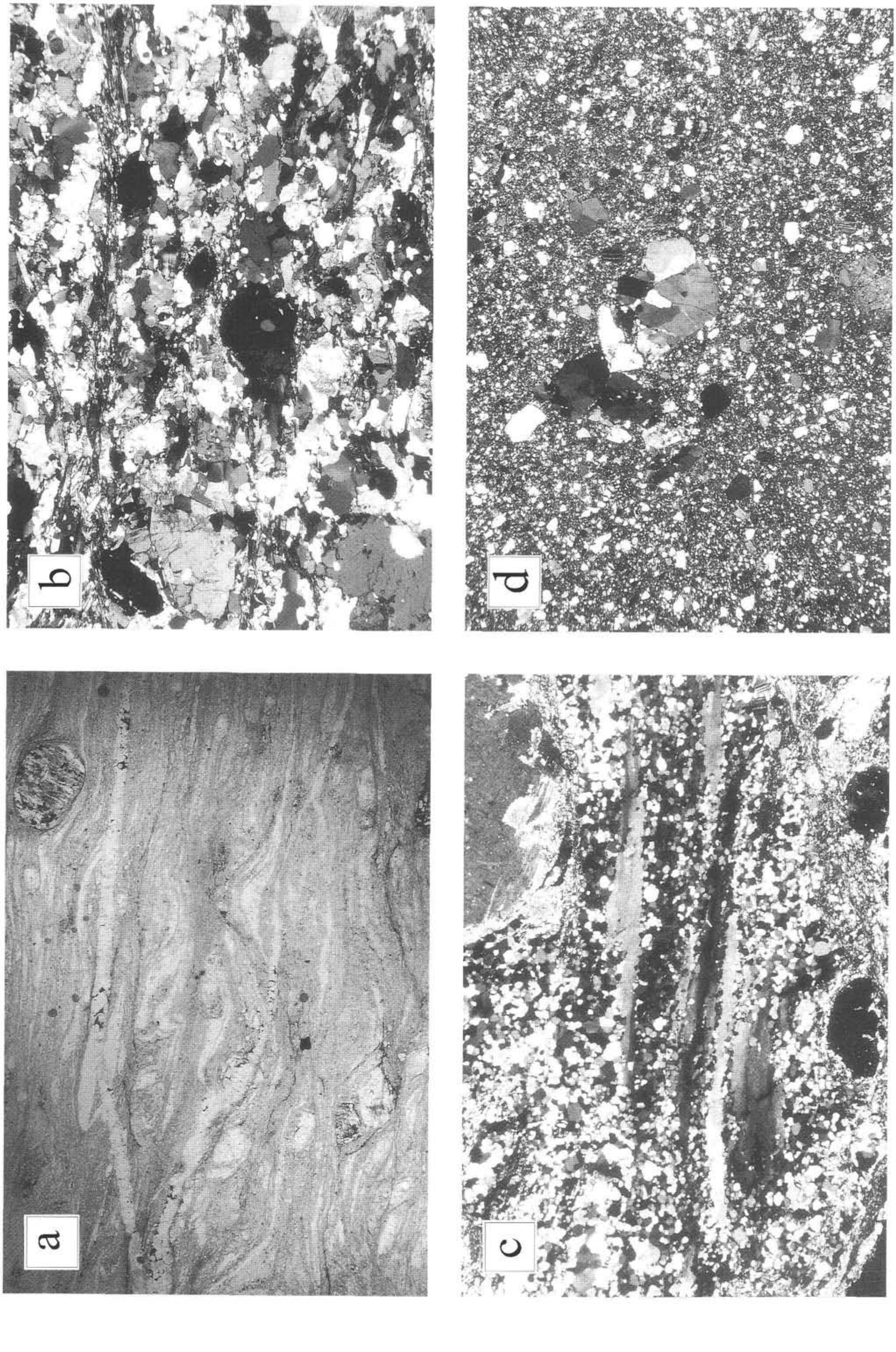
The Rodl Shear Zone is formed by mylonites and protomylonites with foliations dipping steeply to the NW and a subhorizontal mineral stretching lineation (cf. HANDLER et al., 1991; WALLBRECHER et al., 1990). Typical macroscopic features are asymmetric feldspar augen and a pronounced S-C-fabric, indicating sinistral shear.

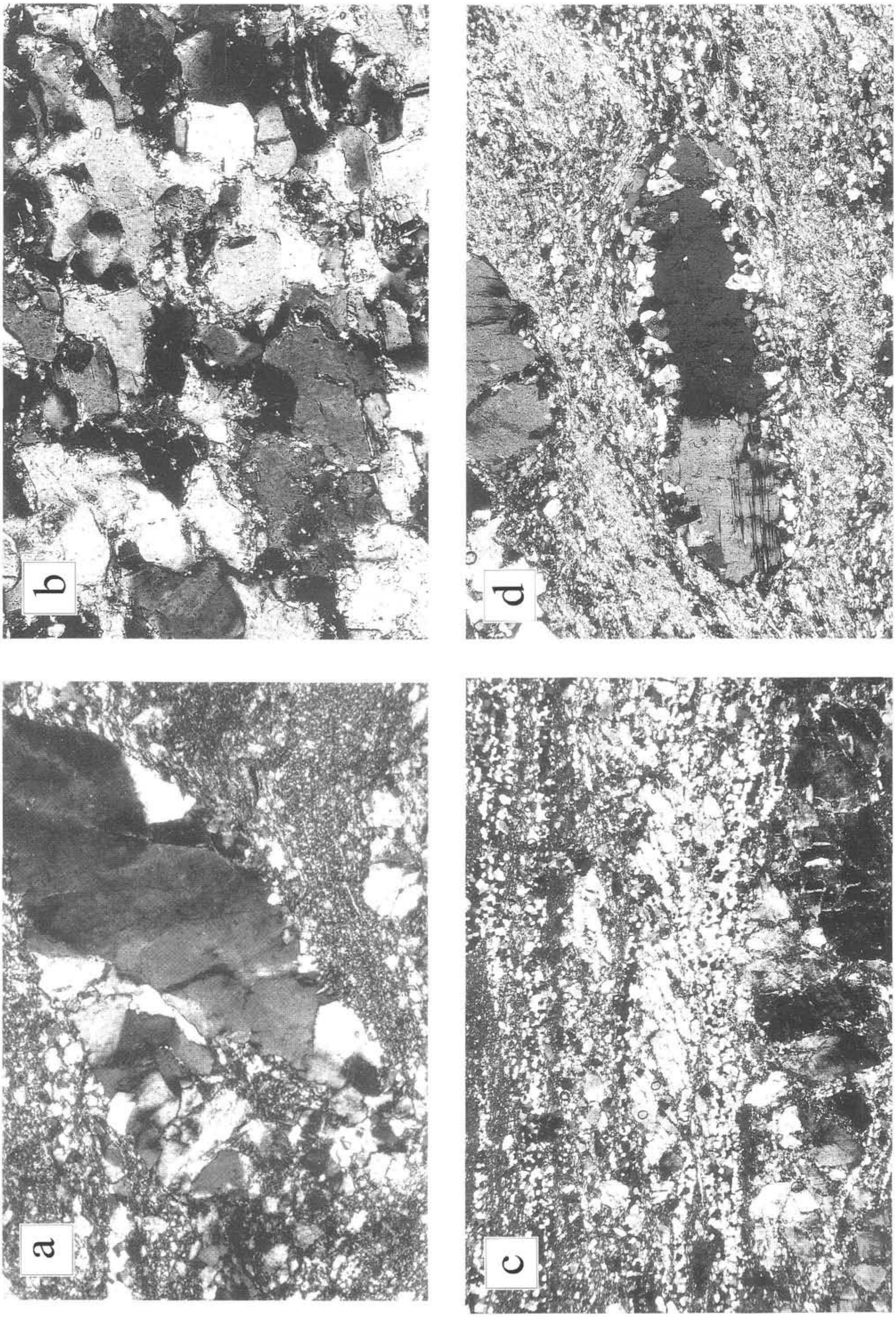
All feldspar grains underwent brittle deformation (Fig. 3c). Synthetic and antithetic low-angle normal microfaults and quartz-filled low angle normal microfaults are common features. In high strain domains feldspar is either completely transformed to quartz and sericite or arranged as feldspar fragments in thin layers parallel to the macroscopic foliation.

Quartz grains in low strain domains, especially at the margin of the shear zone, show an undulous extinction and some subgrain formation. With increasing strain intensity quartz begins to recrystallize along the rims of large subgrains. In the domains which suffered the highest strain, the subgrains, if any, lie parallel to the foliation with length-width ratios of 5:1 or higher. These strongly deformed rocks show alternating layers of recrystallized, equidimensional quartz grains, layers of very fine grained quartz and feldspar, layers of brittely deformed K-feldspars, and layers almost entirely of phyllosilicates (Fig. 2c). The thicknesses of these layers range between 50 and 200 m, their lengths reach, in some cases, up to 5 cm.

Crystallographic preferred orientations of quartz show an arrangement of <c>-axes either in oblique girdles or clusters

Fig. 2 →
(a) Photomicrograph of a mylonite (Pfahl Shear Zone); large feldspar grains act as rigid bodies in a fine-grained matrix consisting of quartz, sericite and feldspar; width of view is 2,1 cm; plane polarized light (PPL). (b) Photomicrograph of a greenschist facies mylonite, Danube Shear Zone; width of view is 4,9 mm; crossed polarized light (CPL). (c) Photomicrograph of a highly deformed mylonite, exhibiting alternating layers of quartz-feldspar and phyllosilicates, Rodl Shear Zone; width of view is 4,9 mm; (CPL). (d) Photomicrograph of a cataclasite, Vitis Shear Zone; width of view is 8,5 mm; (CPL).




a
b
c
d

at 0 or up to 45° to the [XZ] kinematic frame (WALLBRECHER et al., 1990).

3.4 Karlstift Shear Zone

The Karlstift Shear Zone is dominated by protomylonites to orthomylonites (WISE et al., 1984) which were formed as a result of ductile deformation (cf. LOIZENBAUER et al., 1994). The rocks exhibit a well-developed foliation dipping to the WNW. The stretching lineation plunges gently to NNE. The mylonitic fabric is superimposed by low-temperature, brittle deformation. Especially the rocks in the marginal areas show slickensides and extensional fractures.

Microstructures in the mylonites of the Karlstift Shear Zone are dominated by ductile behaviour of quartz and a transitional behaviour of feldspar from brittle to semiductile deformation.

The deformed quartz grains show well-developed recrystallization features with 120° triple-point grain boundaries. Core-mantle textures and undulous extinction of recrystallized quartz grains also can be observed in the mylonites.

The deformation of feldspar is dominated by external rotation and fracturing of the grains. In the marginal areas of the clasts, feldspar often shows recrystallization features (Fig. 3d). Quartz and muscovite occur in pressure shadows of the rotated porphyroclasts. Most of the fractures are synthetic shear fractures or even pure extensional fractures. Mineral reactions of feldspar to mica and biotit to chlorite accompanied fracturing.

In the marginal areas of the Karlstift Shear Zone, where semiductile deformation predominates, these alteration processes of feldspar to mica and chlorite changed the rheological behaviour of the rocks from brittle to ductile. Here the ductile deformation was the result of early fracturing and subsequent cataclastic flow of feldspar and quartz combined with slip movements along planes which are outlined by newly grown micas. Similar deformation mechanisms are also described by EVANS (1990).

In the central parts of the shear zone, the ductile behaviour of the mylonites is due to crystal plasticity and diffusional mass transfer within quartz. In these parts of the fault, feldspar is deformed by rotation and fracturing, again accompanied by alteration to mica. Some feldspar grains exhibit recrystallization features, which indicate the onset of plastic deformation of feldspar.

3.5 Vitis Shear Zone

The Vitis Shear Zone strikes parallel to the Karlstift Shear Zone at a distance of about 30 km to the east and mainly transects the Weinsberg granite. Cataclastic deformation was the dominant deformation mechanism. Foliation and lineation are developed only weakly or, in most cases, not at all. In narrow zones we also can find mylonites showing a well-defined steeply WNW dipping foliation and a stretching lineation plunging gently to NNE. The older fabric is superimposed by a later deformation which shows slickenside features and extensional veins filled with quartz and chlorite.

Cataclastic microstructures are predominant in the Vitis Shear Zone (Fig. 2d). The microfabric is defined by quartz and feldspar porphyroclasts lying in a fine-grained matrix of quartz, feldspar, mica, and chlorite. The quartz grains show undulous extinction indicating intracrystalline slip and contain many fluid inclusion trails which reflect healed microcracks. Feldspar was deformed by fracturing and kinking. The brittle deformation of feldspar was again accompanied by alteration of feldspar to mica and biotite to chlorite.

The cataclasites were formed as a result of brittle deformation of quartz and feldspar clasts from Weinsberg granite. Progressive deformation culminated in the formation of protocataclasites to cataclasites (WHITE, 1982). Intra- and intergranular micro-cracks which are filled with feldspar microclasts and mica are common. They suggest intense alteration of feldspar to mica under the presence of water-rich fluid. A close spatial relationship of fluid inclusion trails to the orientation of micro-fractures suggests that this fluid probably played an important role to fracture propagation and, therefore, to brittle deformation of the Weinsberg granite.

In narrow zones of the Vitis Shear Zone fault-related rocks exhibit ductile deformation. The deformation mechanism which is responsible for the formation of these mylonites is low-temperature crystal plasticity and grain boundary migration of quartz likely under stress conditions which were lower than that prevailing during the formation of the cataclasites.

3.6 Diendorf Shear Zone

The Diendorf Shear Zone is the easternmost shear zone in the southern Bohemian Massif and consists of rocks which underwent mainly brittle deformation. Sometimes a transition to semiductile behaviour had been observed. The protoliths were gneisses and granulites.

An older fabric, formed under high temperature conditions is superimposed by a younger one which exhibits extension cracks parallel to the schistosity and brittle deformation of quartz and feldspar clasts. Quartz was deformed mainly by brittle deformation but sometimes also shows undulous extinction. Because of the rheological behaviour of quartz, the cataclasites must have been deformed under temperature conditions which are near or below that necessary for recovery processes in quartz approximately at 300°C (VOLL, 1976). Feldspar was deformed by fracturing and kinking and exhibits the same mineral reactions as mentioned above.

4. Fluid inclusion studies

To get more detailed information about the P-T conditions that prevailed within the shear zones, fluid inclusions were studied from samples of the Karlstift Shear Zone and of the Vitis Shear Zone. Quartz is the host mineral for all fluid inclusions studied. The size of the fluid inclusions varies from 5 μm to 12 μm. Most of the inclusions show slightly rounded to irregular shapes, negative crystal shape is rare. Since the fluid inclusions occur mainly in trails crossing the grain boundaries, they are interpreted as secondary fluid inclusions (ROEDDER, 1984). Microthermometric measurements were made on a Chaixmeca heating/freezing stage. In both shear zones aqueous fluid inclusions with low salinity are predominant. CO_2-H_2O-NaCl inclusions occur only in younger, cross-cutting quartz veins. The salt concentration in all fluid inclusions studied is below 10 wt.%. At such low concentrations the salt

← Fig. 3
(a) Large feldspar grain, which recrystallized along the rim, possibly due to subgrain rotation recrystallization; Pfahl Shear Zone; width of view is 5,7 mm; (CPL). (b) Feldspar and quartz recrystallization, Danube Shear Zone ; width of view is 2,8 mm; (CPL). (c) Bookshelf structure of a large feldspar grain, Rodl Shear Zone; width of view is 5,7 mm; (CPL). (d) Feldspar grain, which recrystallized weakly along its rim, Karlstift Shear Zone; width of view is 5,7 mm; (CPL).

Table 1
Fluid inclusion data from the Karlstift Shear Zone. All fluid inclusions are two-phase water-rich inclusions with a low salinity. Density values were calculated using equations from BROWN & LAMB (1989), and BROWN (1989). Tm = temperature of last melting; Th = homogenization temperature; salt concentration is given in wt.% of NaCl-equivalent.

host rocks	Tm [°C]	NaCl-equiv. [wt. %]	Th [°C] range	Density [g/cm³] range
mylonite	-5.9 to -0.0	average 4.5	170-220	0.884-0.920
semiductile rock	-5.4 to -0.4	average 5.1	180-230	0.940-0.962
younger quartz	-0.6 to -0.0	average 0.5	220-340	0.669-0.817

Table 2
Fluid inclusion data from the Vitis Shear Zone. Fluid inclusions are water rich with a low salinity. All fluid inclusions occur as two-phase fluid inclusions. Density values were calculated using equations from BROWN & LAMB (1989), and BROWN (1989). Tm = temperature of last melting; Th = homogenization temperature; salt concentration is given in wt.% of NaCl-equivalent.

host rocks	Tm [°C]	NaCl-equiv [wt. %]	Th [°C] range	Density range
Weinsberg granite	-2.3 to -0.2	Average 1.5	179-329	0.767-0.886
Cataclasites	-4.8 to -0.7	Average 4.0	170-230	0.866-0.929
Syntectonic veins	to -0.2	Average 4.0	170-240	0.875-0.918
late-tectonic quartz	-5.4 to -3.6	Average 7.0	160-370	0.923-0.943

chemistry does not dramatically influence the calculated density values of fluid inclusions (POTTER, 1977; POTTER et al., 1978). Therefore, we calculated the isochores for all inclusions as $NaCl_{equiv.}$, although some of the solutions also contain small amounts of KCl and $Fe/MgCl_2$, as indicated by the eutectic temperatures of -22.8°C and of -35°C to -40°C, respectively (see BORISENKO, 1977; CRAWFORD, 1981). Especially in the vicinity of biotite which is altered to chlorite, $NaCl\text{-}Fe/MgCl_2\text{-}H_2O$ inclusions are common. All aqueous fluid inclusions studied show homogenization into the liquid state.

4.1 Fluid inclusion data of the Karlstift Shear Zone

In the Karlstift Shear Zone fluid inclusions were studied in quartz grains that occur within the high temperature *mylonites*, within the *semiductile rocks*, and within later *extensional quartz veins* (see Table 1).

Nearly all quartz grains within the mylonites are recrystallized and hence poor in fluid inclusions. A few quartz grains appear within feldspar clasts and were protected from later deformation and recrystallization. Many of the fluid inclusions trapped within these protected quartz grains trail subparallel to extensional cracks

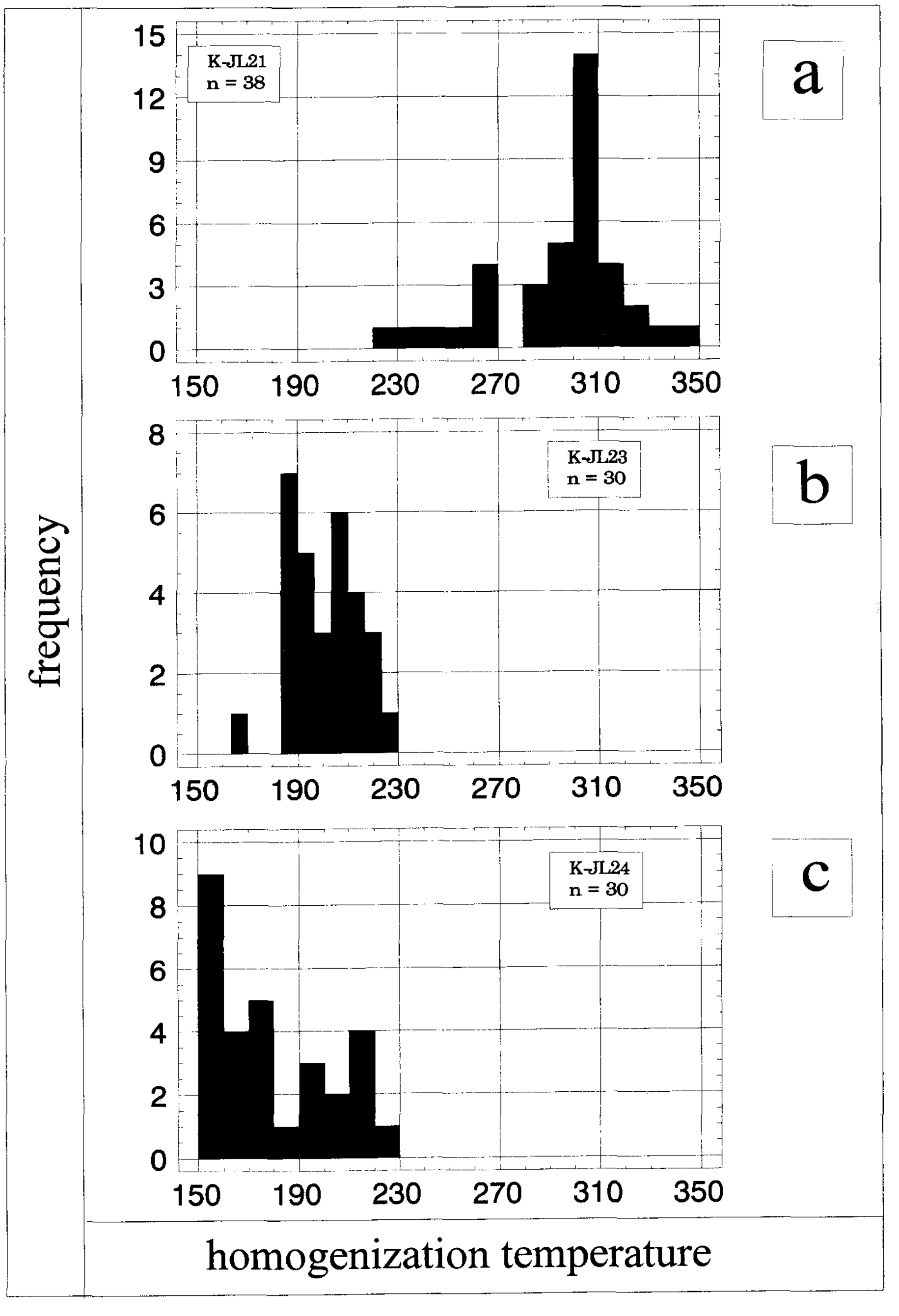


Fig. 4
Frequency histograms of the homogenization temperatures (T_h) of fluid inclusions in the Karlstift Shear Zone. a) Inclusions within the extensional quartz veins show a well-defined peak at 300°C. b) T_h of fluid inclusions within the high temperature mylonites show a peak at c. 180°C. c) Fluid inclusions within the semiductile rocks have a Th peak at approximately 150°C. n = number of measurements.

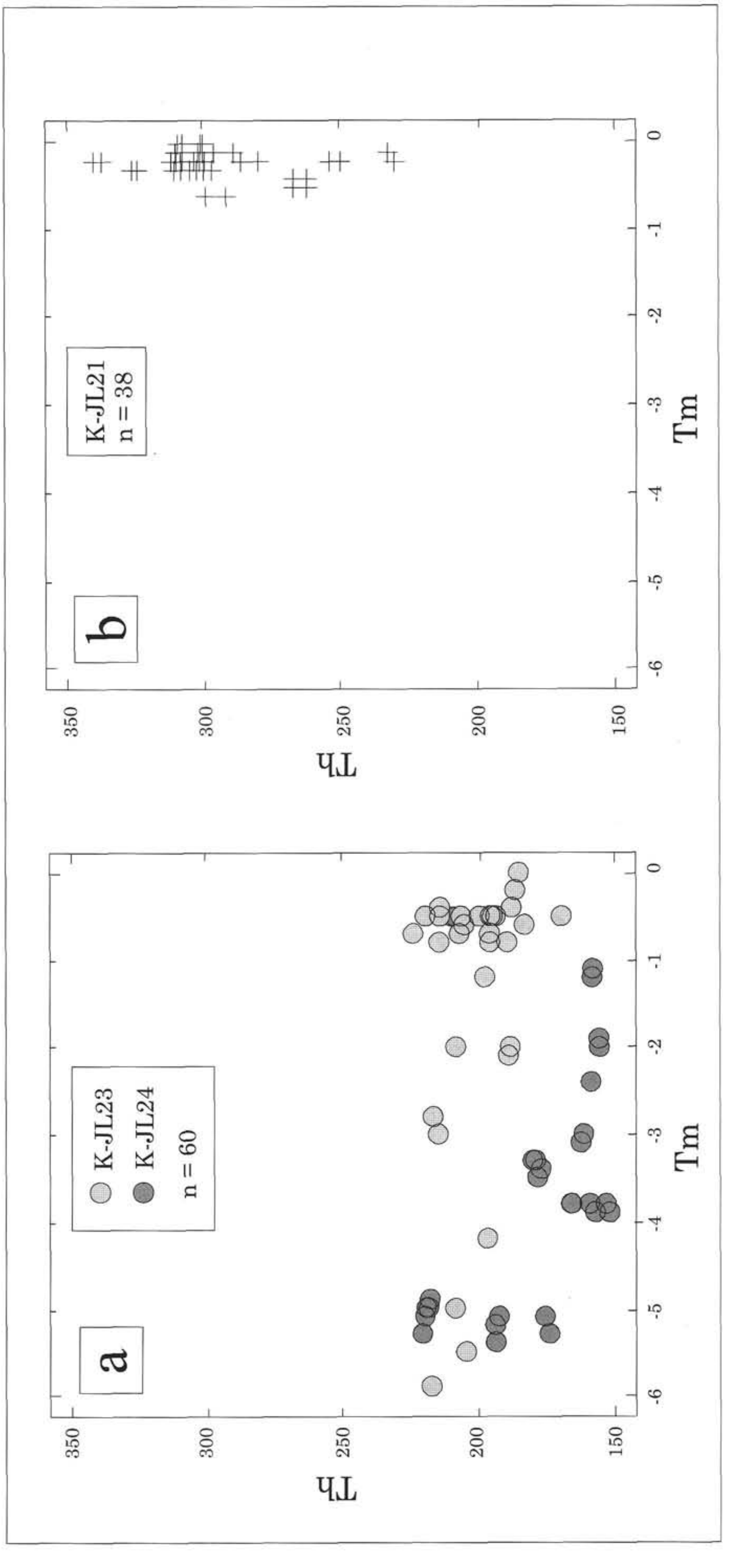


Fig. 5
Melting temperatures (T_m) plotted against homogenization temperatures (T_h) of the aqueous brine inclusions within the Karlstift Shear Zone. a) T_m-T_h-values of the mylonites (K-JL23) and of the semiductile rocks (K-JL24) are shown. b) Values of the extensional quartz veins (K-JL21) are illustrated.

that occur in feldspar clasts. Some of the trails are oriented parallel to the external foliation. The salt concentration varies from nearly pure water to 8.9 wt.%. The salt content is higher in quartz grains which occur near mica-filled cracks within feldspar clasts. Homogenization temperatures range between 170°C and 220°C (Figs. 4, 5). The density of the fluid inclusions varies between 0.88 g/cm³ and 0.92 g/cm³ according to their salt concentrations and homogenization temperatures (Table 1 and Fig. 10).

Fluid inclusions in quartz grains within *semiductilely deformed* rocks show density ranges between 0.94 and 0.96 g/cm³ (Table 1). Fluid inclusion trails are subparallel or inclined with angles between 30° to 40° to external foliation. The salt concentration varies between 1.8 wt.% and 8.4 wt.% whereby fluid inclusions with lower homogenization temperatures and higher densities show a lower salt concentration than inclusions with higher homogenization temperatures and lower densities (Fig. 6).

Fluid inclusions from *extensional quartz* veins have low densities and are very poor in salt concentration (Figs. 4, 5). Most of the fluid trails parallel the extensional gashes. Homogenization temperatures of the water-rich inclusions are high; they vary between 220°C and 340°C. Three-phase fluid inclusions containing H_2O-CO_2-NaCl are also common in these quartz veins.

4.2 Fluid inclusion data of the Vitis Shear Zone

The Vitis Shear Zone mainly transects the Weinsberg granite, which was the protolith for all fault-related rocks within this fault zone that we studied. In order to get information about the chemical and physical changes that took place during deformation, fluid inclusions were studied from *undeformed Weinsberg granite,* from *fault-related rocks,* and from late tectonic *extensional quartz veins* (see Table 2).

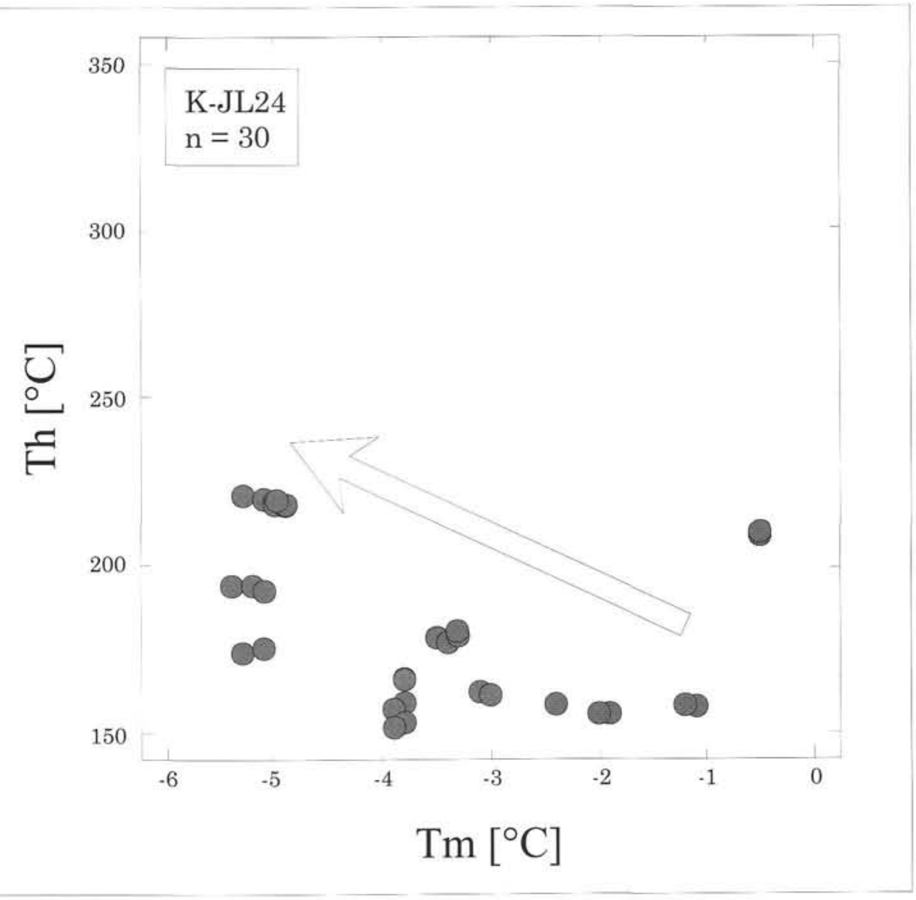


Fig. 6
White arrow indicates the increase of salt concentration (= decreasing Tm) with decreasing density (= increasing Th). Sample from semiductile rocks of the Karlstift Shear Zone. n = number of measurements.

Fluid inclusions within the *undeformed Weinsberg granite* contain only a small amount of salt (from 0.3 wt.% to 3.8 wt.% $NaCl_{equiv.}$). Homogenization temperatures range between 179°C and 329°C (Figs. 7, 8). Orientation of the fluid trails is irregular.

In the *cataclasites* and *syntectonic quartz veins* fluid inclusions show a higher salt content (ranging from 1.2 wt.% to 7.5 wt.%) compared with that of the protolith. The homogenization temperatures of the fluid inclusions in both rock types show a peak at 215°C (Figs. 7, 8). The orientation of the fluid inclusion trails in the cataclasites is variable. Within the syntectonic quartz veins, the trails are oriented subparallel to each other with an angle of about 30° to the main slip direction of the Vitis Shear Zone.

In *late-tectonic quartz veins* two generations of aqueous fluid inclusions can be distinguished. One generation exhibits low homogenization temperatures ranging between 170°C and 280°C (Figs. 7, 8) and a high amount of salt (5.8 wt.% to 8.4 wt.%). The second generation of aqueous fluid inclusions shows very high homogenization temperatures of about 360°C with a low salt concentration (below 1 wt.% $NaCl_{equiv.}$). Three phase fluid inclusions containing H_2O-CO_2-NaCl are also common in these quartzes.

5. Discussion

5.1 Microstructures and textural investigations

A large variety of microstructures of both quartz and feldspar are developed in these major shear zones.

Feldspar recrystallization can be observed in the Pfahl, Danube and Karlstift Shear Zones. In all the other shear zones feldspar grains underwent brittle deformation. According to VOLL (1976) and TULLIS & YUND (1980, 1987) feldspar recrystallization is assumed to take place only at temperatures above approximately 450-500°C. Therefore, such temperatures must have prevailed at some stages of the deformation in the Pfahl, Danube and Karlstift Shear Zones.

Quartz recrystallized in the Pfahl, Danube, Rodl, Karlstift and locally in the Vitis Shear Zones. No evidence for recrystallization processes can be found in the Diendorf Shear Zone. The temperature necessary for recrystallization of quartz is thought to be ca. 300°C (VOLL, 1976; TULLIS & YUND, 1980).

The types of crystallographic preferred orientations of quartz-rich mylonites measured vary considerably from shear zone to shear zone. Quartz crystallographic preferred orientations are thought to reflect the dominant glide system. The activation of a certain glide system is dependent on critical resolved shear stress on the one hand and temperature on the other hand (LISTER et al., 1978; LISTER & PATERSON, 1979; LISTER & HOBBS, 1980; LISTER & DORNSIEPEN, 1982; HOBBS, 1985). Therefore we used crystallographic preferred orientations as an indicator for temperatures during shear zone activity.

In both the Pfahl and the Danube Shear Zones [Z]-parallel <c>-axis maxima were observed. Such patterns are assumed to reflect the activation of prism <c> glide active only at temperatures above 650°C (MAINPRICE et al., 1986). Apart from these patterns, other crystallographic preferred orientations measured in these two shear zones and in the Rodl Shear Zone indicate rhomb-gliding and basal <a> gliding. Mylonites of the Karlstift and Vitis Shear Zones show only crystallographic preferred orientations which indicate basal <a> glide. The Vitis Shear Zone and the Diendorf Shear Zone are "cooler" strike-slip zones; no plastic deformation of quartz can be found. Therefore, temperatures must have been close to 300°C or lower.

5.2 Fluid inclusion data

All fluid inclusions in both the Vitis Shear Zone and in Karlstift Shear Zone, are dominated by water rich fluids with a low amount of salt. The salt composition depends on the mineral reactions that took place during the deformation. Therefore, H_2O-NaCl-KCl inclusions are common because of the reaction from Na/K feldspars to muscovite and to quartz. Fluid inclusions within quartz grains occurring near biotite which altered to chlorite by retrograde metamorphism contain NaCl-(Fe/Mg)Cl_2-H_2O solutions. All these reactions need a water rich fluid. K^+, Na^+ and $(Mg, Fe)^{+2}$ ions are released and partly trapped as salt solutions within the quartzes (Table 3).

Table 3
Reported mineral reactions which are observed within the rocks of the shear zones, too. Note that all reactions need a water-rich fluid.

Mineral reaction	Reference
3 microcline+2H+=muscovite+6 SiO_2+$2K^+$	EVANS (1990)
3 microcline+H_2O=muscovite+6 quartz+$2K^+$+O^{-2} 3 albite+H_2O+K^+=muscovite+6 quartz+ Na^++O^{-2} 2 biotite+$3H_2O$=chlorite+3 quartz+$2K^-$+$(Mg, Fe)^{+2}$+O^{-2}	CRAWFORD et al. (1979)

The amount of the salt concentration is related to the evolutionary stage of deformation. It increases during deformation and during retrograde metamorphism. Evidence for this is given by the increase of salt contents within fluid inclusions from undeformed Weinsberg granite (sample Vit-JL12) with about 1 wt.% $NaCl_{equiv.}$ to late tectonical extensional quartz veins (sample Vit-JL29) with more than 7 wt.% $NaCl_{equiv.}$ (Table 2). Assuming that fluid inclusions with higher densities were trapped at an earlier stage of retrograde metamorphism than those with lower densities, these reactions must also have taken place in the Karlstift Shear Zone, because the salt concentration from high density inclusions is lower than that from inclusions with lower density (Fig. 6). The assumed progressive entrapment of high density FIs to low density FIs is very likely since BÜTTNER & KRUHL (1997) and BÜTTNER (1997) describe a clockwise retrograde P-T path for the fault zones within the southern Bohemian Massif.

The water-rich fluid inclusions which occur within the extensional quartz veins of the Karlstift Shear Zone have very low salt concentrations and very high homogenization temperatures. Because the densities are low, these inclusions might have been trapped at a very high crustal level. Since the inclusions consist of nearly pure H_2O, this fluid must have been trapped independently from the salt richer fluid described above, or fluid mixing occurred. In any case, these fluid inclusions reflect a very late event of the Variscan deformation act.

In the Vitis Shear Zone similar fluid inclusions with high homogenization temperatures and low salt content occur within late extensional quartz veins. In these rocks we discriminate between two generations of inclusions (Fig. 9). A first generation, which is the older one, was trapped during greenschist-facies conditions, whereas the second generation was built under lower pressure conditions and might reflect a later tectonic event. Since the fluid inclusions trapped within the extensional quartz veins of both the Karlstift and the Vitis Shear Zone show similar properties (Fig. 9), they are interpreted to have been trapped during the same event, which is considered to represent a late stage of the Variscan strike-slip movement.

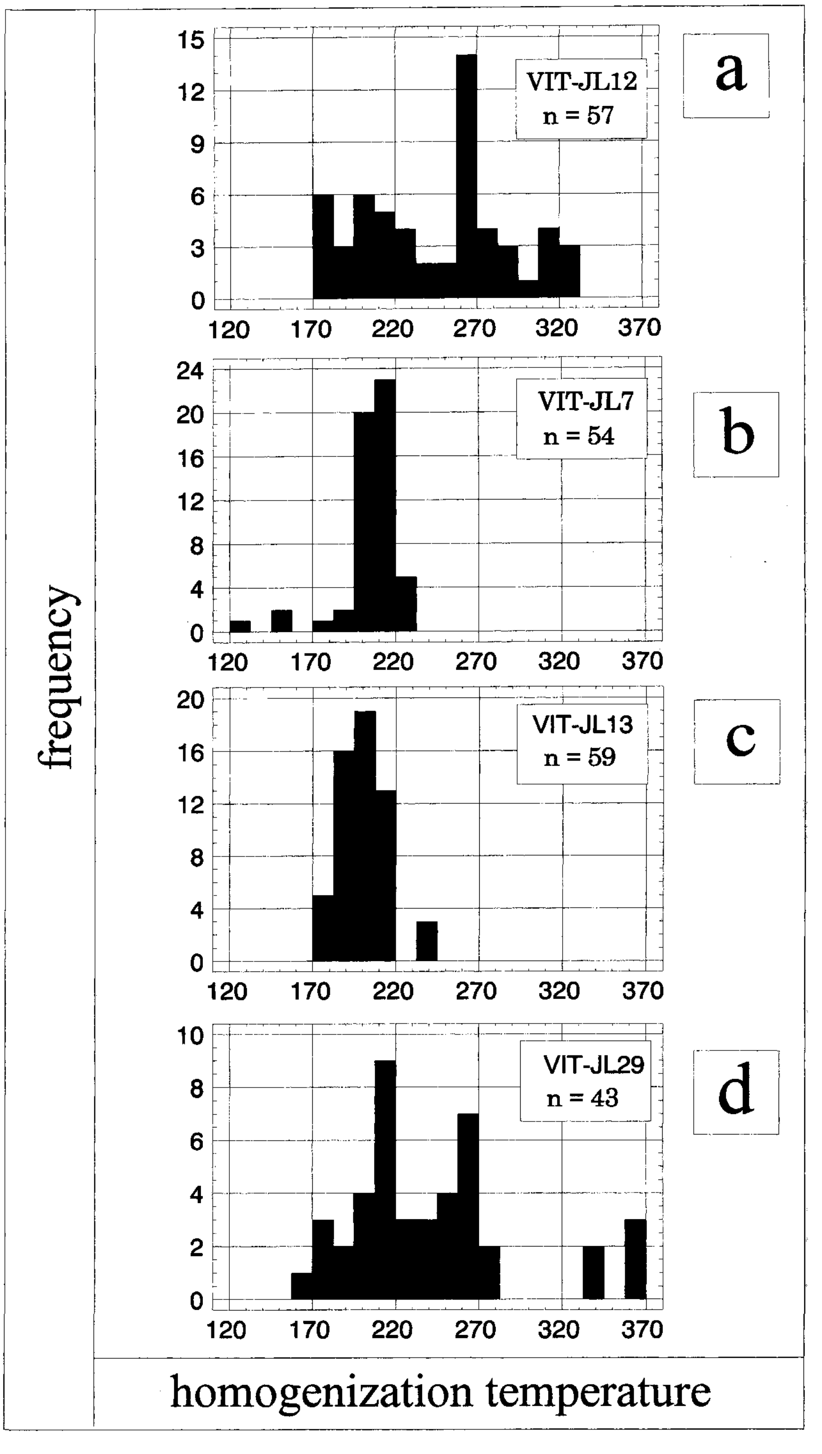


Fig. 7
Frequency histograms showing the homogenization temperatures (T_h) of the fluid inclusions occurring within the Vitis Shear Zone. a) Fluid inclusions within the undeformed Weinsberg granite show T_h ranging between 170°C and 330°C. (b) In the cataclasites fluid inclusions show a well defined maximum at about 220°C. c) T_h of fluid inclusions within the syntectonic quartz veins show a peak at 200°C. d) Fluid inclusions within the late tectonic quartz veins display two pronounced peaks, one at approximately 220°C and one at c. 270°C. A third peak is weakly defined at approximately 370°C. n = number of measurements.

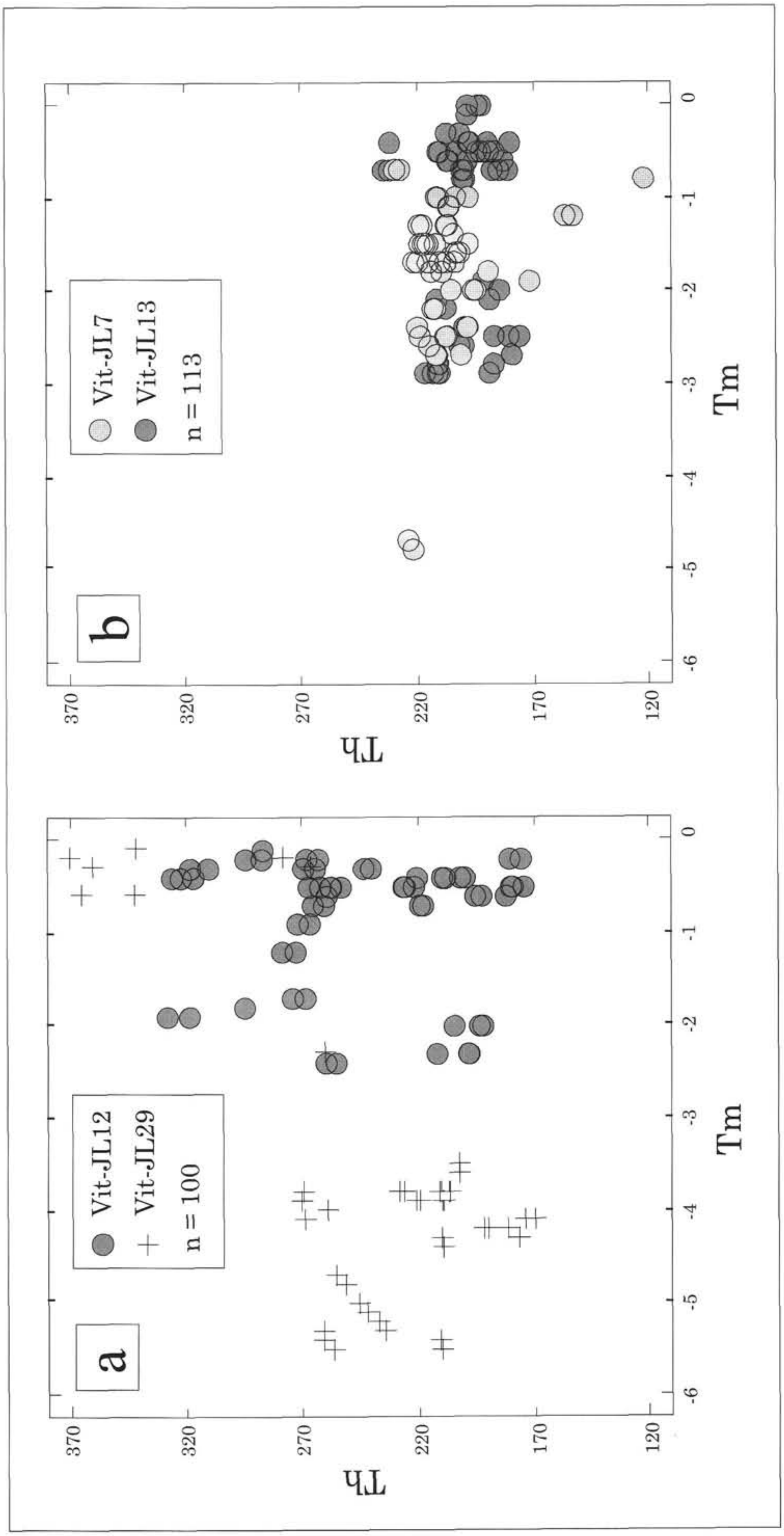
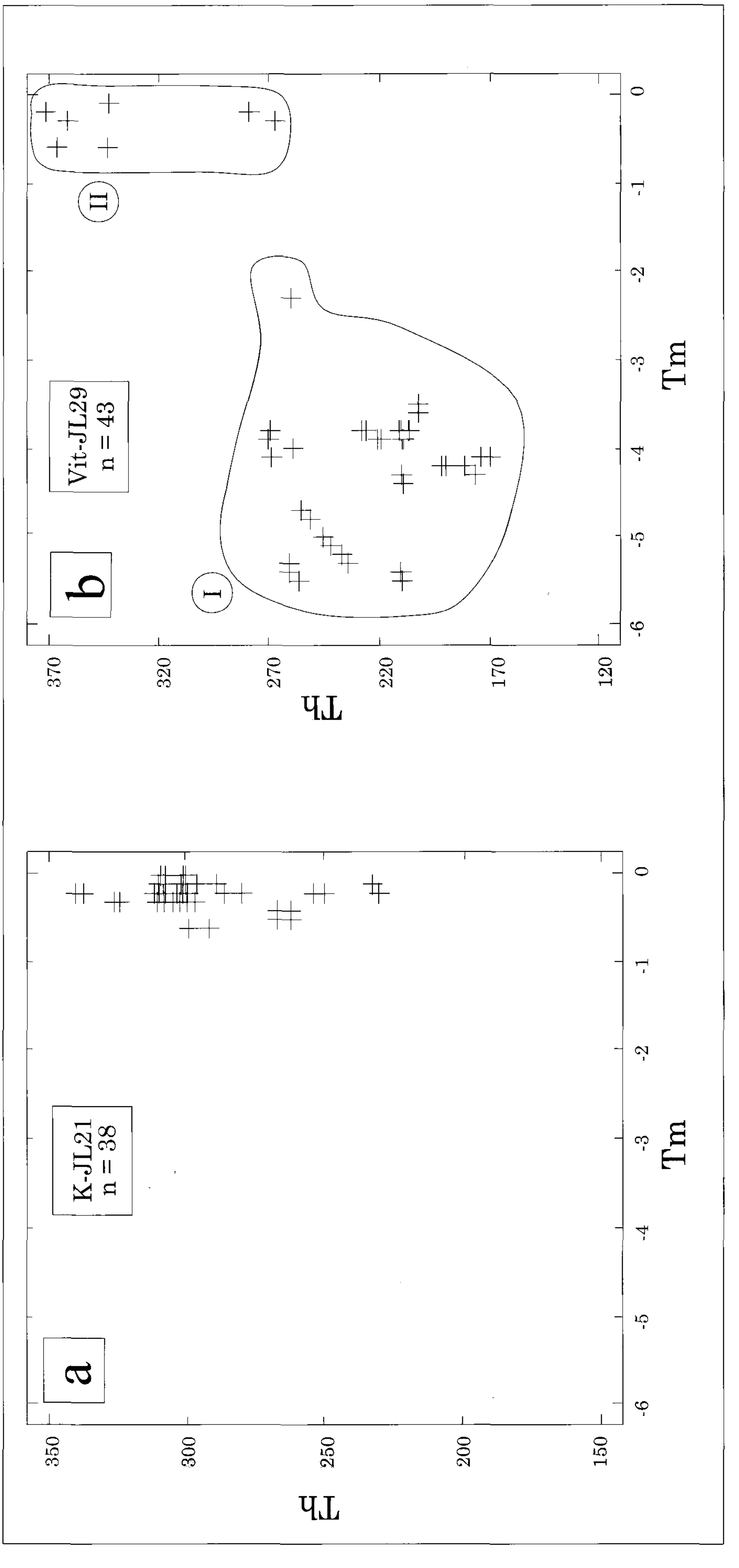


Fig. 8
Plot of melting temperatures (T_m) versus homogenization temperatures (T_h) of the aqueous brine inclusions within the Vitis Shear Zone. a) T_m-T_h-values of the of the undeformed Weinsberg granit (Vit-JL12) and late tectonic quartz veins (Vit-JL29). b) T_m-T_h-values of cataclasites (Vit-JL7) and fault related quartz veins (Vit-JL13).

We assume that inclusions with the highest densities must have been trapped during an early stage of retrograde metamorphism. Therefore, combining the isochores of the higher density fluid inclusions with the temperature data from microfabric analysis, we get the P-T conditions that prevailed during or immediately after peak metamorphism. In the Vitis Shear Zone pressures ranged between ~180 MPa and 260 MPa at estimated temperatures between 280°C and 320°C. In the Karlstift Shear Zone the pressures ranged between ~400 MPa and 450 MPa at temperatures between 400°C and 450°C (Fig. 10).

The pressure difference between the two shear zones indicates different crustal levels for the deformation. Fault-related rocks in the Vitis Shear Zone must have been initially formed at crustal depths of about 7 km, whereas those of the Karlstift Shear Zone should have formed at a depth of about 13 km (Fig. 11). The different crustal depths of shear faults suggest an asymmetric exhumation history for the Karlstift Shear Zone and for the Vitis Shear Zone. The fluid inclusions within the late tectonic quartz veins show homogenization temperatures higher than 300°C, which also indicates low pressures. Since these temperatures are minimal formation temperatures of the vein rocks and since they are similar to the formation temperatures of the fault related rocks, we expect that an isothermal decompression occurred during the exhumation of the cataclasites within the Vitis Shear Zone.

Fig. 9
T_m-T_h plot of the late tectonic quartz veins occurring within the Karlstift Shear Zone (a) and the Vitis Shear Zone (b). a) Tm-Th data of the Karlstift Shear Zone indicate low salinity and hight homogenization Temperatures. b) Because of their composition and their homogenization temperatures two generations of fluid inclusions are distinguished (I and II). Note the similar T_m-T_h values of fluid inclusions in a) and Type II fluids in b).



6. The model

A wide variety of pressure-temperature conditions of various shear zones in the southern Bohemian Massif can be derived from various microstructural investigations. Since "higher" temperature conditions are only evident in the westernmost Pfahl and Danube Shear Zones and in the Karlstift Shear Zone, strike-slip must have either taken place during earlier deformation stages or at deeper crustal levels. A model combining these aspects is presented here. It is based on the indenter model of TAPPONNIER & MOLNAR (1976) and TAPPONNIER et al. (1982), although other models, e.g., by ARTHAUD & MATTE (1977) and MATTE (1986) are also known.

As a result of large-scale northeastward directed transpression of an Early Paleozoic terrane (i.e., the Gföhl and granulite nappe of the Moldanubian) onto a Late Proterozoic terrane (i.e., the Moravo-Silesian and the Monotonous and Variegated Series), crustal thickening occurred in the internal parts of the orogen (Fig. 12a). After this main tectonic event, shear activity initiated on the dextral shear zone set of the Pfahl and Danube Shear Zones and in the sinistral Karlstift Shear Zone (Fig. 12b). Hereby, the lack of recrystallized feldspar grains should not be misinterpreted, since shear could also have taken place in the other shear zones, but high-temperature structures did not survive the subsequent deformation and metamorphic stages. At the onset of strike-slip movement, the shear zones were located at deep crustal levels, where temperatures were high enough to cause feldspar recrystallization and to enable prism <c>-slip in quartz. The higher temperatures may also have been caused by a mass of late-Variscan intrusions. Shearing then proceeded further to the east and began to affect both sets and led to the for-

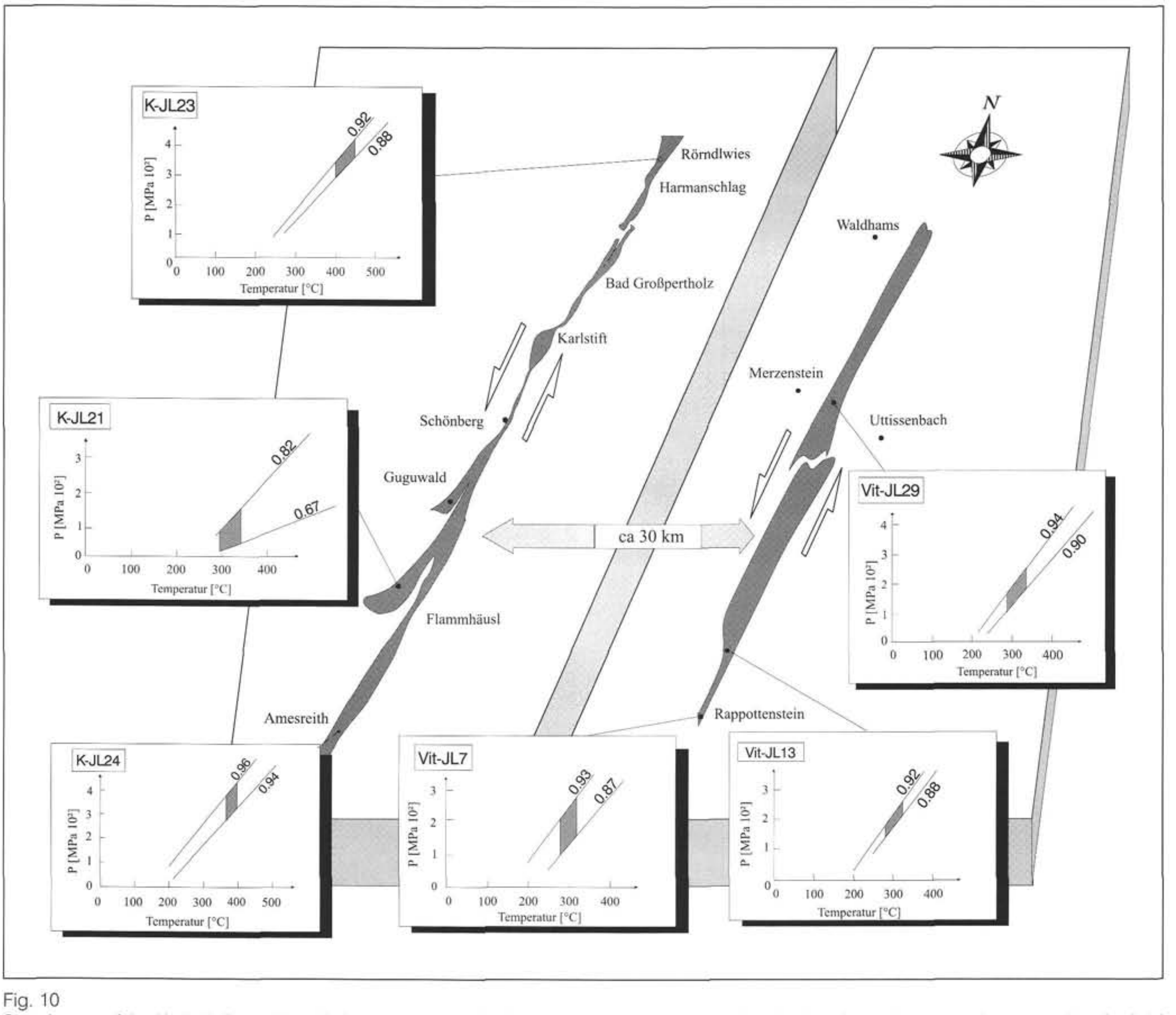


Fig. 10
Sketch map of the Karlstift Shear Zone (left one) and the Vitis Shear Zone (right one) indicating the locations where samples were taken for fluid inclusion studies. P-T plots of the fault related rocks occurring within Karlstift Shear Zone: mylonite (K-JL23), semiductile rock (K-JL24), late tectonic quartz veins (K-JL21) and of that one which occur within the Vitis Shear Zone: cataclasite (Vit-JL7), syntectonic quartz vein (Vit-JL13), late tectonic quartz vein (Vit-JL29 of generation I). Stippled squares illustrating the P-T conditions prevailed during deformation. These P-T values result by combining the isochores (mean and highest) and temperatures estimated from microfabric analyses.

mation of mylonites in all shear zones under greenschist-facies metamorphic conditions (Fig. 12c). $^{40}Ar/^{39}Ar$ dating of synkinematic sericite sampled in the Rodl and Danube Shear Zones gave plateau ages of about 290 Ma, which are interpreted to date cooling through the appropriate closure temperatures of 375 ± 25°C (BRANDMAYR et al., 1995). Locally, in the Vitis and Karlstift Shear Zones, cataclasites were formed under the presence of a water-rich fluid. At that time the Diendorf Shear Zone, consisting solely of cataclasites, was located at the highest crustal level. Shearing then propagated further to the north and opened the pull-apart basins of České Budějovice and Trebon, the Blanice, the Jihlava, and the Boskovice furrows as extensional basins in Riedl orientation (Fig. 13). In these basins, sedimentation began in Westphalian C and continued up to Autunian (Early Perm). Simultaneously, an asymmetric isostatic exhumation of the southern Bohemian Massif took place. Whereas the crust in the east (in the area of the Diendorf Shear Zones) and in the north (where sedimentation in the Permian basins took place) stayed more or less at the same crustal level without prominent exhumation and with minor erosion, the internal parts rose considerably. Erosion exposed the high temperature rocks of the western shear zones. Shearing continued in some parts during this process, overprinting the ductile fabric with brittle deformation.

7. Acknowledgements

This research was supported by the Austrian Science Foundation (FWF), Project No. S 4713 Geo. K. Stüwe and U. Schüssler as well as F. Neubauer and J. Kruhl contributed useful reviews of the manuscript and are gratefully acknowledged. We also thank H. Fritz (Graz) and H. Högelsberger (Vienna) for fruitful discussions.

References

ARTHAUD, F. & MATTE PH., 1977: Late Paleozoic strike-slip faulting in Southern Europe and Northern Africa: Result of a right lateral shear zone between the Appalachians and the Urals. Geol. – Soc. Amer. Bull., **88**, 1305-1320.

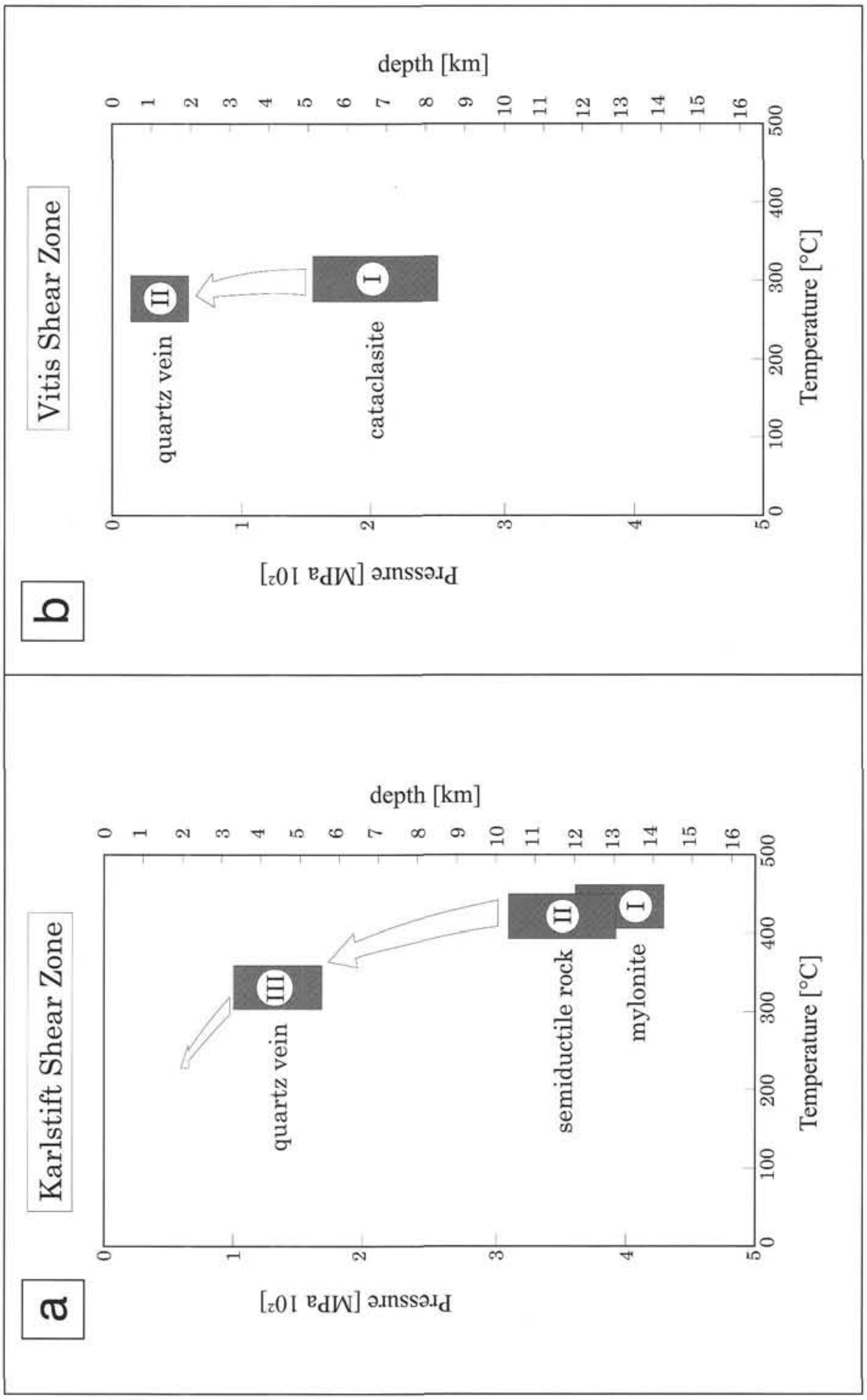


Fig. 11
Exhumation path for a) the Karlstift Shear Zone and b) for the Vitis Shear Zone. In both cases we interpret an isothermal decompression caused by rapid exhumation. Since the mylonites of the Karlstift Shear Zone were formed in a deeper crustal level than the cataclasites of the Vitis Shear Zone, the amount of exhumation of the two shear zones must have been different.

BLACIC J. D., 1975: Plastic-deformation mechanisms in quartz: The effect of water. – Tectonophysics, **27,** 271-294.

BORISENKO A. S., 1977: Study of the salt composition of solutions in gas-liquid inclusions in minerals by the cryometric method. – Soviet. Geol. & Geophys., **18,** 11-19.

BRANDMAYR M., HANDLER R., LOIZENBAUER J., PLATZER R. & WALLBRECHER E., 1993: Microstructural investigations on shear zones in the Southern Bohemian Massif: Evidence for different lithospheric levels and/or non-contemporaneous deformation? – Terra abstracts, Abstracts Supplement 2, **5,** 5.

BRANDMAYR M., DALLMEYER R. D., HANDLER R. & WALLBRECHER E., 1995: Conjugate shear zones in the Southern Bohemian Massif (Austria): Implications for Variscan tectonothermal activity. – Tectonophysics, **248,** 97-116.

BROWN P. E., 1989: FLINCOR: A fluid inclusion data reduction and exploration program: Second Biennial Pan-American Conference on Research on Fluid Inclusions, January 1989, Program with Abstracts, Blacksburg, Virginia Polytechnic Institute, 14.

BROWN P. E., & LAMB W. M., 1989: P-V-T properties of fluids in the system H_2O-CO_2-NaCl: new graphical presentations and implications for fluid inclusion studies. Geochimica et Cosmochimica Acta, **53,** 1209-1221.

DEN BROK S. W. J., 1992: An experimental investigation into the effect of water on the flow of quartzite. – Geologica Ultraiectina, **95,** 178 p.

DEN BROK S. W. J. & SPIERS C. J., 1991: Experimental evidence for water weakening of quartzite by microcracking plus solution-precipitation creep. – Journ. Geol. Soc. London, **148,** 541-548.

BÜTTNER, S., 1997: Die spätvariszische Krustenentwicklung in der südlichen Böhmischen Masse: Metamorphose, Krustenkinematik und Plutonismus. – Frankfurter Geowissenschaftliche Arbeiten, Serie A, Geologie-Paläontologie, **16,** 208 S., Frankfurt am Main.

BÜTTNER, S. & KRUHL, J. H., 1997: The evolution of a late-Varican high-T/low-P region: the southeastern margin of the Bohemian massif. – Geol. Rundsch., **86,** 21-38.

CARLSWELL D. A., 1991: Variscan high P-T metamorphism and uplift history in the Moldanubian Zone of the Bohemian Massif in Lower Austria. – Eur. J. Mineral., **3,** 323-342.

CRAWFORD M. L., FILER J. & WOOD C., 1979: Saline fluid inclusions associated with retrograde metamorphism.- Bull. Mineral., **102,** 562-568.

CRAWFORD M. L., 1981: Phase equilibria in aqueous fluid inclusions. In Hollister, LS and Crawford ML (eds.) Short Course in Fluid Inclusions: Applications to Petrology, Vol 6, Min. Ass. of Canada: 157-181.

DALLMEYER R. D., NEUBAUER F. & HÖCK V., 1992: Chronology of late Paleozoic tectonothermal activity in the southeastern Bohemian Massif, Austria (Moldanubian and Moravo-Silesian zones: $^{40}Ar/^{39}Ar$ mineral age controls. – Tectonophysics, **210,** 135-153.

EVANS J. P., 1990: Textures, deformation mechanisms, and the role of fluids in the cataclastic deformation of granitic rocks. In: KNIPE R. J. & RUTTER E. H. (eds): Deformation Mechanisms, Rheology and Tectonics. – Geol. Soc. Special Publication, **54,** 29-39.

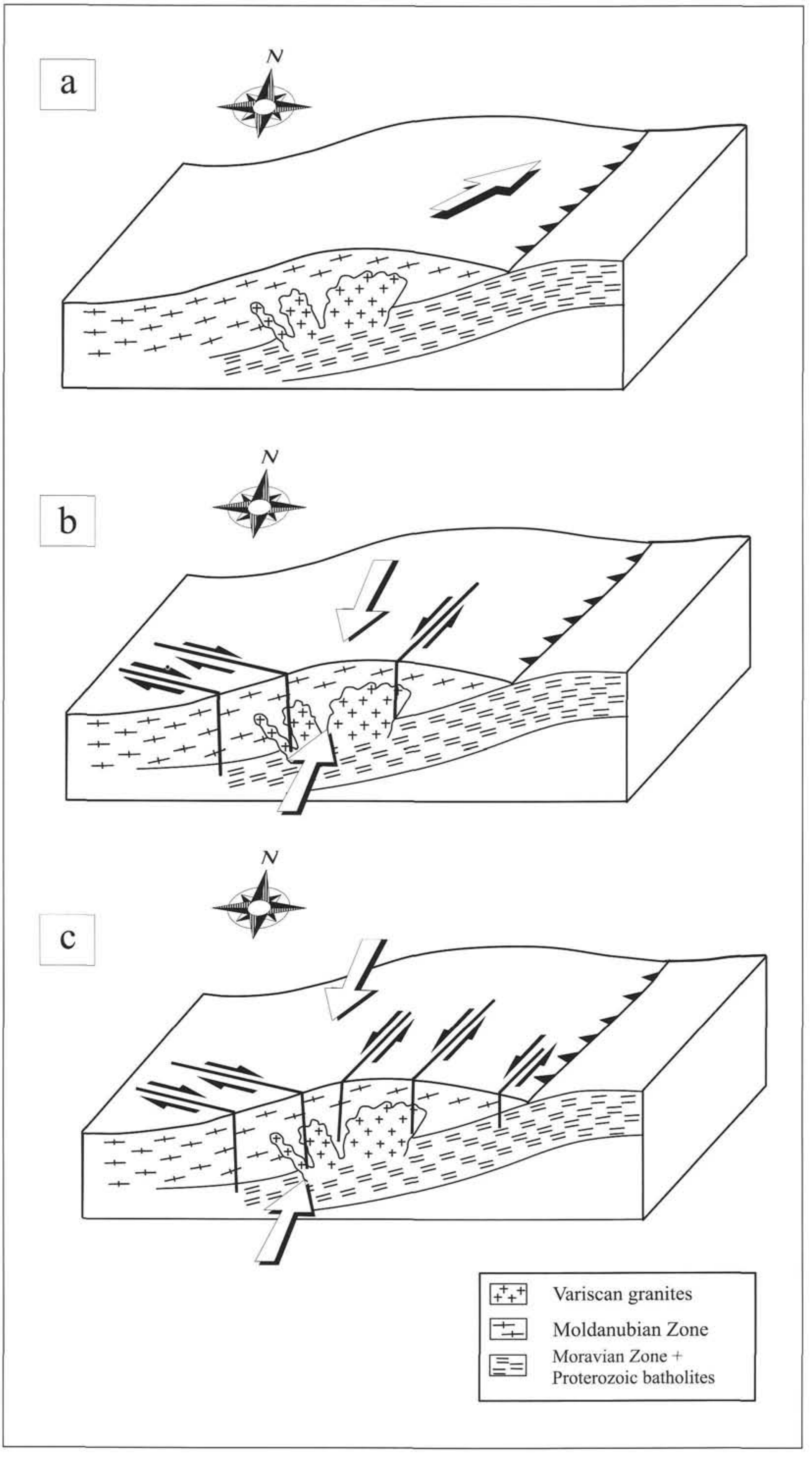


Fig. 12
(a) Northeastward directed transpression of an Early Paleozoic terrane onto a Late Proterozoic terrane. Arrow indicates direction of major thrusting (after FRITZ et al., 1996). (b) Initial shear zone activity in the Danube, Pfahl and Karlstift Shear Zones. Arrows indicate major compression directions. (c) Contemporaneous shear zone activity in all shear zones. Arrows indicate major compression directions.

FRANKE W., 1989: Tectonostratigraphic units in the Variscan belt of Central Europe. In: DALLMEYER R. D. (ed): *Terranes in the Circum-Atlantic Paleozoic Orogens*, Special Paper 230, 67-90.

FRASL G., 1970: Zur Metamorphose und Abgrenzung der Moravischen Zone im niederösterreichischen Waldviertel. – Nachr. Dtsch. Geol. Ges., **2,** 55-60.

FRIEDL G., VON QUADT A., OCHSNER A. & FINGER F., 1993: Timing of the Variscan orogeny in the Southern Bohemian Massif (NE-Austria) deduced from new U-Pb zircon and monazite dating. – Terra abstracts, Abstract supplement No. 1, **5,** 235-236.

FRITZ H., 1994: The Raabs Serie, a Variscan ophiolite in the SE-Bohemian Massif: A key for the tectonic interpretation. – Journal of the Czech Geological Society, **39**/ 1, 32-33.

FRITZ H. & NEUBAUER F., 1993: Kinematics of crustal stacking and dispersion in the southeastern Bohemian Massif. – Geol. Rundsch., **82,** 556-565.

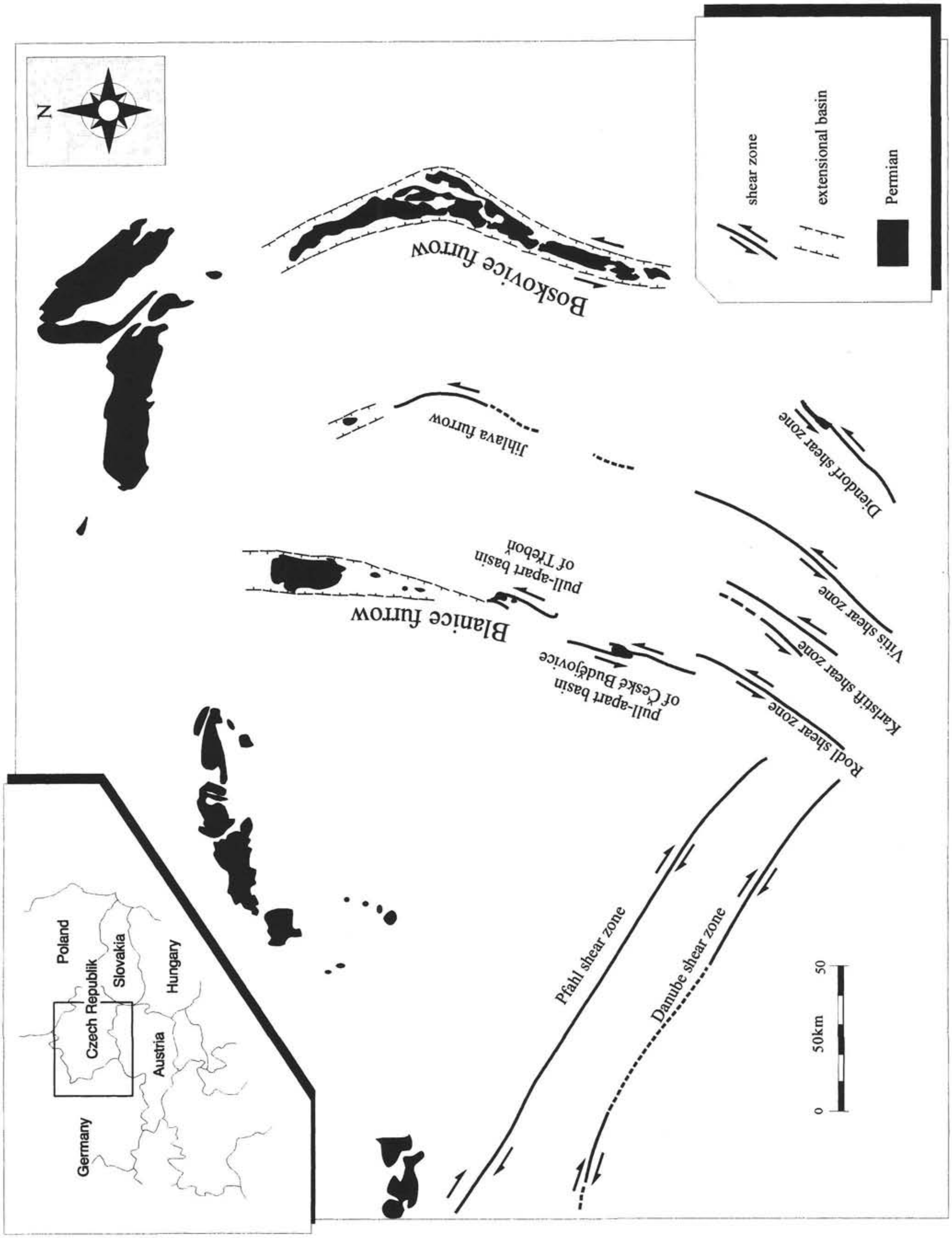


Fig. 13
Opening of the Blanice and the Boskovice furrows as a result of shear zone propagation towards the North.

FRITZ H., DALLMAYER R. D. & NEUBAUER F., 1996: Thick-skinned versus thin-skinned thrusting: Rheology controlled thrust propagation in the Variscan collisional belt (The southeastern Bohemian massif, Czech Republic – Austria). – Tectonics, **15**, 6, 1389-1413.

FUCHS G. & MATURA A., 1976: Die Geologie des Kristallins der südlichen Böhmischen Masse. – Jahrb. Geol. Bundesanst., **119**, 1-43.

FUSAN, O., KODYM, O., MATEJKA, A. & URBANEK, L., 1967: Geological Map of Czechoslovakia, M 1:500 000, Praha.

GREEN H. W., GRIGGS D. T. & CHRISTIE J. M., 1970: Syntectonic and annealing recrystallization of fine-grained quartz aggregates. In: PAULITSCH P. (ed): Experimental and natural rock deformation. – 272-335, Berlin-Heidelberg (Springer).

GRIGGS D. T. & BLACIC J. D., 1965: Quartz: anomalous weakness of synthetic crystals. – Science, **147**, 292-295.

HANDLER R., BRANDMAYR M. & WALLBRECHER E., 1991: The Rodl Shear Zone in the Southern Bohemian Massif. – Zbl. Geol. Paläont. Teil I, **1991**, 69-86.

HOBBS B. E., 1985: The geological significance of microfabric analysis. In: WENK H. R. (ed): Preferred orientation in deformed metals and rocks: An introduction to modern texture Analysis. – 463-483, Academic Press.

HODGKINS M. A. & STEWART K. G., 1994: The use of fluid inclusions to constrain fault zone pressure, temperature and kinemtatic history: an example from the Alpi Apuane, Italy. – J. of Struc. Geol., **16**, 1, 85-96.

HÖCK, V., MONTAG, O. & LEICHMANN, J., 1997: Ophiolite remnants at the eastern margin of the Bohemian Massif and their bearing on the tectonic evolution. – Mineralogy and Petrology, **60**, 267-287.

JAOUL O., TULLIS J. & KRONENBERG A. K., 1984: The effect of varying water content on the creep behaviour of Heavitree quartzite. – J. Geophys. Res., **89**, 4298-4312.

KLOETZLI U. S., 1993: Einzelzirkon-207Pb/206Pb-Datierungen an Gesteinen der südlichen Böhmischen Masse (Rastenberger Granodiorit, Weinsberger Granit) – Mitt. Österr. Miner. Ges., **138**, 123-130.

KLOETZLI U. S. & PARRISH R. R., 1996: Zircon U-Pb and Pb-Pb geochronology of the Rastenberg granodiorite, South Bohemian Massif, Austria. – Min.Petr., **58**, 197-214.

KRONENBERG A. K.; KIRBY S. H., AINES R. D. & ROSSMANN G. R., 1986: Solubility and diffusional uptake of hydrogen in quartz at high water pressures: Implications for hydrolytic weakening. – J. Geophys. Res., **91**, 12723-12744.

KRONENBERG A. K. & TULLIS J., 1984: Flow strengths of quartz aggregates: grain size and pressure effects due to hydrolytic weakening. – J. Geophys. Res., **89**, 4281-4297.

KRONENBERG A. K. & WOLF G. H., 1990: Fourier transform infrared spectroscopy determinations of intragranular water content in quartz-bearing rocks: implications for hydrolytic weakening in the laboratory and within the earth. – Tectonophysics, **172**, 255-271.

LISTER G. S., PATERSON M. S. & HOBBS B. E., 1978: The simulation of fabric development in plastic deformation and its application to quartzite: The model. – Tectonophysics, **45**, 107-158.

LISTER G. S. & DORNSIEPEN U. F., 1982: Fabric transitions in the Saxony granulite terrane. – J. Struct. Geol., **4**, 81-92.

LISTER G. S. & HOBBS B. E., 1980: The simulation of fabric development in plastic deformation and its application to quartzite: The influence of the deformation history. – J. Struct. Geol. **2**, 3, 355-370.

LISTER G. S. & PATERSON M. S., 1979: The simulation of fabric development in plastic deformation and its application to quartzite: Fabric transitions. – J. Struct. Geol. **1**, 2, 99-115.

LOIZENBAUER J., WALLBRECHER E. & FRITZ H., 1994: P-T conditions and deformation mechanisms of strike slip faults within the southern Bohemian Massif: A fluid inclusion study and microfabric analysis. – Mitt. d. Österr. Mineral. Gesellschaft, Conference Preprint, **139**, 84-86.

MAINPRICE D. H., 1981: The experimental deformation of quartz polycrystals, PhD-thesis Austr. Nat. Univ., Canberra, 171S.

MAINPRICE D., BOUCHEZ J. L., BLUMENFELD P. & TUBIA J. M.; 1986: Dominant c-slip in naturally deformed quartz: Implications for dramatic plastic softening at high temperatures. – Geology, **14**, 819-822.

MATTE PH., 1986: Tectonics and plate tectonics model for the Variscan belt of Europe. – Tectonophysics, **126**, 329-374.

MATTE P., MALUSKI H., RAJLICH P. & FRANKE W., 1990: Terrane boundaries in the Bohemian Massif: Result of large-scale Variscan shearing. – Tectonophysics, **177**, 151-170.

PLATZER R. & WALLBRECHER E., 1993: Rheological control of shear location within the Danube Shear Zone, Bohemian Massif, Austria. – Terra abstracts, Abstract supplement 1, **5**, 208.

POTTER R. W., 1977: Pressure corrections for fluid inclusions homogenisation temperaatures based on the volumetric properties of the system NaCl-H2O. – J. Res. U.S. Geol. Surv., **5**, 603-607.

POTTER R. W., CLYNNE M. A. & BROWN D. L., 1978: Freezing point depression of aqueous sodium solutions. – Ec. Geol., **73**, 284-285.

ROEDDER E., 1984: Fluid inclusions. – Rev. Min. Vol. 12, Chelsea, Michigan, 644 S.

SCHARBERT S., 1987: Rb-Sr Untersuchungen granitoider Gesteine des Moldanubikums in Österreich. – Mitt. Österr. Miner. Ges., **132**, 21-37.

SCHARBERT H. G. & FUCHS G., 1981: Metamorphe Serien im Moldanubikum Niederösterreichs. – Fortschr. Mineral., **59**, Beih. 2, 129-152.

SCHEIDEGGER A. E., 1976: Untersuchungen des Beanspruchungsplanes im Einflußgebiet der Diendorfer Störung. – Jb. Geol. B.-A., **119**, 83-95.

SCHULMANN K., LEDRU P., AUTRAN A., MELKA R., LARDEAUX J. M., URBAN M. & LOBKOWICS M., 1991: Evolution of nappes in the eastern margin of the Bohemian Massif: A kinematic interpretation. – Geol. Rundsch., **90**, 73-93.

SCHULMANN K., MELKA R., LOBKOWICS M., LEDRU P., LARDEAUX J. M. & AUTRAN A., 1994: Contrasting styles of deformation during progressive nappe stacking at the southeastern margin of the Bohemian Massif (Thaya Dome). – J. Struct. Geol., **16**/3, 355-370.

SUESS F. E., 1908: Die Beziehungen zwischen dem moldanubischen und moravischen Grundgebirge in dem Gebiet von Frain und Geras. – Verh. Geol. Reichsanst., 393-412.

SUESS F. E., 1912: Die moravischen Fenster und ihre Bezihung zum Grundgebirge der Hohen Gesenke. – Dkschr. Akad. Wiss. Wien, math.-natw. Kl. **88**, 541-631.

TAPPONNIER P. & MOLNAR P., 1976: Slip-line field theory and large scale continental tectonics. – Nature, **264**, 319-324.

TAPPONNIER P., PELTZER G., LE DAIN A.Y., ARMIJO R. & COBBOLD P., 1982: Propagation extrusion tectonics in Asia: New insights from simple experiments with plasticine. – Geology, **10**, 611-616.

TERZHAGI K. V., 1923: Die Berechnung der Durchlässigkeitsziffer des Tones aus dem Verlauf der hydrodynamischen Spannungserscheinungen. – Sitzungsber. Akad. wissensch. Wien, Math.-Naturw. Kl. Abt. IIa, **132**, 125-138.

THIELE O., 1976: Ein westvergenter kaledonischer Deckenbau im niederösterreichischen Waldviertel. – Jahrb. Geol. Bundesanst., **119**, 75-81.

TULLIS J., CHRISTIE J. M. & GRIGGS D. T., 1973: Microstructures and preferred orientation of experimentally deformed quartzites. – Geol. Soc. Amer. Bull., **84**, 297-314.

TULLIS J. & YUND R. A., 1980: Hydrolytic weakening of experimentally deformed Westerly granite and hale albite rock. – J. Struct. Geol. **2**, 4, 439-451.

TULLIS J. & YUND R. A., 1985: Dynamic recrystallization of feldspar: A mechanism for ductile shear zone formation. – Geology, **13**, 238-241.

TULLIS J. & YUND R. A., 1987: Transition from cataclastic flow to dislocation creep of feldspar: Mechanisms and microstructures. – Geology, **15**, 606-609.

VOLL G., 1976: Recrystallization of quartz, biotite and feldspars from Erstfeld to the Leventina Nappe, Swiss Alps, and its geological significance. – Schweiz. mineral. petrogr. Mitt., **56**, 641-647.

WALLBRECHER E., BRANDMAYR M. & HANDLER R., 1990: Kinematische Untersuchungen an Blattverschiebungszonen in der Südlichen Böhmischen Masse. – Österr. Beitr. Met. Geoph H3, **1990,** 97-120.

WALLBRECHER E., DALLMEYER R. D., BRANDMAYR M., HANDLER R., MADERBACHER F. & PLATZER R., 1991: Kinematik und Alter der Blattverschiebungszonen in der Südlichen Böhmischen Masse. – Arbeitstagung Geol. B.-A., **1991,** 35-48.

WHITE S., 1982: Fault rocks of the Moine thrust zone: A guide to their nomenclature. – Textures Microstruct., **4,** 211-221.

WISE D. U., DUNN D. E., ENGELDER J. T., GEISER P. L. A., HATCHER R. D., KISCH S. A., ODOM A. L. & SCHAMEL D., 1984: Fault-related rocks: Suggestions for terminology. – Geology, **12,** 391-394.

Manuscript received: 10. 06. 1998 ●
Revised version received: 26. 08. 1999 ●
Manuscript accepted: 14. 09. 1999 ●

Zeitschrift/Journal: Austrian Journal of Earth Sciences

Jahr/Year: 1997

Band/Volume: 90

Autor(en)/Author(s): Brandmayr M., Loizenbauer Jürgen, Wallbrecher Eckard

Artikel/Article: Contrasting P-T conditions during conjugate shear zone development in the Southern Bohemian Massif, Austria. 11-29